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FINAL PROJECT REPORT

EXTREME EVENTS PHASE 2

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DISCLAIMER

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Renewable Energy Technologies
- Transportation

Extreme Events Phase 2 is the final report for the Extreme Events project (contract number CEC-MR-08-03), conducted by Pacific Northwest National Laboratory, University of Wisconsin-Madison, Electric Power Research Institute, BACV Solutions, Southern Company, CIEE/PIER, University of Alaska – Fairbanks, and KEMA. The information from this project contributes to PIER's Energy Systems Integration Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

The electrical transmission system of California, like all interconnected transmission systems, is vulnerable to extreme events in which complicated chains of exceptional events cascade to cause a widespread blackout across the state and beyond. These large blackouts always have a substantial impact on citizens, business and government, and although they are rare events, they pose a substantial risk. Much is known about avoiding the first few failures near the beginnings of the cascades, but there are no established methods for directly analyzing the risks of the subsequent long chains of events. The project objective is to find ways to assess, manage and mitigate the risk of extreme blackout events. Since this is a difficult and complex problem, multiple approaches are pursued, including examining historical blackout data, making detailed models of the grid, processing simulated data from advanced simulations, and developing and testing new ideas and methods. The methods include finding critical elements and system vulnerabilities, modeling and simulation, quantifying cascade propagation, and complex systems and statistical analyses. The project team combines leading experts from industry, a national laboratory and academia.

Keywords: blackout, branching process, cascading failure, critical corridors, extreme events, heavy tail, outages, risk, critical, contingency, earthquake, electric, grid, OPA, power, TRELSS, WECC

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

The high voltage transmission grid for California is part of the larger Western power grid, a complicated and intricately coordinated structure with hundreds of thousands of components that underpins the electrical supply and hence the way of life for California citizens, business and government. Although the transmission grid is normally very reliable, extreme events in which disturbances cascade across the grid and cause large blackouts do occasionally occur with direct costs to society running to billions of dollars. Although such extreme events are infrequent, historical statistics show that they will occur. The electric power industry has always worked hard to avoid blackouts, and there are many practical methods to maintain reliability. However, the cascading-failure problem is so complex that there are no established methods that directly analyze the risk of the large blackouts. The overall project objective is to assess the risk of extreme-blackout events and find ways to manage and mitigate this risk. Managing the risk of extreme events is particularly important as society moves toward environmental sustainability. A reliable transmission grid is essential for enabling renewable energy sources and electric cars, especially as the grid itself evolves to a "smart" grid.

Purpose

A diverse team of experts from industry, a national laboratory, and academia develops and compares multiple approaches to analyze the risk of extreme events. The collaborating institutions are Pacific Northwest National Laboratory, BACV Solutions, Electric Power Research Institute, KEMA, Southern Company, the University of Alaska-Fairbanks, and the University of Wisconsin-Madison. The research comprised two phases. Phase 1 developed, adapted and validated methods on initially limited-size grid models. Phase 2 further developed, applied and illustrated these methods on more complete grid models. This report describes the final results completed in Phase 2 and the project conclusions.

Project Objectives

A variety of approaches were pursued in Phase 2. Historical blackout and line-trip data were processed to provide benchmarks for simulation and analysis. Simulation approaches included the Transmission Reliability Evaluation of Large-Scale Systems (TRELSS) and Oak Ridge – PSERC – Alaska (OPA) simulations: TRELSS is a leading industry simulation of cascading failure that describes the detailed cascading consequences of initial contingencies, with representation of many mechanisms of cascading failure including overloads, voltage problems, and the actions of protection and operators; OPA is a research-grade simulation of cascading failure incorporating probabilistic modeling and complex system effects. Both approaches provided simulated data for development and validation of analysis methods. New approaches using high-level models included branching processes, complex systems and statistical analyses.

The research outcomes are summarized according to the six "use cases" established to define project goals.

Use Case 1: Establish grid models and demonstrate their use in state-of-the-art cascading-failure simulations. Phase 2 extended the work being performed using the TRELSS software from a reduced-order model of the Western Interconnection to the full system model. The research team developed a process for generating a significant number of probable and non-redundant initiating events (~38,000) which yield results associated with other use cases such as identifying critical elements and system metrics.

The project demonstrated the use of the OPA simulation that accounts for complex system effects on approximate grid models with thousands of buses.

Use Case 2: Quantify extreme-event risk on grid models by improving, testing, and comparing multiple approaches. The team obtained estimates of extreme-event probabilities from analyses of historical blackout from the North American Electric Reliability Corporation (NERC) and line-trip data from a WECC utility and from simulated data produced by applying OPA to the grid models. Blackout risk was quantified using the NERC data with an approximate blackout cost assumption. Although extreme events only occur occasionally, the NERC data show a substantial risk of extreme events in the WECC. The OPA simulation computes the blackout probabilities accounting for complex system effects as the power system gradually adjusts itself to changes made. The OPA simulation has been calibrated to the WECC grid and validated in the sense that there is a good match between the OPA simulation results and the historical data. Statistical limitations for minimum sample sizes to estimate probabilities of rare events were established. Branching process models track the overall progress of a cascading blackout in a probabilistic way. Two quantities that indicate the progress of the cascade were analyzed: line outages and load shed. Testing on simulated data suggests that the branching-process models can predict the statistics of the total number of transmission lines outaged in extreme events. For similar predictions based on the line-trip data from a WECC utility, an accelerating propagation was observed, and the prediction of the probabilities of the total number of transmission lines outaged with a branching process that accounts for the acceleration gave a close match to the observed data. A new method for similarly predicting the distribution of load shed was also devised and tested. An initial prediction was made of how cascading extends the impact of an earthquake in terms of the total number of lines outaged.

Use Case 3: Identify network vulnerabilities, critical corridors, worst-case scenarios, and/or operational margins as well as parameters that correlate with extreme-event risk. Efforts focused on the development and validation of methods for processing and analyzing the voluminous simulation data to find critical components and conditions of the system. Methods were developed for identifying critical event sequences based on their occurrence in many simulated blackouts and for detecting initial line outages that are critical for initiating large blackouts and clusters of line outages that recur in the propagation of many cascades. Both of these methods look for patterns or combinations of weak elements that recur frequently in the simulated data. A scheme for ranking initiating events in order of severity was developed. Several parameters of the operational state such, as line loading margins and initial outages, were found to be correlated with large blackouts. A graph-theoretic analysis was developed to efficiently compute critical sets of transmission lines that separate the grid and are worst-case vulnerabilities in terms of the maximum power disrupted.

Use Case 4: **Quantify reliability benefits of transmission grid upgrades.** A study of distributed generation with the OPA simulation showed that increasing the proportion of variable distributed generation could, in some cases, increase the long-term frequency of the largest blackouts. When the OPA simulation computes reliability, it accounts for the long-term complex systems effect of the transmission grid slowly upgrading in response to blackouts.

Use Case 5: **Define metrics of extreme-event risk and ways to communicate the risk.** New metrics of cascading outage propagation were developed and tested on both simulated and real data. These metrics describe how much the cascade propagates in terms of transmission lines outaged or load shed as the cascade proceeds. These metrics are one measure of overall system resilience. Conventional blackout indices were reviewed and the problems caused by extreme events for indices that sum or average annual statistics were discussed. The project recommends the separate specification of small, medium, and large blackout probabilities and risks, or the use of distributions of blackout probability with respect to blackout size. An initial approach to better communicate blackout risk was found.

Use Case 6: Evaluate strengths and limitations of existing state-of-the-art simulation and analysis methods and define a road map for feasible enhancements. Two simulation approaches, deterministic and probabilistic, were used in this study to determine the strengths of each approach. The probabilistic results matched well with historical data and accommodated the upgrading of systems over time. The deterministic model's strength was the ability to simulate at the interconnection level using a tool that currently aligns with the methods NERC requires for Category D compliance. Both approaches made key discoveries in being able to identify locations within a system that are critical to either initiating or propagating large blackouts. Terms such as critical lines, critical clusters, and critical corridors are introduced. Road maps for technology advancement are provided and address issues of metrics, simulation, and application enhancements with the ultimate goal being industry acceptance and adoption of the approaches brought forward in this study.

Project Outcomes

The project has made substantial progress in finding new ways to understand and quantify extreme event risk and to compute worst-case scenarios from comprehensive contingency lists. The project established a range of grid models and ran advanced simulations to produce simulated extreme events. The project has framed problems of extreme event risk, and developed a variety of methods to process and monitor simulated and observed data to enable the quantification and mitigation of extreme event risk. The near-term emerging technology transfer opportunities include systematic generation of Class-D extreme event scenarios and a method to monitor the propagation of line outages using standard utility data.

This project has a number of potentially useful lessons that can be gleaned for policy makers, planners and operators of the power transmission grid, which in turn have implications for the ratepayers. Among these results are a few of note:

1. From a global perspective, the power transmission system in the Western Region, like those in the rest of the United States and most other developed countries, behaves in a

way characteristic of many large complex systems that are pushed to near their limit. Namely, there is a real risk of large-scale blackouts that is inherent to the system. Though the large blackouts are relatively rare, the economic impact of these large failures exceeds the impact of the much more frequent small failures. The project made substantial progress in characterizing this risk so it can be managed appropriately. The existence of this intrinsic risk is something that planners, policy makers and rate payers must be educated about in order that informed decisions can be made about managing this risk.

2. From the area of operations, the project has found that the average fractional load (the load divided by the limit) of the transmission lines is a good surrogate for the risk of large failures. If this average is kept below approximately 50 percent, the probability of large failures appears to decrease. If validated, this suggests a monitoring tool and operational strategy, which could have a significant impact on the reliability of the system. This in turn has major implications for the rate payer; operating at less than 50 percent of line capacity would lead to improved reliability for the users but would probably require investment in both the transmission capacity and demand-side control.

3. From the area of long time monitoring, the project has identified a possible system metric (called lambda-gaga) that will allow determination of the proximity of the system to the point at which large blackouts become more probable. If found to be valid, this will allow the effects of changes such as deregulation, smart grid penetration, changes in operational regulations and procedures, as well as changes in generation characteristics (such as increased wind and solar power, and so forth), to be quantified. From the point of view of the ratepayer, this metric can be used to look at the efficacy of these changes and potentially even to roll them back if they are found to degrade the operational characteristics.

4. From the area of the impact of the ongoing changes in the penetration of de-centralized and sustainable generation, the project has found that high-reliability decentralized generation can greatly improve the reliability of the power transmission grid. However, if the decentralized generation is high variability, as is the case with wind and solar in many places, the operation of the grid can be severely degraded. This can result in an increased probability of large blackouts and a higher frequency of failures. The project results suggest that one of the critical factors is the generation margin. If the high-variability non-centralized generation is brought online as an increase in the generation capacity margin, it is likely to improve the network robustness; however, if over time that margin declines again (as the demand increases) to the standard value, the grid could undergo a distinct decline in reliability characteristics. This suggests a need for care in planning and regulation as this decentralization increases. It should be noted that the worst case occurs when highly centralized high-variability generation such as large wind farms and the like, is added without the necessary increase in generation margin. The penetration of the de-centralized generation in the system has numerous clear effects on the rate payer, from decreased electricity costs and increased reliability, if implemented carefully, to decreased reliability and a concomitant increase in costs if not.

It is important to note that because this is a research project, many of these results need further validation. In addition to further comparison with data, more systematic and detailed studies are necessary to confirm these results and to give more quantitative prescriptions in all of these areas.

Benefits to California

Using the tools developed under this project, California benefits from this research through, increased reliability of the electrical grid through quantification of risks of extreme events, systematic computation of worst-case scenarios, identification of critical components and conditions that can be upgraded, and new ways to monitor and assess extreme event risk. Increased reliability will enhance the security and welfare of California citizens.

CHAPTER 1: Introduction

On August 10, 1996, a blackout started in the northwestern United States and cascaded to disconnect power to about 7,500,000 customers over the West Coast, including millions of customers in both northern and southern California. Power remained out for as much as nine hours, snarling traffic, shutting down airports and leaving millions in triple-digit heat. An initially small power-system disturbance, a sagging power line, cascaded into a complicated chain of subsequent failures leading to a widespread blackout. Although such extreme events are infrequent, historical statistics show they will occur. The resulting direct cost is estimated to be in the billions of dollars, not including indirect costs resulting from social and economic disruptions and the propagation of failures into other infrastructures such as transportation, water supply, natural gas, and communications.

Large blackouts pose a substantial risk that must be mitigated to maintain the high overall reliability of an electric power grid. As the control of the power grid becomes far more complex with the increasing penetration of new generation sources such as wind and solar power and new electric loads such as electric cars, maintaining high reliability of the electric grid becomes even more critical.

The backbone of electric power supply is the high-voltage transmission grid. The grid serving California is part of the larger Western Interconnection, administered by the Western Electricity Coordinating Council (WECC), which extends from the Mexican border well into Canada and from the Pacific coast to the Rocky Mountains. The western power grid is an impressively large and complex structure. While the extent of this grid provides it with certain reliability benefits, it also adds vulnerabilities because it provides multiple paths for any local disturbance to propagate. This is the problem of cascading failure; a series of failures occur, each weakening the system further, making subsequent failures more likely.

Research Objectives

This research develops new methodologies/constructs to assess, through modeling, simulation, and analysis, the risks to stability of the electric transmission grid and provides strategies for mitigating these risks. The first phase developed risk-assessment techniques that address the probabilistic nature of potentially harmful operational events, including the dynamic interactions of events. By developing techniques to address the complexity of failures involving many components, this research is intended to improve the state of the art of transmission-system risk assessment.

The second phase performed a risk assessment on the transmission grid and its western interconnections that are under management by the California Independent System Operator (CAISO) and the California investor-owned utilities (IOUs) and illustrates the manifestation of these risks on a state-of-the-art simulation of the transmission grid. The results will provide both technical and policy participants useful insights regarding transmission systems' vulnerabilities and the value of investments that would prevent cascading failures. An objective of this project is to identify approaches for avoiding or mitigating an extreme event, especially a cascading outage, to limit its impact on the electric system and the California customers served by that system.

Efforts in Phase 2 developed processes to discover the worst-case scenarios and initiating events. The ability to test and compare cascading-failure risk analysis using the variety of tools developed in Phase 1 and optimized during Phase 2 is integral to the overall efforts accomplished.

Relationship to PIER Goals

The project meets the PIER Goal of developing planning and operational tools that will improve transmission system reliability. The envisioned tools will help engineers, planners, and operators make intelligent choices that maintain system integrity while operating the system at maximum capacity and accommodating a proliferation of new independent power sources. These tools will also improve long-range planning for critical transmission paths.

Project Overview

This project was commissioned at the request of the California Institute for Energy and the Environment (CIEE); it brings together academic and industrial researchers to develop methods to identify and assess risk of extreme events inherent to the operation of the transmission grid of California and the western United States.

The research team comprises the following organizations:

- Pacific Northwest National Laboratory (PNNL)
- University of Wisconsin-Madison (UWM)
- University of Alaska-Fairbanks (UAF)
- BACV Solutions, Inc.
- KEMA
- Electric Power Research Institute (EPRI)
- Southern Company

Mark Morgan (PNNL) is the project leader, Ian Dobson (UWM) is the technical lead for the project, and Lorraine Hwang (University of California Berkeley CIEE) is the research coordinator.

The goals of the effort are to establish grid models for simulation and analysis, quantify extreme event risk, identify key system vulnerabilities, and quantify reliability benefits of upgrades. A variety of approaches for tackling these complicated and challenging aspects of extreme events will be used and compared; then the strengths and limitations of the various approaches will be evaluated and the road ahead will be surveyed.

Phase 1 Review

The research steps taken in Phase 1 were:

- Model Development: With the assistance of the CAISO, limited size (~1000-bus) grid models for the Western Interconnection and a California-centric model were developed. The WECC system-wide model (~16,000 buses) was the source model for these reductions. Several other models were developed and studied while these models were being prepared. The system models were validated against the base case using traditional tools, such as the General Electric Company (GE)'s Positive Sequence Load Flow software (PSLF), and converted to the forms needed for the various simulations and analysis methods used in the project.

- Simulations and data: The developed grid models were analyzed with several simulations. The Transmission Reliability Evaluation of Large-Scale Systems (TRELSS) is a commercially available tool initially developed by EPRI and Southern Company for cascading-failure analysis. Automated tools were developed to generate initiating events, and simulation runs were performed for more than 38,000 initiating events. The Oak Ridge/PSERC/Alaska (OPA) model is a research-grade simulation incorporating probabilistic modeling and complex system effects. These simulations produced large quantities of output describing many cascading events, and software to read and process the simulation outputs. Historical blackout data from the NERC and a Western Electricity Coordinating Council (WECC) utility were obtained and analyzed to understand and quantify system behavior.

- Results analysis: Several new analysis techniques were developed with promising initial results. Methodologies were developed for identifying critical corridors and transmission lines based on the frequency of their occurrence in many simulated blackouts. Branching process models were validated and used to efficiently predict statistics of blackout size and extent. New metrics that describe how cascading propagates were developed. A brittleness robustness analysis based on graph theoretic methods identified critical sets of transmission lines in the grid. An initial prediction was made of how cascading extends the impact of an earthquake. Initial comparisons of the various simulation and analysis approaches and the historical blackout data have been made in order to validate the results and highlight the different assumptions. These research results supported the general objective of being able to identify, recommend, and analyze metrics to quantify severity of blackouts in California and the Western Interconnection. This project provides a set of indices that could be used to categorize and assess the risk of blackouts and extreme events.

Phase 1 activities were performed on reduced-order models of the WECC and California-centric systems. Phase 2 is the logical extension of this effort, deepening the analysis and using models with higher fidelity to actual grid topology. This report describes the efforts taken during Phase 2 based upon the lessons learned during the initial phase, the advice provided by the Project Advisory Committee, and the leadership provided by the CIEE research coordinator for this project.

Appendices

By design this report is a concise accounting of the research performed during the second phase of the project. To ensure that full value of the work is realized, where appropriate, appendices have been included to provide a more complete explanation of the work that was performed. Appendices B through G fulfill this objective.

Appendix A is a compilation of the publications released and presentations made resulting from the Extreme Events research project.

CHAPTER 2:
Methodologies

Two different approaches were used in the study for cascading failure simulations. These approaches are briefly explained in the following sections. Sources of data used in this study are also described as well as the branching process as it applies to extreme events.

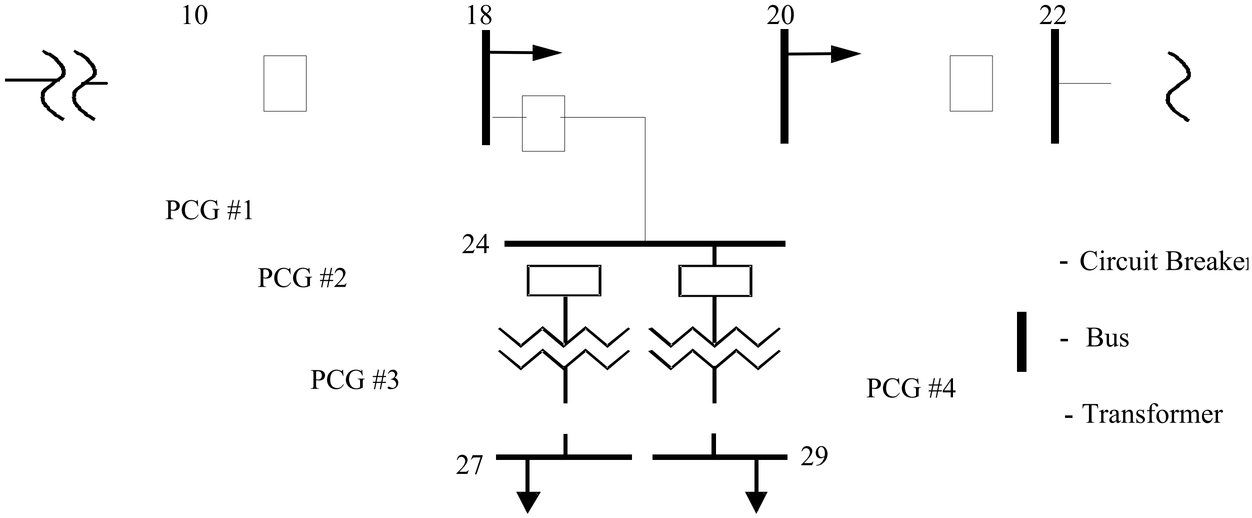
TRELSS Cascading Failure Simulation Approach

The first method simulates network vulnerability to cascading failures due to a pre-specified set of initiating events. This methodology is implemented as part of the TRELSS software package [EPRI 1982a, 1982b, 1988a, 1988b, 2000, 2003; Hardiman et al. 2004].

This approach uses a full nodal model for the power system to be analyzed. A fundamental requirement in this methodology is the identification of what are termed Protection and Control Groups (PCGs). A PCG roughly corresponds with the primary zone of protection. PCGs can be automatically identified by TRELSS by first imposing a predetermined breaker location that is based upon long-established system protection practices, and then PCGs are traced by a network-trace algorithm. For the Extreme Events Phase 2 studies, such a method was utilized because breaker locations for the utilized full WECC power-flow case were unavailable.

Figure 1 illustrates sample PCGs. Four PCGs have been identified in a portion of a system as shown above. If the breakers protecting the line spanning buses 10 and 22, a primary PCG, trip, then the secondary PCGs 2, 3 and 4 get isolated and all loads at buses 27 and 29 in addition to loads at buses 18 and 20 will be unserved.

Figure 1: Sample Protection and Control Group



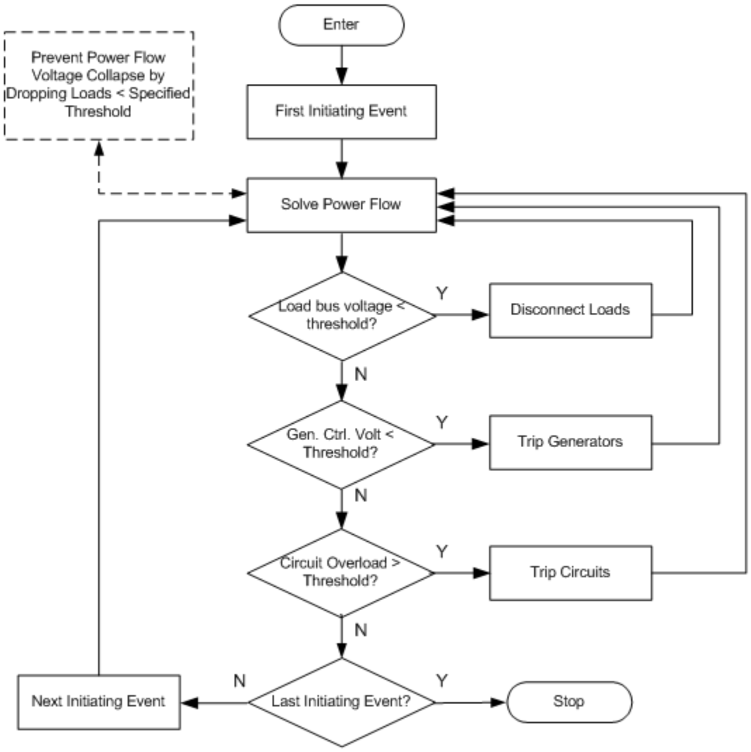
The essential input data to simulate cascading failures in TRELSS are:

- Power Flow Case in an appropriate format (Typically Siemens Energy, Inc., Power Technologies International PSS®E Raw Data); other formats can be converted.
- Actual breaker locations, though if this information is not available breaker locations can be automatically created through the use of the TRELSS PCG functionality.
- A list of initiating events that act as the trigger for cascading failure analysis.

The Algorithm for Cascading Failure Analysis

The flow chart shown in Figure 2 illustrates the method of cascading failure analysis implemented in TRELSS. The analysis shown is for a single load level; other load levels are simulated in a similar fashion analyzing the impact of initiating events upon the power system.

Figure 2: Flowchart of Cascading Failure Analysis



The starting point of this analysis is a list of initiating events supplied by the user. An initiating event can be supplied as a combination of transmission line, generator, and/or transformer outages. If a line-section outage is specified, the PCG it belongs to is identified as well as any dependent components that may go out of service as a result of the outage of the primary PCG. Other user specifications include: a "voltage collapse" threshold to prevent the power flow solution from diverging, a load-bus tripping threshold that to some extent models the setting of a low-voltage relay, a generator control voltage tripping threshold, and an overload threshold for tripping overloaded lines.

Starting with the first initiating event, the identified PCGs are simultaneously taken out of service. A power flow solution is attempted, and if voltage collapse conditions are detected at certain buses then the loads at these buses are tripped out of service. This assures that a power-flow solution is reached to the extent possible given that the extreme events being analyzed comprises outage of a large number of components.

The solved power flow system state is now first scrutinized for load-bus voltages that are below the user-specified threshold. If under-threshold buses are detected then the loads at these buses are tripped, mimicking the action of a low-voltage relay or a motor stalling. The resulting system becomes the starting point for the next power flow solution.

If no load-bus voltages are below threshold, generator terminal voltages are examined to identify the ones that are below that specified threshold. If any of them are found, the corresponding generators are tripped and another power flow solution is attempted.

If neither load bus voltages nor generator terminal voltages are lower than the respective specified thresholds, then circuits that are overloaded above the specified limit are identified. The PCGs containing the highest loaded line segment are determined and tripped. This then forms the cascading outage.

The tripping sequence is continued until the power flow solution is unable to converge or a maximum of 20 cascading power flows is reached.

The resulting load loss for each cascade is tabulated and reported, including system violations such as overloads and voltage violations. The amount of load loss for each category of tripping is also reported.

This procedure is repeated for each initiating event until the user specified initiating events list is exhausted. The initiating events list can have tens of thousands of initiating events.

OPA Model Summary

The Oak Ridge-PSERC-Alaska (OPA) simulation [Carreras 2004] is a research-grade simulation for studying the long-term reliability and complex dynamics of a power system that experiences blackouts caused by cascading line outages and is slowly being upgraded to maintain reliability. There is further discussion of OPA in Appendix C1.

OPA represents cascading outages and line overloads with a DC load-flow model. Starting from a solved base case, blackouts are initiated by random line outages. Whenever a line is outaged, the generation and load are re-dispatched using standard optimization methods. The optimization avoids load shedding where possible. If any lines were limited during the optimization, then these lines are outaged according to a fixed probability. The process of generator redispatch and testing for outages is iterated until there are no more outages. This modeling neglects many of the cascading processes in blackouts and the timing of events, but it is consistent with basic network and operational constraints.

The distinctive feature of the OPA simulation is that it also models how power systems slowly are upgraded over time. This makes a power system a complex system. As the average load on the entire power system slowly increases, lines involved in blackouts are upgraded, and generation is increased to maintain margins and coordinate with the line increases. There is a strong feedback loop by which the power grid adjusts its upgrading according to its reliability. If there are few blackouts, there are few upgrades, and operational margins tend to decrease. If there are many blackouts, and in particular large blackouts, then the system upgrades more. OPA simulates this process until it settles down to a stable pattern of blackouts, which describes the long-term reliability of the power system. If one makes a change to the power system, the OPA model accounts not only for the immediate change in reliability, but also the long-term change in reliability as the system adjusts itself to the changes.

An important feature of OPA is that the patterns of loading change randomly for each cascade simulated. This implies that, in addition to having random triggering events, a range of operating states are sampled as the network evolves. Moreover, there are some random choices about which lines trip as the cascade proceeds. It is realistic to have some "noise" in the operating state and in the cascade propagation so that a full range of different cascading behaviors is simulated and so that the blackout statistics produced by OPA are based on appropriate sampling of these behaviors.

The simple representation of the cascading and upgrading processes is desirable both for studying only the main interactions governing the complex dynamics and for pragmatic reasons of model tractability and simulation run time. OPA requires very long runs (up to tens of thousands of cascades) in order to track the complex dynamics of the upgrading. The input data for OPA is a DC load-flow description of the network, line-flow limits, and parameters controlling the probabilistic tripping of lines, average growth rate and upgrading of lines and generation. The output data describes a series of cascading blackouts as the power system gradually evolves, including the line tripping and load shed in stages of each blackout. Thus OPA produces statistics such as probability distributions of the number of line failures and amount of load shed. (More precisely, when the evolving system settles down to have stationary statistics, the distributions of the number of lines outaged and fraction of load shed can be obtained.)

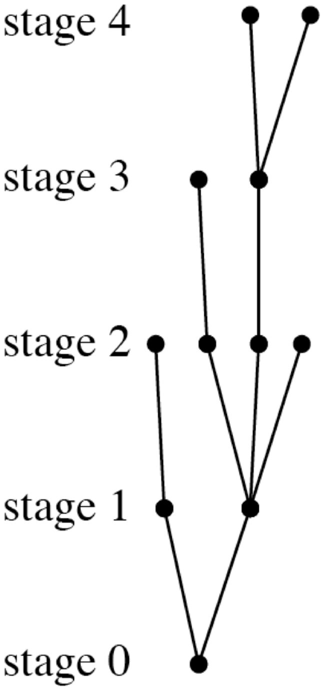
Key features of OPA of use in the project are:

- OPA systematically samples from the operating state of the system.
- OPA makes some probabilistic choices in simulating the cascades.
- OPA models complex system effects as the network evolves to compute the statistics of the long-term reliability.

Branching Processes

The Galton-Watson branching process gives a high-level probabilistic model of how the failures in a blackout propagate. A number of initial failures propagate randomly to produce subsequent failures in generations or stages. Each failure in each generation (a "parent" failure) independently produces a random number 0, 1, 2, 3, ... of failures ("children" failures) in the next generation. The distribution of the number of children is called the offspring distribution. The children failures then become parents to produce another generation, and so on. If the number of failures in a generation becomes zero, then all subsequent generations have zero failures and the cascade stops. An example of a cascade starting from one initial failure in the first generation is shown in Figure 3.

Figure 3: An Example of a Cascade Produced by the Galton-Watson Branching Process



The mean number of children failures for each parent is the parameter λ. λ is the average family size and λ quantifies the tendency for the cascade to propagate, since large family sizes will cause the total number of cascades to grow faster. The branching-process model does not represent any of the physics or mechanisms of the failure propagation, but after it is validated, it can be used to predict the total number of failures from an assumed random or deterministic number of initial failures. The intent of the branching process modeling is not that each parent failure in some sense "causes" its children failures; the branching process simply produces random numbers of failures in each generation that can statistically match the outcome of cascading processes.

The parameter λ measures the propagation in real data or in simulated data. The parameters of a branching-process model can be estimated from a much smaller data set, and then predictions of the total number of failures can be made based on the estimated parameters. While it is sometimes possible to observe or produce large amounts of data to make an empirical estimate of the total number of failures (and this is the way the branching-process prediction is validated), the ability to do this via the branching-process model with much less data is a significant advantage that enables practical applications. The simplicity of the branching-process model also allows a high-level understanding of the cascading process without getting entangled in the various mechanisms of cascading. The branching-process model should be seen as complementary to approaches with detailed modeling of the mechanisms of cascading failure. This project validates, improves, and exploits the application of branching processes to cascading-failure blackouts.

In the project terminology, “failure” of a component can include automatic or manual de-energizing of the component so that it is not damaged but is unavailable to transmit power, or a component malfunctioning or the component becoming damaged. Other types of failures are human errors or errors in software or operational procedures.

The eventual behavior of the branching process is governed by the propagation parameter λ. In the subcritical case of λ (each parent failure has on average less than one child), the failures will die out; this usually corresponds to either no blackout or a small blackout. In the supercritical case of λ (each parent failure has on average more than one child) the failures increase exponentially until the system size or saturation effects are encountered. At the critical case of $\lambda=1$, the branching process has a power-law distribution of the total number of failures with a heavy tail, as observed in the real blackout data.

Historical Data

NERC Data

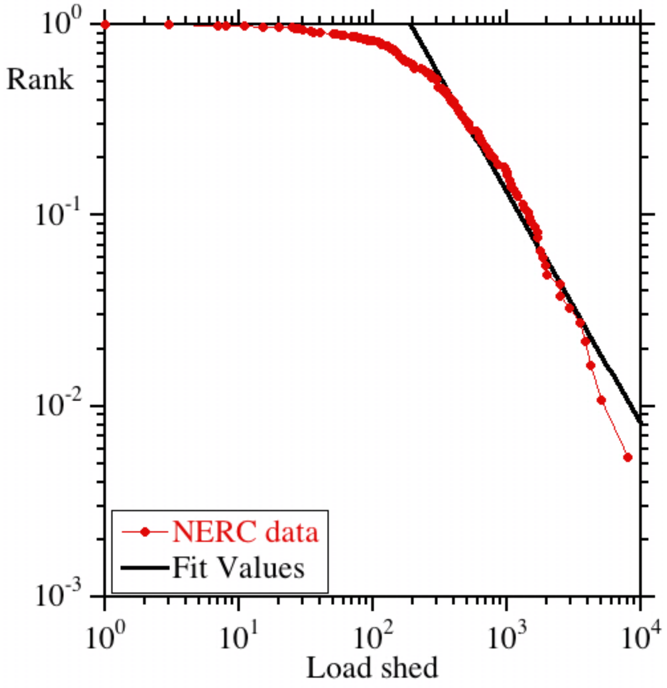
The North American Electric Reliability Corporation (NERC) has made public data for reportable blackouts in North America. Blackouts in the WECC for the 23 years from 1984 to 2006 have been analyzed. The 298 blackouts in the WECC data occur at an average frequency of 13 per year. The main measures of blackout size in the NERC data that are used in the project are load shed (MW) and number of customers affected. Blackout duration information is also available, but the data quality is less certain.

The empirical probability distributions of WECC blackout size can be obtained from the data. For example, Figure 4 shows the empirical distribution of load shed. (Note the log-log scale. A straight line on a log-log plot indicates a power law in the distribution. For example, if the straight line has slope -1, then the number of blackouts larger than a given size is halved when the given size is doubled. The power law indicates a heavy tail in the distribution.) The heavy tail in the distribution in Figure 4 indicates that larger blackouts are more likely than predicted by conventional risk analysis methods. The heavy tail can be understood qualitatively as a result of cascading failure. As the blackout proceeds, the system is weakened and it tends to become more likely that further failures, and hence larger blackouts, will occur.

The NERC data follows from government reporting requirements. The thresholds for the report of an incident include uncontrolled loss of 300 MW or more of firm system load for more than 15 minutes from a single incident, load shedding of 100 MW or more implemented under emergency operational policy, loss of electric service to more than 50,000 customers for 1 hour or more, and other criteria detailed in the U.S. Department of Energy forms EIA-417 and OE-417. The NERC data has some imperfections that include missing or incorrect data. Both the power system and reporting practices change somewhat over time.

The NERC data is foundational to the project in providing evidence that extreme events have substantial risk, an important clue that power systems are complex systems, and in benchmarking the OPA simulation.

Figure 4: Probability of WECC Blackouts Exceeding x MW Load Shed as a Function of x (Complementary Cumulative Probability Distribution of Load Shed)



Line-Trip Data

The transmission line outage data set consists of 8864 automatic line outages recorded by a WECC utility over a period of ten years. This is an example of the standard utility data reported to NERC for the Transmission Availability Data System (TADS). The data for each transmission line outage include the trip time. More than 96 percent of the outages are of lines rated 115 kV or above. Processing identified 5227 cascading sequences in the data. Some of these cascades are long sequences of events, but most are short. The line-trip data is invaluable to the project and proved to be essential in understanding propagation of line failures, validating branching process models and the OPA simulation, and developing methods to monitor the power system.

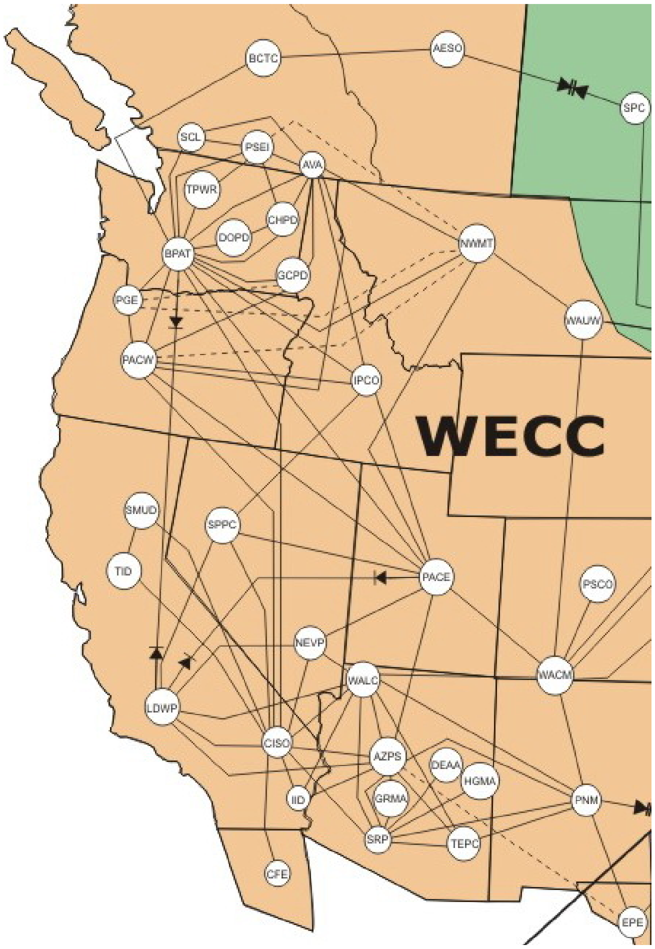
CHAPTER 3:
Network Model Summary

Summary of Models Used in Phase 2 of the Study

TRELSS Models

In Phase 2 of the project, a full WECC nodal model was used in cascading-failure analysis in TRELSS. The base case for simulation is the WECC Summer 2009 high load planning case. The full WECC interconnection system comprises 37 balancing authorities (BAs), 14,324 high- and medium-voltage transmission lines, 6,533 transformers, a total of 16,157 buses of which 8,230 are load buses, and 3,307 generating units. The grid has 62 major transmission paths between different areas. An illustration of the WECC BAs structure and the power flow gates between the BAs is shown in Figure 5.

Figure 5: Balancing-Authorities Structure of the Western Interconnection



Source: [NERC 2007]

This is the first-of-its-kind attempt to simulate the entire WECC system for cascading analysis.

During Phase 1 of the project, a uniform WECC reduced model and a California-centric reduced model were developed and used in TRELSS simulations. The system was reduced from 16,157 buses in the full WECC system to 1,328 buses in the reduced system. The California reduced model was reduced to a 992-bus system in which all the five main control zones in the California system, that is, Southern California Edison, Los Angeles Department of Water and Power, San Diego Gas and Electric, Imperial Irrigation District, and Pacific Gas and Electric were retained. All tie lines between these zones and external areas were represented by equivalent generating units. A comparison between simulation results for reduced models and the full WECC model is given in Chapter 5 of this report.

OPA Grid Models

During Phase 2 of this project, a series of reduced WECC grid models were used with OPA to investigate the vulnerabilities of the WECC system. The grid models and the use of OPA were validated by successfully reproducing the statistical characteristics of the actual WECC blackouts as shown in Chapter 5. These models were then used to develop and test methodologies to study the system and indices to characterize the system.

A variety of reduced WECC grid models were extensively exercised with OPA. These include grid model sizes of 225, 1553, and 2507 buses. All of these grid models, as well as the full WECC model, are called “uniform” because they represent all of the WECC at a uniform level of detail. The full WECC model can be run, but at present code speeds will not produce useful statistics in a reasonable amount of time because of the large number (hundreds of thousands) of runs needed to sample the various initiating triggers, system states, and cascades and to capture the complex dynamics of the upgrading grid. For future work, two techniques are being used to accelerate OPA to make the investigation of the 16,000-bus model more feasible. Even though the full model could not be analyzed at this time, studying the reduced WECC models of different sizes was fundamental to understanding scaling in interpreting the various results. Various results in this work come from the 225-bus, 1553-bus and 2507-bus models with some studies being limited to the first two due to speed limitations. Some further work was also done on a 1080-bus California-centric model.

Professor Chen-Ching Liu of University College Dublin graciously provided the WECC 225 bus AC load flow model. This model was originally created with some input and guidance from CAISO and used in a PSERC project. The 1553- and 2507-bus models are reductions of a 16,000-bus model of WECC. Ms. Irina Green of CAISO performed the reductions. CAISO and PNNL provided AC load models for the 1553- and 2507-bus uniform WECC models to the University of Wisconsin in PSS®E format. Wisconsin wrote software to read these files, check the data, reduce it to DC load flow, verify the match between AC and DC, and produce input files for OPA.

Scalability

Phase 1 of the research project focused on processes for evaluating risk and system performance using reduced-order models of the WECC and California. The efforts of the initial phase were on usefulness of these methods.

Work during Phase 2 was to scale up to larger system models. This would answer the questions of whether the processes used in this research were feasible on larger system models and whether full system models would yield different results than reduced-order models. This latter question becomes important since it would influence the model size system engineers would require to perform system risk analysis.

TRELSS Scalability to Full WECC Model

Since TRELSS is a production-grade program and has been used for over 15 years, there were no significant limitations in the software to enhancing it to read and solve a larger power flow model. The main limitation was imposed because of two different storage mechanisms utilized for contingency analysis and for the remedial-actions power-flow update. The former utilizes the well-known [B′] and [B″] system matrices [Kothari and Nagrath 2008] whereas the latter utilizes the full-Jacobian matrix whose dimensions are correspondingly larger. To simulate the full WECC model, significant effort was expended to modify the software structure so that the enhanced version is now capable of handling 25,000 buses and 37,500 transmission lines.

OPA Scalability

Scalability is a valuable characteristic of computational tools in general; however for tools used to simulate the power transmission system it is even more important because of the desire to investigate the behavior of portions from subsets of the system, though reduced models of the system, all the way to the full system. As discussed elsewhere in this report, accurately assessing the risk of extreme events as well as investigating intrinsic vulnerabilities in the system and impacts of changes lead to two different but complementary requirements. One is the ability to sample a combination of large numbers of initiating events and different system states, and the other is to sample these enough to generate reasonable statistics. To fulfill these requirements, a very large number of simulated cascades are needed, a number that unfortunately grows with the system size. The OPA code has much more stringent requirements for speed because it represents not only cascading, but also the complex dynamics of the slow upgrading of the power system, which requires simulation of many more cascades in order to capture a wide range of initiating events in the wide range of system states that the evolving system samples. OPA was built as a research code aimed at long simulations (many simulated cascades), but on relatively small systems. Because it was not optimized for larger systems the Simplex solver, an optimizing linear programming (LP) solver, that was used scales as the system size to the third power, making it slow on large systems. While usable results rather than code development was the major focus of this project, some effort was devoted to increasing the computational efficiency of OPA to make simulations with the larger network systems feasible.

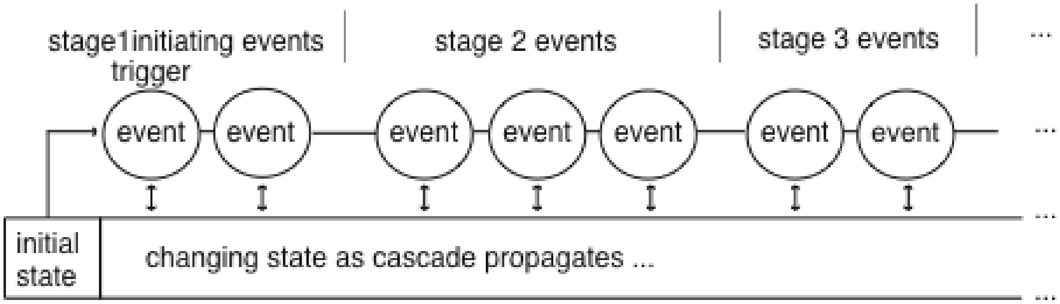
To this end three approaches have been developed. The first was a parallel Monte-Carlo approach, which performed simultaneous independent calculations in parallel. This approach has been very successful with a near-perfect scaling as expected in a Monte Carlo approach. Unfortunately, this has the disadvantage of not allowing system dynamics to be tracked for long times as all the parallel pieces are independent. In complex systems such as the power transmission grid, the long time dynamics have been shown to be important. So while this approach can be used for statistics and for some studies such as the vulnerability studies discussed elsewhere, it has limitations. The second approach was to replace the matrix solver with a state-of-the-art sparse matrix solver, appropriate because the power transmission grid is a highly sparse system. This was successfully completed and was found to increase the computational speed for larger systems but not by a large enough factor to make the largest simulations (using the WECC 16,000-bus system for example) feasible. The third approach has been to replace the entire Simplex solver with a new sparse simplex solver called the COIN-OR Linear Programming (CLP) solver. This promises to significantly increase the computational efficiency, perhaps by as much as a factor of 10. This approach is currently in the debugging stage. When fully tested, it will enable analysis of the largest systems if it performs as expected.

CHAPTER 4:
Extreme Event Risk

Anatomy of Cascading Failure

Cascading failure can be defined as a sequence of dependent events that successively weakens the power system [Baldick et al. 2008]. The events are often some individual power system component being outaged or damaged or mis-operating, but can also include a device functioning as designed but nevertheless contributing to the cascade, or actions by operators, software, or automatic controls. As shown in Figure 6, cascading failure starts with a trigger event and proceeds with further events. All the events interact with the system state as the cascade proceeds. The occurrence of each event depends on the system state, and the system state is affected by every event that has already occurred, and thus the system state changes throughout the cascade. The progressive weakening of the system as the cascade propagates is characteristic of cascading failure.

Figure 6: Anatomy of Cascading Failure



Possible trigger events include short circuits due to lightning, tree contacts, or animals, severe weather, earthquakes, operational or planning errors, equipment failure, or vandalism. The system state includes factors such as component loadings, which components are in service, generation margin, hidden failures, situational awareness, and weather.

The trigger event may immediately cause further events, which, together with the trigger event itself, form the initiating events. The initiating events are the first stage of cascading failure. The events occurring after the initiating events are also grouped into stages. Sometimes the stages of the cascade are referred to as generations. Two methods of grouping the events into stages are used in the project:

Method 1: The events are grouped into stages according to their timing. Events that occur in quick succession are grouped into the same stage. For example, one criterion is that a new stage starts whenever an event is separated in time from its preceding event by more than one minute. This criterion is related to the time scale of fast automatic control and protection devices, which typically act in less than one minute. That is, if one event leads to a following event of the trip of another component in less than one minute, then both events will be grouped in the same stage. The project used this method of grouping events into cascades to process real line-outage data.

Method 2: The events are grouped into stages according to how they are produced in a simulation. To simulate cascades, the computer code passes through the same calculations many times. To start the simulated cascade, the trigger event is generated (by choice or randomly), and the initiating events (Stage 1) are the trigger event together with any other events that have happened *after* the first pass through the simulation. Subsequent passes through the simulation produce the subsequent stages of the cascade (Stages 2, 3, …), until the simulated cascade stops.

Substantial cascading events are rare because often the initial system state is robust enough that it withstands the first few events and the cascade stops. But in an unfavorable initial system state, a trigger event can lead to many further events that become a substantial cascade and blackout. It is these large cascading events that cause the most damage and are classified as "extreme events."

The anatomy of cascading affects how simulations should sample or select the cases of cascades to be run. Each cascade is strongly influenced by the initial system state and by the trigger event, and indeed by the joint combination of the choice of initial system state and the trigger event. For example, a given trigger event will lead to further cascading events in some initial system states and will not propagate at all in other initial system states. Another example is that a given cascade might stop at the fourth event when the cascade starts from some initial system states and continue past the fourth event when the cascade starts from some other initial system states. It follows that trigger events and initial system states must be jointly sampled for each simulated cascade.

The anatomy of cascading affects the strategies for monitoring or mitigating cascading failure. It is possible to monitor or mitigate each of the triggers, the initiating events, and/or the further events in the cascade. It is useful to distinguish these for several reasons. The triggers and the subsequent propagation of events have different mechanisms, so that different approaches are needed to mitigate the triggers or mitigate the propagation. Moreover, the triggers and the propagation have different effects on the risks of small, medium, and large blackouts, so that managing these risks may require different combinations of mitigations for triggers and/or propagation. Limiting the triggers and initiating events reduces the frequency of all blackouts, but can in some cases actually increase the occurrence of the largest blackouts, whereas limiting the propagation tends to reduce the larger blackouts, but may have no effect on the frequency of the smaller events.

The initiating events can be associated with the cause of the trigger events and the immediately following actions of the protection system. Separate consideration of trigger events with different causes is the key to mitigating the triggers, since the response of the power system equipment and the possible mitigation differ depending on the cause. The causes of the triggers should also inform the mitigation of the initiating events. The further cascading events are best thought of as associated with the overall system resilience, and are often correlated with the overall "system stress." There is a much wider variety of multiple mechanisms and "causes" for the propagation of the further cascading events, often entirely different from the mechanisms and causes for the initiating events. Therefore mitigation of the propagation should be considered separately from the mitigation of the initiating events or triggers.

Oftentimes cascading events are classified by their root cause, which is the cause of the triggering event. However, classifying larger cascading events by root cause does not address the multiple, or underlying, "causes" of the propagation of the cascade. Establishing chains of causation that occurred in an instance of cascading is an essential and valuable practice. However, notions of causes (and blame) often can become murky in complicated cascades. For example, it is possible that automatic or manual control decisions that are advantageous in many standard system operational states and are overall beneficial may occasionally be deleterious.

Since the larger cascading failures result from both initiating events and the subsequent propagation of events, it is important to monitor and mitigate both the initiating events and the propagation. While the monitoring and mitigation for initiating events and for the propagation should be different, the mitigation has to be considered jointly. Decreasing the risk of initiating events while increasing the risk of propagation (or vice versa) may not minimize the overall cascading risk.

Some project results using this structure are:

- The OPA simulation reproduces quite closely the observed statistics of WECC in terms of distributions of blackout size and lines tripped. One factor contributing to this match is thought to be the joint sampling of trigger events and initial system states.
- The propagation of lines outaged in cascades can be monitored from standard TADS data reported to NERC. Note that the number of lines outaged in the initiating events can also be monitored from standard TADS data.
- Lines that are more often triggers for larger blackouts can be identified.
- Clusters of lines that outage together more often during propagation can be identified. Note that these lines often differ from the lines that more often trigger large blackouts.

Probabilistic Approach to Simulation of Rare Events

Cascading failure in power systems is inherently probabilistic. There are significant uncertainties in the initial state of the power system, in the triggering events, and in the way that the cascading events propagate or stop. The initial state of the power transmission system is always varying and includes factors such as patterns of generation and loading, equipment in service, weather, and situational awareness. Examples of trigger events are lightning, earthquakes, shorts involving trees and animals, equipment failure, and operational errors. The progress of cascading events depends on exact conditions and thresholds, can be very complicated, and can involve combinations drawn from dozens of intricate mechanisms, some of which involve unusual or rare interactions, that span a full range of physical and operational factors. It is appropriate to understand all these uncertainties probabilistically. Large blackouts are particular samples from an astronomically large set of possible but unusual combinations of failures.

From a modeling perspective, the underlying probabilistic view is driven by several factors. It is impossible to enumerate all the possible large blackouts because of the combinatorial explosion of possibilities. While some selected mechanisms of cascading failure can be usefully approximated in a simulation, it is well beyond the current state of the art to represent all (or even only the physics-based) mechanisms in great detail in one simulation. The full range of power system phenomena involved in cascading failure occur on diverse time-scales, and obtaining the full data (such as fast dynamical data) is difficult for the large-network cases needed to study large cascading blackouts. Most important, such a simulation, even if otherwise feasible, would be too slow. This does not mean that improvements in deterministic simulation of more mechanisms in more detail on larger models are not useful, it simply means that the problem of cascading failure is sufficiently difficult and complicated that these improvements have practical limitations, and should be pursued carefully and in a balanced way. There is a temptation to expand the modeling of the aspects of the problem that are better known and neglect those aspects that are poorly known. The project has made substantial progress in increasing the size of grid models that can be analyzed both deterministically and probabilistically. However, which cascading mechanisms to model and how much model and grid detail to use for each mechanism trade off with the requirements of sampling and simulation speed, and remains an open problem. It should be noted that probabilistic modeling is a useful way to approximate more detailed deterministic models.

A probabilistic understanding of cascading failure does not necessarily imply that the reliability rules must also be probabilistic. Indeed, it is useful to probabilistically evaluate deterministic reliability rules in order to evaluate their effectiveness in mitigating risk. For example, the effect of the deterministic N-1 criterion on long-term blackout risk is evaluated using OPA in [Ren et al. 2008]. Analysis of a past blackout as a deterministically causal sequence of events can suggest specific upgrades to mitigate cascading failure. However, the upgrades need to be evaluated in a probabilistic setting to evaluate their effect on blackout risk. To summarize, the evaluation of extreme event risk must be done in a probabilistic setting because risk is defined in a probabilistic setting, but the upgrades or rule changes being evaluated are often obtained in a deterministic setting. At the same time, it should be noted that extension or generalization of the current deterministic rules to probabilistic rules is a promising topic.

The current reliability rules are in a deterministic framework that requires the power system to withstand a selection of initiating events that stress the power system to a certain extent. Corresponding to this, some state-of-the-art blackout simulations subject several instances of the power system state to a selected list of contingencies, and examine the deterministic response of the power system to these stressors. A deterministic simulation can check the power system compliance with specific deterministic rules, but cannot evaluate whether these deterministic rules are the correct rules; that is, whether the rules are effective in mitigating risk. This is particularly important when generalizing current reliability rules to extreme events.

Probabilistic simulations work by sampling cascades of failures. Since appropriate sampling is essential in generating valid results from probabilistic simulations, the required sampling is discussed later in this section. From a deterministic point of view, the results from probabilistic simulations are a list of possible cascading events with specific values or thresholds assumed at each point of each cascade at which a random decision is simulated. Deterministic simulations also take a sample from a pool of system states and initiating events, even if the cascade simulation then proceeds deterministically. If this sampling is done in a way that reflects the frequency of the system states and initiating events, the results can be interpreted in either a deterministic or a probabilistic framework. If the results are interpreted deterministically, the results show the response to a defined list of stressors. If the results are interpreted probabilistically, some conclusions about risk may be possible. Thus there can be some overlap between deterministic and probabilistic simulations.

Both probabilistic and deterministic simulations require modeling compromises, and in particular require the selection of the cascading failure mechanisms to be modeled and how much each mechanism is approximated. Sometimes probabilistic models can be effective in approximately summarizing more detailed deterministic models.

Uniform sampling is important because it allows the frequency of events in the simulation results to be interpreted as probabilities of the events, which is basic for any risk analysis of the results. The sampling of cascading failures in simulations should be uniform in two senses:

1. Ideally, all the sources of uncertainty should be probabilistically modeled and sampled over their entire range of uncertainty. The simulation should model uncertainties in the system state, the trigger events, and the progress of the cascade. It may sometimes work to have one source of uncertainty to be modeled as uncertainty elsewhere. For example, uncertainty in line loading can substitute for uncertainty in line limits. At a minimum, it is necessary that there is overall sufficient noise to drive the system into a full range of outcomes. It is not realistic or properly sampled if the same cascading sequence recurs multiple times.
2. The probabilities of events should be approximated. For example, events of roughly equal probability should be sampled with equal probabilities.

Statistics of Rare Events: How Many Observations are Enough?

This section summarizes results on statistics of rare events. Details are in Appendix D2.

When observing rare events in real data or in simulations, it is necessary to consider how many observations are needed in order to draw justifiable conclusions (“One swallow does not a summer make”). The required number of observations of rare events has a large effect on the practicality of the observations, since it governs how long real data must be observed or how many runs of the simulation are needed.

Examples of events of interest are “a blackout bigger than 1000 MW,” or “a particular transmission line trips during a cascade,” or “a particular sequence of three specific lines trips during a blackout with more than 100 MW shed.” Of course, the event must be precisely specified in order to be analyzed.

Suppose that there are n independent observations or simulation runs, and a rare event is observed h times. h stands for the number of “hits” or occurrences of the rare event. The best estimate of the probability of the event is h/n. The difficulty for small numbers of hits h is that this probability estimate is useless if it is wildly different from the real probability. So it is required that the probability estimate be reliably sufficiently accurate. Quantitatively, this means that if the n observations are done 20 separate times, it is expected that 19 out of 20 times the estimated probability will be within a factor of two of the real probability. These particular numbers of “19 out of 20” and “within a factor of two” can be varied according to the risk preferences of the user of the probability estimate. This section uses these particular numbers, and the results for different choices of these numbers are given in Appendix D2.

Given the requirement that 19 out of 20 times the estimated probability will be within a factor of two of the real probability, it is now straightforward to state the main results derived in Appendix D2:

- 11 hits on the event are needed to estimate the probability of the event.
- 3 hits on the event are needed to conclude that its probability is greater than zero.
- Appendix D2 works out how many hits of two events are needed in order to conclude that one event is more likely than the other.

Having a sufficient number of hits of a rare event is not the only requirement for obtaining useful estimates of probabilities from simulations. It is also necessary to include all the possibilities and sample them uniformly so that there is no bias toward a particular subset of outcomes. This is discussed in Chapter 4.

Blackout Indices and Risk Communication

This section summarizes results on blackout indices and risk communication. Details are in Appendix D1.

Standard blackout indices measure blackout size by load shed, energy unserved, duration, number of blackouts, and number of customers affected. In the project, the indices most commonly used are the frequency of reportable blackouts and the distributions of the load shed or the number of lines outaged. Distributions are a meaningful way to represent the chances of blackout that do not reduce the data to a single number.

Standard blackout indices are problematic when applied to extreme events. The number of blackouts becomes dominated by the smaller distribution-system blackouts of lower impact. There can be very large variability in some indices if extreme events are included in their calculation. This large variability is inherent to the statistics of extreme events (it is a consequence of heavy tails in the distribution of blackout sizes). Hence, extreme events are sometimes excluded from blackout index calculations, and the way that this is done will skew the index.

For example, annual mean blackout size shows a large variability when extreme events are included in the calculation, and this makes the annual mean perform very poorly. According to Appendix D1, based on the heavy-tailed distribution of WECC historical data, the mean blackout size is about 1500 MW. However, the annual mean has a huge standard deviation of 2000 MW. This implies that in 85 percent of the years in which the annual mean is calculated, it will have an error differing from the true mean of 1500 MW by more than 500 MW. It takes 50 years of observations to obtain a 50-year mean with the smaller standard deviation of 280 MW.

In WECC, one could consider small blackouts to be less than 100 MW load shed, medium blackouts to be between 100 MW and 1000 MW load shed, and large blackouts to be more than 1000 MW load shed. The historical data implies that large blackouts are rarer than medium blackouts, but that the large blackouts are more risky than the medium blackouts because their cost is so much higher.

The new metrics of cascade propagation λ proposed by the project can be combined with a quantification of initiating event statistics to give promising ways to quantify the probability of extreme events. Future work would advance this approach for various measures of blackout size and seek a better determination of blackout cost so that better risk estimates could be made.

The probabilities of extreme events are best communicated to non-expert audiences with representative examples of natural frequencies of events rather than probabilities, conditional probabilities, and distributions. This is further discussed in Appendix D1. It is also necessary to communicate the uncertainty and variability in estimates.

This research effort also introduces a new metric for cascade impact: severity index. This metric is discussed in Chapter 5.

Risk of Large Blackouts

This section makes a rough estimate of the relative risks of large and medium blackouts, based on the historical data for WECC blackouts. Appendix D3 gives details.

The project makes the simple assumption that direct blackout costs are proportional to energy unserved. (Little is known about large blackout costs, but this is assumption is common.) Energy unserved is load shed times blackout duration. Project work for NERC North American data suggests that that blackout duration is proportional to the square root of load shed. This implies that blackout cost is proportional to load shed to the power 1.5.

Based on these cost assumptions, a rough calculation of large and medium blackout risk can be made. The NERC WECC blackouts are divided into small (<100 MW) medium (100 – 1000 MW) and large blackouts (>1000 MW). The largest recorded blackout is 30,390 MW. Small blackouts are not systematically covered by the reported data and are put aside. According to the data, the large blackouts have about 1/3 the probability of the medium blackouts. The average large blackout is roughly 8 times the size of the average medium blackout, so its cost is roughly 20 times larger. Since risk is probability times cost, the risk of an average large blackout is roughly 7 times the risk of an average medium blackout.

A better, but still rough, calculation (see Appendix D3) that improves on using averages estimates that the risk of large blackouts is roughly 11 times the risk of medium blackouts. The estimate is quite sensitive to the cost assumptions and to the largest blackout that occurs in the historical data. The estimate is conservative in only accounting for direct costs; the indirect costs of large blackouts can sometimes be very large. Future work could improve the cost and risk estimates. Although this rough calculation has many uncertainties, the conclusion that the risk of large blackouts is greater than that of medium blackouts is warranted. This conclusion supports the project focus on extreme events.

CHAPTER 5:
Results, Analysis, and Application to California and the Western Interconnection

Cascading Simulation Results Using TRELSS

This section gives an overview of efforts to analyze cascading outages for the full WECC model in TRELSS.

The first step for the TRELSS simulation was to prepare a large set of initiating events and conduct simulations. The results were further analyzed by ranking initiating events and critical corridors were identified.

Selection of Initiating Events

Power system cascading failures may occur due to the loss of several important elements, such as multiple generating units within a power plant, parallel transmission lines or transformers and common right-of-way circuit outages. The failure of these elements may widely propagate through the interconnected power network and result in a local or wide-area blackout. These kinds of failures that cause severe consequences are initiating events to a cascading failure. Some of the selected initialing events are in NERC Category D. Such events are not routinely analyzed by system planners and operators due to complexity of such events.

The selection of initiating events is a critical step in accurately simulating and analyzing large-scale cascading failures. Successful identification of initiating events can help effectively identify the most severe disturbances and help system planners propose preemptive system reinforcements that will improve both the security and the reliability of the system. Analyzing too few initiating events may not be sufficient to reveal critical system problems. At the other extreme, scanning all combinations of initiating events in a bulk power system is computationally impossible. As an example, the Western Interconnection contains approximately 20,000 transmission lines. Screening all combinations of N-2 contingencies requires approximately 199,990,000 simulation runs, which is beyond the capability of available simulation tools; for example, if time per run were 90 seconds, the total run time would be about 570 years.

Currently, only 5-50 contingencies are selected annually to perform extreme event analysis to comply with NERC requirements in the WECC system. The selections of these contingences are based on the experience of power grid operators and planners, that is, knowing critical elements in their systems. This limited set of events is included in the list created in this study.

In this study, eight categories of initiating events were collected for the entire WECC system from multiple sources such as historical disturbance information, known vulnerable system elements, engineering judgment, transmission sensitivity analysis methods and others. A large list with more than 35,000 initiating events was created for the full WECC model. The different types of initiating events are summarized below.

WECC Annual Contingency List Report

These events are selected from the annual stability analysis report from WECC. For each of the approved operating cases, such as heavy summer or heavy winter, a few transient simulations are performed to estimate the stability problems in the system. The annual contingency list changes for different study years. Most of these contingencies are N-1; few N-2 and N-3 cases are considered. Seventy-two initiating events in this category were collected after removing duplicates.

Complete Power Plant Outage

This type of initiating events considers the loss of all generating units within a single power plant. A MATLAB®[1] code was developed to collect generating unit information, including which power plant they belong to, using both the PSLF and WECC Transmission Expansion Planning Policy Committee (TEPPC) databases in Ventyx PROMOD IV software. A total of 1,110 events in this category were collected. These events are N-x, where x is the number of units in a single power plant.

Substation Outage

This type of initiating event considers the complete loss of a substation (bus) in the WECC model. It is used to simulate extreme events that result in a complete outage of all elements within a substation. A total of 8,000 initiating events in this category was generated considering all substations with voltage levels higher than 115 kV.

The Loss of Two Transmission Lines Based on Contingency Sensitivity Study

In this category, an N-2 contingency list was generated based on results of the full N-1 transmission line contingency analysis for the WECC model using the GE PSLF tool. For each N-1 line contingency analysis, any overloaded transmission line (the megavolt-ampere (MVA) flow exceeds its thermal capacity), together with the initial N-1 contingency line, was considered as one candidate for the N-2 contingency list. After removing repeated events a total of 26,278 events was selected.

Parallel Circuits Transmission Line Outage

Many of the higher-kV lines are made of two or more circuits on a common tower to increase their transmission capacity. However, during catastrophic events such as thunderstorms, lightning strikes or tornadoes, all the circuits of a multi-circuit transmission line can be out of service leading to huge power-transfer capacity loss. This contingency list considers all the transmission lines that have two or more parallel circuits originating and ending on the same buses. A total of 996 initiating events in this category was collected.

Common Right of Way and Line Crossings Outage

This outage list contains common corridors or common right-of-way (ROW) lines. Common ROW is defined by WECC as "Contiguous ROW or two parallel ROWs with structure centerline separation less than the longest span of the two transmission circuits at the point of separation

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[1] MATLAB is a registered trademark of The MathWorks, Inc.

or 500 feet, whichever is greatest, between the two circuits" [WECC 2009].This list of initiating events is very important since the right-of-way lines generally fall within similar geographical areas and any natural calamity can easily cause the outage of these transmission lines. A total of 53 initiating events in this category was collected using the information given in [BPA 2004].

Flow Gates Between Balancing Authorities

The flow gates between various balancing authorities represent important transmission-path gateways transporting large amounts of power. Loss of a flow gate can cause major problems for a balancing authority, especially if the BA is normally a power importer without sufficient local generation to meet demand. A total of 54 initiating events in this category was collected.

Major Transmission Interfaces in the WECC System

This event considers outages of major transmission interfaces or paths between different major load and/or generation areas as identified in WECC power-flow base planning case. These interfaces are the backbone of the WECC power grid, and the loss of any of these paths can have large impact. A total of 62 initiating events in this category was collected.

Summary of Simulation Results

A total of 33,124 unique initiating events was created based on the initiating event types mentioned in the previous section. An initiating event can be a combination of transmission-line, generator, and/or transformer outages. If a line section outage is specified, the PCG it belongs to is identified along with any dependent components that may go out of service as a result of the outage of the primary PCG. Table 1 summarizes the results obtained from the simulation of the created list of initiating events.

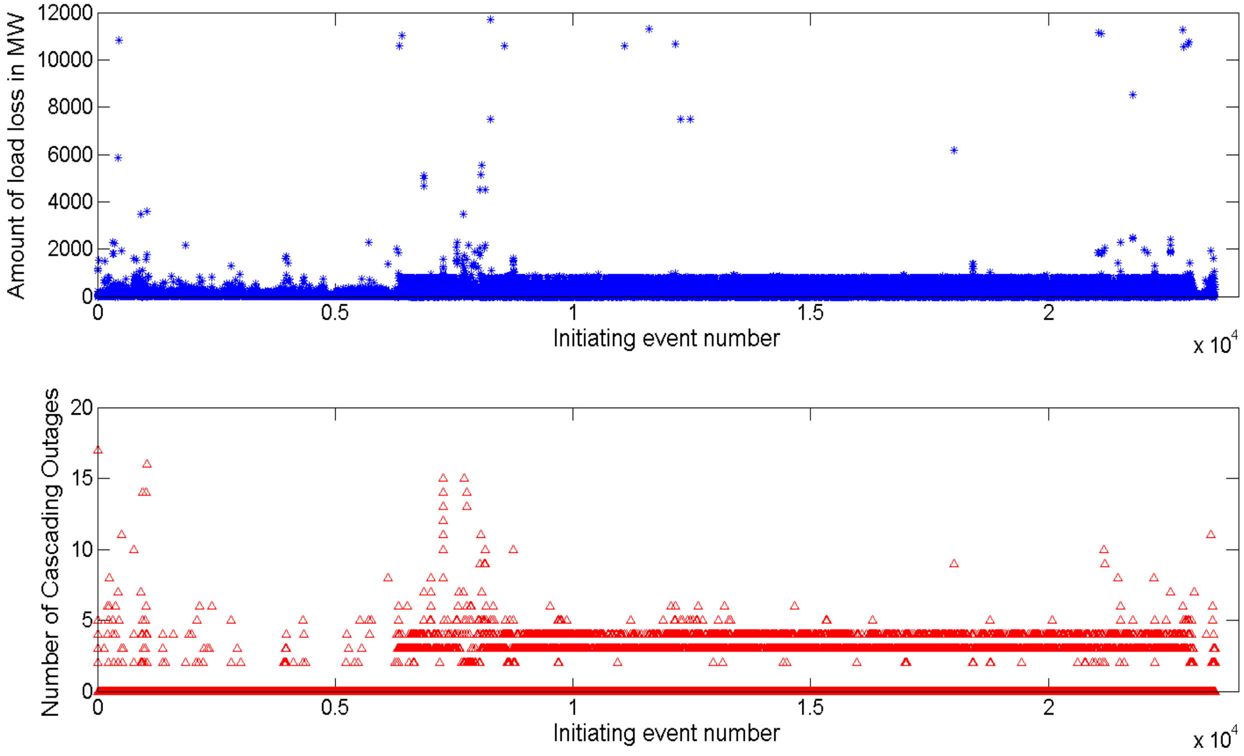
Table 1: Summary of Simulation Results

Type of Case	Number of Cases
Non-converged cases immediately after initiating event	114
Non-converged cases after a few power flow iterations	1,228
Cases with either load loss and/or cascading failures	22,315
Cases without load loss	9,467

From the summary in Table 1, around 4 percent of the 33,124 cases resulted in a non-converged power flow solution after the initiating event. Some cases fail to converge immediately after the initiating event; other cases diverged after a few iterations with certain amount of load loss or a number of cascading failures.

The amount of load curtailment and number of cascades associated with each initiating event is shown in Figure 7.

Figure 7: Load Loss and Number of Cascading Outages Associated with Different Initiating Events as Ordered in the Initiating Events List



The following sections show how cascading outage results are analyzed by ranking the severity of initiating events causing cascading outages. The concept of critical corridor analysis is also introduced. With severe initiating events and critical corridors identified, effective controls or system enhancements can be designed to eliminate the weakest cascading paths and prevent the critical sequences of events from occurring.

Ranking of Initiating Events

Ranking the severity of initiating events is needed to identify the most critical events, so that system reinforcements and remedial actions could be designed to assist in handling those events and prevent or arrest cascading failures.

Since TRELSS does not reflect system transient behavior (only steady-state analysis is possible), divergence of power flow following severe contingencies can be a good indicator of system instability that can lead to blackout. Such criteria have been used in commercial power system simulation packages to assess voltage security problems [Powertech 2010]. The size and duration of the blackout depends largely on the severity of the initiating event and the stress level of the operating condition prior to the contingency. For the cases that diverged immediately after the initiating event, it is not possible to either estimate the eventual amount of load lost or the number of cascading failures; hence, the severity of these cases can neither be compared with other divergent cases nor with convergent cases that do result in load loss and/or cascading failures. Thus, two different comparison metrics are defined: Level I cases represent divergent cases and Level II cases represent converged cases.

Ranking of Initiating Events for Level I Cases

In general, there is a direct correlation between the importance of an element taken out of service and the severity of the disturbance. Because all the cases in this category do not converge, a simple ranking method was employed that uses the number of elements lost in the initiating event:

Severity_index1 = 1/number of elements lost in the initiating events

Fewer lost elements in the initiating event (for example, loss of two important transmission lines) indicate a higher severity index value. Again, this approach is very simple and does not provide much insight. Further investigation is required to estimate the details of the diverged cases in power flow solution. By properly modeling system components and relay devices, time-domain simulation can be used to find out the exact amount of load loss and number of cascading failures.

Ranking of Initiating Events for Level II Cases

Level-II cases enter a new steady-state operating condition following the initiating event although a large amount of load loss may occur during the disturbance.

While a straightforward ranking could be based on the amount of load curtailment, that does not take into consideration the likelihood of initiating events occurring. In other words, the lower the number of lost elements in the initiating events, the higher the probability of the event occurring. Also, the number of cascades needs to be considered because longer cascade sequences increase the potential of severely affecting system recovery. Based on these considerations, a severity index is defined that considers the amount of load loss, the number of cascading outages, and the total number of failed elements in the initiating event.

$$\text{Severity\_index2} = (Ls + M * Nc)/Nk$$

Where Ls is the total amount of load curtailment in MW; M is the weighting factor that quantifies the impact of cascading failures; Nc is the total number of cascading PCG actions in each simulation, and N_k is the total number of failed elements in the initiating event. The weighting factor M was set to 50 based on incremental tests to balance the effects of the amount of load curtailment and number of elements out of service in the initiating event.

Figure 8 shows the ranking of the most severe initiating events based on the severity index and the associated load loss, number of cascades and number of elements lost in the initiating event. Table 2 lists the most severe cases in this category; the most severe is caused by the loss of two transmission lines shedding 6191.9 MW of load in nine stages.

Figure 8: Initialing-Event Ranking Based on Severity Index and the Associated Load Loss, Number of Cascades and Number of Lost Elements in the Initiating Event

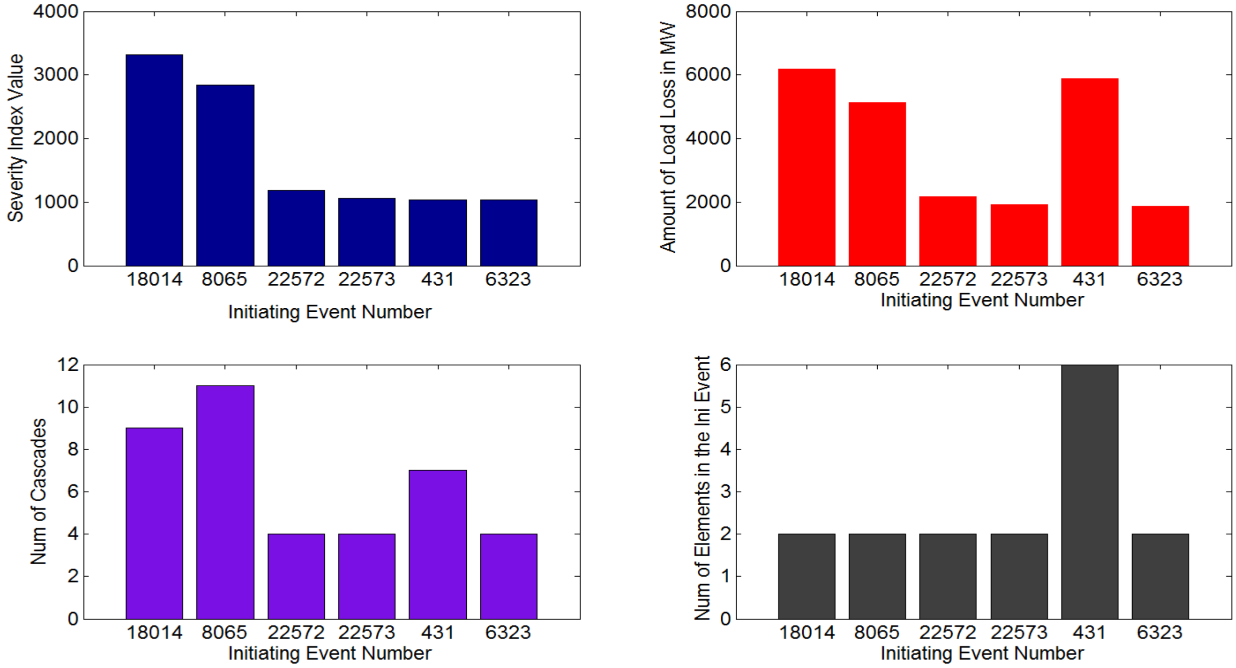


Table 2: Examples of the Most Severe Cases in the "Level II" Category

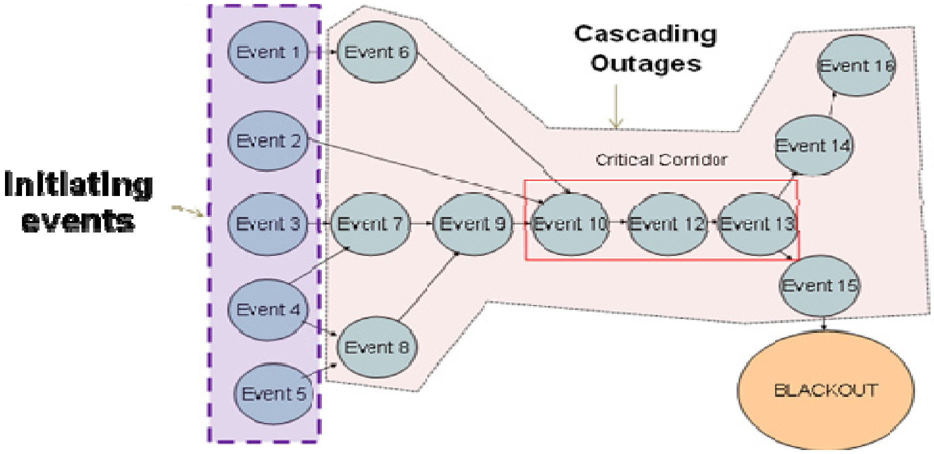
Initiating Event No.	Load Loss (MW)	Number of Cascading Outages	Number of Elements in Initiating Event	Severity Index
18014	6191.9	9	2	3320.95
8065	5140.3	11	2	2845.15
22572	2162.4	4	2	1181.2
22573	1910.2	4	2	1055.1
431	5870.2	7	6	1036.7
6323	1857.9	4	2	1028.95

Critical Events Corridors Analysis

Although no two blackouts follow the same sequence of events, similar partial sequences of cascading outages may exist in a particular power system. Partial patterns in which transmission lines, generators or buses are forced out in a certain order can repeatedly appear across a variety of initiating events and system conditions. These patterns can result from multiple different initiating events, and therefore are seen as parts of different cascading processes. Figure 9 illustrates the hypothesis of these "critical event corridors." Critical-corridor identification can be used to recommend transmission-system enhancements, protection-system modification, and remedial actions to help eliminate these most frequently observed, and therefore most probable, critical sequences that lead to severe consequences.

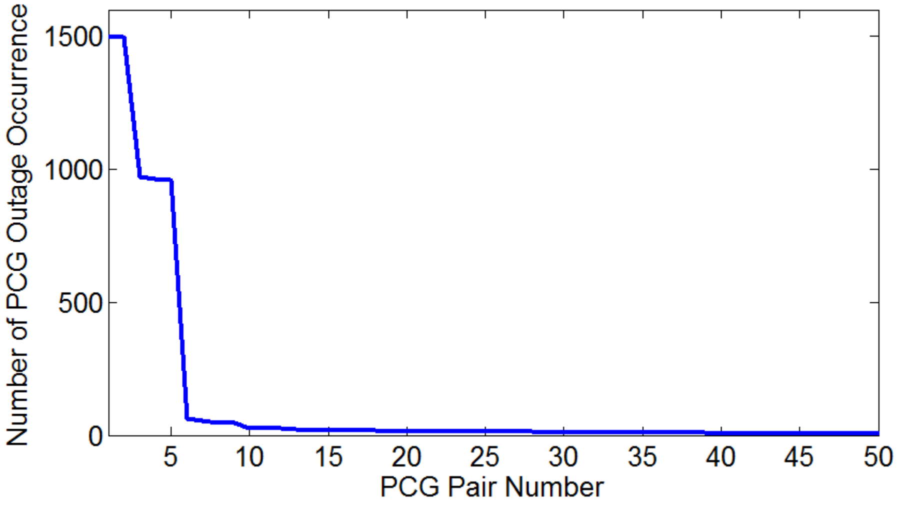
A new approach was developed to analyze the results of cascading-outage analysis to identify the weakest cascading paths in the system. The proposed methodology is based on searching for repeating paths (corridors) or sequences of events that may exist in multiple cascading-failure processes. These event corridors are ranked according to their frequency of occurrence and number of cascades within the critical corridor.

Figure 9: Illustration of the Hypothesis of Critical Corridors



A set of MATLAB codes for comprehensive critical event-corridor analysis has been developed. The main functions include reading TRELSS output files, performing in-depth analysis of the simulation results, identifying critical event corridors, and grouping different types of critical corridors based on the number of stages. A graph of the most frequently occurring PCG pairs in the WECC system is shown in Figure 10. More details regarding the functionality of the code are provided in Appendix B.

Figure 10: The Most Frequently Occurring PCG Pairs Identified in the WECC System



How Can TRELSS Results Analysis be Used?

TRELLS results will point out weak points in the system, which will enable system planners to prepare short-term and long-term improvements.

Short-term enhancements may include:

- Substation reconfiguration to reduce the number of elements that can be in outage within the substation
- Change in the protection schemes, such as changing the structure of the PCGs
- Change in generation dispatch patterns to relieve critical transmission paths
- Selection of optimal locations for high penetration of renewables to minimize effects on system reliability; if location choice is not under control of the BA, results can point out potential extreme events due to the concentration of renewable resources in few locations

Long-term enhancements may include:

- Transmission line reinforcements either by adding flexible AC transmission systems (FACTS) or by building new lines
- Addition of storage devices
- Better resource planning such as choosing optimal locations for new conventional power plants

Methods for Assessing Critical Elements and Conditions Developed Using OPA

As described in Chapter 2, the OPA simulation model was developed to study the failures of a power transmission system under the dynamics of an increasing power demand due to system growth and the engineering responses to these failures. In the OPA simulation model, the power demand is increased at a constant rate and is also modulated by random fluctuations. The generator maximum power is automatically increased when the capacity margin falls below a given level.

Using OPA, the project has been able to study and characterize the mechanisms behind the heavy power-law tails in the distribution of the blackout size. These heavy tails obtained in the numerical calculations are consistent with those observed in the study of the blackouts for real power systems. Most importantly, this model makes it possible to separate the underlying causes for cascading blackouts from the triggers that generate them and therefore to explore system characteristics that enhance or degrade robustness and reliability of the power transmission grid. Utilizing these abilities it is now possible to look for vulnerabilities in the system, find system-state metrics that could be used to judge the likelihood of an extreme event, explore the effects of system changes such as distributed sustainable generation on the robustness of the grid, and look for overall operational state quantities that correlate with extreme events.

Appendix C describes details of the work summarized in this chapter.

Finding Multiple Line Outages That Are Critical Initiating Events

In designing and operating power transmission systems, the standard practice is the application of the N-1 criterion to most lines and some higher order criteria for a few lines. This, combined with engineering and operator intuition, has been a rather effective way to establish robust power transmission systems. However, there are several problems that intrinsically limit the overall effectiveness of such an approach when it is extended to extreme events.

One of the problems with this approach is the impossibility of applying higher order criteria, N-2, N-3 and so on, to all, or even many, of the components of the system. The number of potential combinations increases so rapidly that it makes the calculations impossible now and in the foreseeable future. This is important because to prevent large cascading events requires the testing of multiple simultaneous failures, a rare but not impossible scenario.

A second problem is that all of these tests should be done under all possible conditions of the power system if they are to be effective in evaluating risk. An initiating event for an extreme event is the combination of both a triggering event and the state of the system. In this type of analysis of the robustness of the grid, the goal should be the identification of initiating events. To test all possibilities is again impossible, only even farther out of reach.

Therefore, it is important to complement the standard test of power systems with other ways of detecting vulnerabilities of the system to initiating events and to the propagation of the cascading failures. For this, the project uses a series of strategies discussed in detail in Appendix C to assess the vulnerabilities to triggers.

Some of the important conclusions from this work are:

- It is possible with a fairly simple strategy to find trigger events that can cause a blackout with near certainty, as shown in Figure 11.
- Using the same strategy it is possible to trigger extreme events that have high probability, as shown in Figure 12.

Figure 11: Probability of a Blackout by the Outage of *k* Lines in the WECC 1553 Node Network

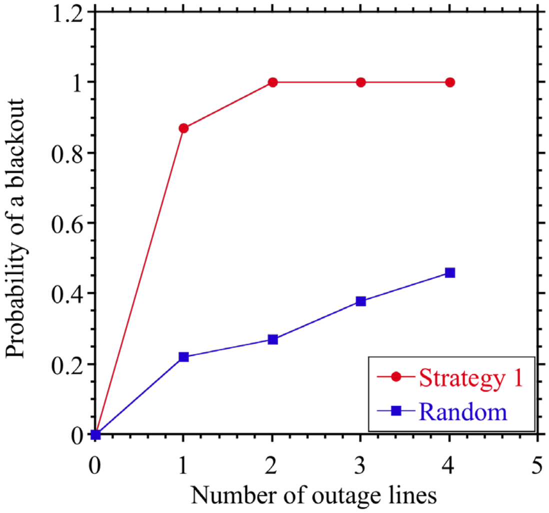
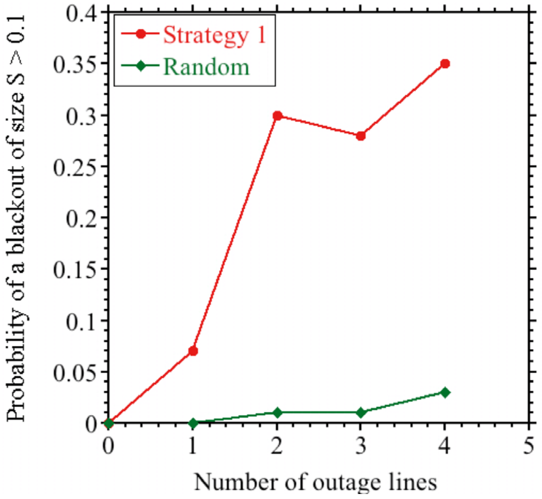


Figure 12: Probability of a Large Blackout by the Outage of *k* Lines in the WECC 1553 Node Network



The end result is that extreme events can be triggered by a few line outages if:

- The lines are strategically selected
- The timing is right

In this way, conditions that lead to the extreme events can be identified. This method has been applied here to two WECC network models, and the most critical lines to trigger such events have been identified.

Finding Line Clusters That Are Critical During Propagation

Finding the triggers for large blackout is only the first step. Most large blackouts have two distinct parts, the triggers/initiating event followed by the cascading failure. The cascade can be made up of as few as one subsequent stage or as many as dozens or even hundreds of stages. The cascading part of the extreme event is critically dependent on the "state" of the system: how heavily the lines are loaded, how much generation margin exists, and where the generation exists relative to the load. However, during large cascading events there are some lines whose probability of overloading is higher than the others. Statistical studies of blackouts using the OPA code allow the identification of such lines or groups of lines for a given network model, thereby providing a technique for identifying at risk (or critical) clusters. These lines play a critical role in the propagation of large events because they are likely to fail during the propagation of the cascade, making it more likely that the cascade will propagate further and turn into an extreme event. Therefore, it is clearly very important to identify them.

The statistical correlation analysis of the most frequently overloaded lines during numerical simulations of blackouts using the OPA code provides an approach to study the vulnerability of a grid model to the propagation of large cascades. Sampling from many different system states with many different triggers is difficult but important because the vulnerabilities that are already recognized are the ones that will already be protected against. It is therefore the unknown weaknesses that are likely to cause the rare, large failures.

Appendix C3, which describes the details of the results from this work, is summarized here.

Using an evolving system to sample many system states and many trigger possibilities, a synchronization matrix containing all the combinations of lines that fail together for large events can be constructed (Figure 13).

From the synchronization matrix, the critical clusters can be extracted and ranked according to their importance (based on frequency, size or both) (Figure 14).

Figure 13: Synchronization Matrix Can Be Used to Find the Critical Clusters with a Threshold to Include Only Those Clusters Associated with the Largest Failures

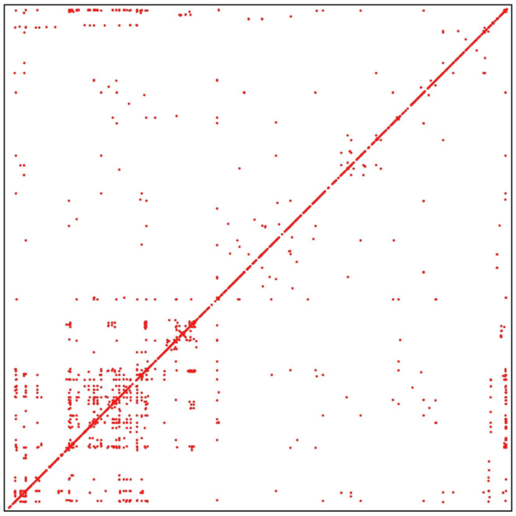
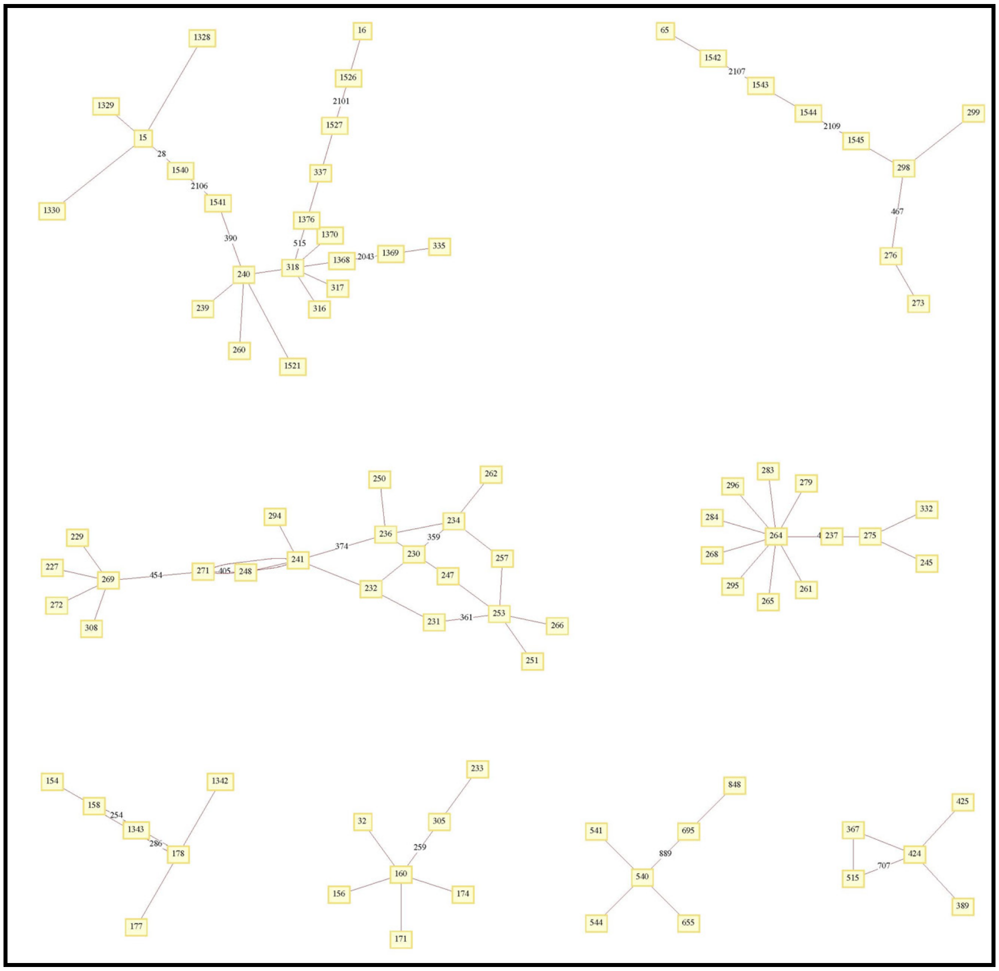


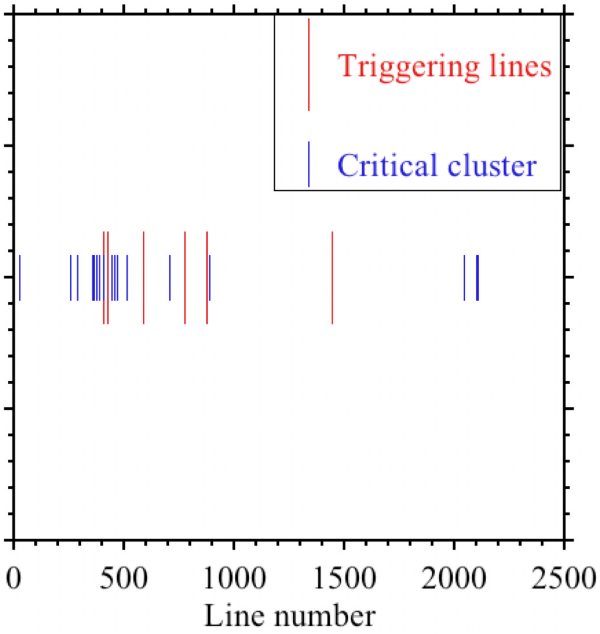
Figure 14: The Dominant Critical Clusters for Extreme Events Found Using the Synchronization Matrix Analysis



Once the critical clusters are identified, a more detailed analysis of their vulnerability can be carried out.

The identification of these two types of critical lines (the ones that may trigger an event and the ones that foster its propagation) gives us the information needed in order to apply mitigation strategies to reduce the incidence and consequences of large blackouts. It should be noted that lines that are critical in triggering large blackouts are not necessarily the same lines that are critical in the propagation of the cascade. In most of the systems tested, it is seen that these two sets of lines are generally different (Figure 15).

Figure 15: The Lines Triggering Large Blackouts and the Lines of the Dominant Critical Cluster for the WECC 1553 Node Network. (All Numbering is Artificial to Prevent Any Correspondence with Real Data.)



This distinction becomes an important issue when dealing with mitigation since strengthening the triggering elements will not necessarily deal with the critical lines most involved in the cascading. An effective evaluation of the consequences of line outages in a network needs to be done both under widely varying conditions of the network and with many combinations of triggers. The OPA dynamical simulation model allows such an evaluation.

System State Parameters that Correlate with Large Blackouts

In a complex system, extreme events may be triggered by a random event. However, the much-higher-than-Gaussian probability of extreme events (the heavy tail) is a consequence of the correlations induced by operating near the operational limits of the system and has little to do with the triggering events. The result is that the extreme-event distribution is independent of the triggering events. Therefore, trying to control the triggering events does not lead to a change of the power-tail distribution. A careful reduction of triggering events may reduce the frequency of blackouts but will not change the functional form of the size distribution. The process of trying to plan for and mitigate the triggering events can in fact lead to a false sense of security since one might think one is having an effect on risk by doing so when in reality, the unexpected triggers which will certainly occur will lead to the same distribution of blackout sizes.

In these complex systems, an initiating event cannot be identified by just the random trigger event, but by the combination of the triggering event and the state of the system. This “state of the system” can be characterized by different measurements of the parameters of the system. In the case of power systems, for example, the system state includes the distribution and amounts of loads and power flows in the network. A simulation model like OPA is continually changing the network loading and power flows. This, importantly, gives a large sample of initiating events. The statistics of the results reflect many combinations of initial events and system states.

It is also important to distinguish between blackout initiating events and general cascade initiating events. In power systems, a cascade, in particular a very short cascade, does not always lead to a blackout. Therefore, those two sets of initiating events are different. Within the OPA simulations, a blackout is defined as any event in which the fraction of load shed is greater than 0.00001. However, for comparison with the reported data we use fraction of load shed being greater than 0.002, which is consistent with the NERC reporting requirements from emergency operations planning standard EOP-004-1.

As discussed, the blackout initiating events in the power systems calculations using the OPA simulation model are not determined *a priori*; they are the result of the *a posteriori* analysis of the events. Because if this uniform sampling, the OPA results may then be used to determine the important initiating events and system states which later can be studied in more detail with more detailed models like TRELSS.

For a power transmission system, the number of parameters that help to characterize the state of the system is very large. Therefore, only a small number of "state" parameters that play a critical role in the characterizing the importance of an initiating event and how these parameters correlate with the blackout size are identified in this project. The project investigates:

- The probability of a blackout for given value of the "state" parameters of a network
- How these parameters coupled with an initiating event for a blackout correlate with the final size of the blackout
- Whether the time evolution of any of those parameters can be used as a precursor indicating the possibility of a blackout

Some conclusions, discussed in detail in Appendix C5, can be drawn from these results:

In calculating the probability of a blackout occurring, good measures include the number of lines overloaded in the first iteration, the average fractional line loading every day, the variance of the fractional line loading every day, and the number of lines with a fractional line loading greater than 0.9. They all show strong positive correlation with the probability of a blackout.

When a blackout occurs, the size of the blackout correlates strongly with the number of lines overloaded in the initiating state. This is a very clear correlation. The size also has a positive correlation with the average fractional line loading every day, variance of the fractional line loading every day, and the number of lines with a fractional line loading greater than 0.9 (Figure 16).

The positive correlation of the critical parameters with the size of the blackout is not necessarily due to an increased probability of the largest blackout sizes but rather to a reduced probability of small blackouts.

There is clear evidence of possible precursor measurement for a blackout in the absence of noise, but this signal disappears completely in the presence of a realistic level of noise (Figure 17).

Figure 16: Averaged Size of the Blackout as a Function of the Number of Outages in the Initiating Event for Four Different Network Models

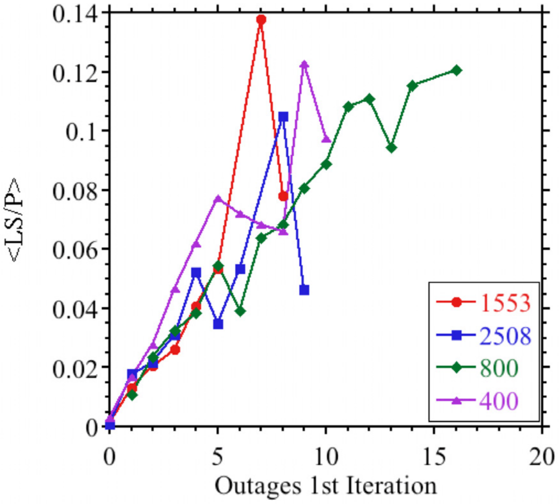
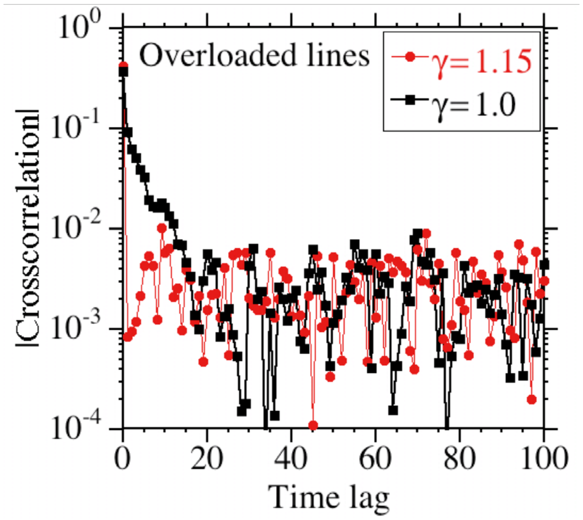


Figure 17: The Cross Correlation of the Size of the Blackout with the Number of Overloads in the Initiating Event Shows a Clear Precursor When the System Noise is Low



Having found a number of system parameters that strongly correlate with blackout probability, and even more importantly with extreme event size, it is possible to consider monitoring these quantities in the real system. The goal there would be to see (1) whether they show variations that are meaningful and the same correlations exist, and (2) if so, whether the noise level is low enough to make any of them useful as a precursor measure—the ultimate objective of the work in this section.

Impact of Distributed Generation

With the increased utilization of local, often renewable, power sources coupled with a drive for decentralization, the fraction of electric power generation that is “distributed” is growing and set to grow even faster. It is often held that moving toward more distributed generation would have a generally positive impact on the robustness of the transmission grid. This intuited improvement comes simply from the realization that less power would need to be moved long distances, and the local mismatch between power supply and demand would be reduced. The project approached the issues of system dynamics and robustness with this intuitive understanding in mind and with the underlying question to be answered, “is there an optimal balance of distributed versus central generation for network robustness?” In the interest of understanding the effects of different factors, the investigation was initiated by intentionally ignoring the differences in the economics of centralized vs. distributed generation and trying to approach the question in a hierarchical manner, starting from the simplest model of distributed generation and then adding more complexity. Since the network robustness is being explored as characterized by the risk of large failures and temporal dynamics, the OPA simulation model was used.

To understand the impact of distributed and renewable generation, and thereby improve the realism of the model, a new class of generation was added to OPA. This distributed generation class allows the project to vary: (1) the fraction of power from distributed generation, (2) the fraction of nodes with distributed generation, (3) the variability of the distributed generation, (4) economic upgrade models for the various types of generation and (5) dispatch models for the distributed generation.

These results, presented in detail in Appendix F, represent the early stages of these investigations using simple smaller networks whose dynamics have been found to scale well to the larger network models. Using OPA to investigate the effects of increased distributed generation on the system, it was found that:

- Increased distributed generation can greatly improve the overall “reliability and robustness” of the system.
- Increased distributed generation with high variability (such as Wind and Solar) can greatly reduce overall “reliability and robustness” of the system, causing increased frequency and size of blackouts.
- Generator capacity margin or generation variability leveling mechanisms are critical to reducing the degradation that can be caused by the increased penetration of sustainable distributed generation.

Figure 18 shows the blackout frequency as the degree of distribution (a surrogate for the amount of distributed generation) is increased. It can be clearly seen that with reliable distributed generation (same variability as with central generation) the overall blackout frequency decreases, while Figure 19 shows a concomitant decrease in the load-shed sizes as the degree of distribution increases. However, Figures 18 and 19 also show a large increase in both the frequency and size of the blackouts when using distributed generation with realistic variability. In some cases, the distributed generation can make the system less robust, with the risk of a large blackouts becoming larger. It is clear that distributed generation can have a range of effects on the system robustness and reliability, coming from the reliability of the generation (wind, solar, and so forth), the fraction that is distributed and the generation capacity margin. Many more aspects of distributed generation such as local storage, demand-side control, and so forth, remain to be investigated.

Figure 18: Blackout Frequency Decreases with Increased Reliable Distributed Generation but Increases Greatly with Increased Highly Variable Distributed Generation

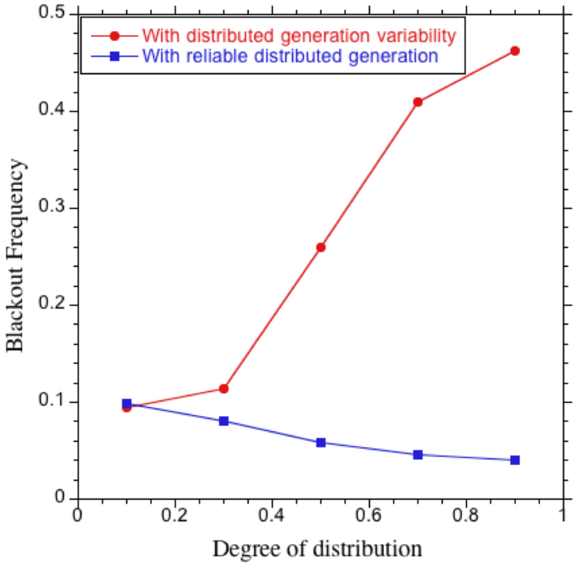
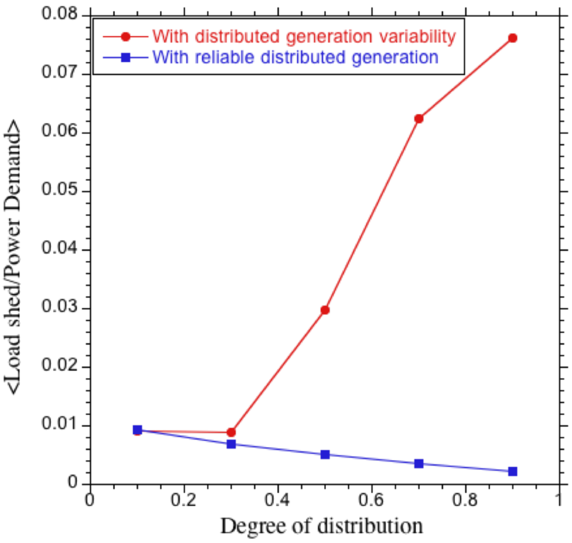


Figure 19: Normalized Blackout Size Decreases with Increased Reliable Distributed Generation but Increases Greatly with Increased Highly Variable Generation

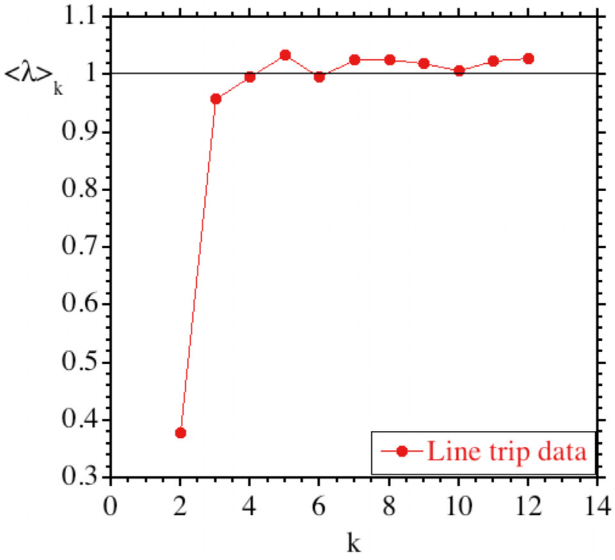


One potentially problematic scenario stemming from this behavior is that as the early penetration of distributed generation comes on line, it will actually make the system more reliable and robust since it will effectively be adding to the capacity margin. However, as new distributed generation is added, the system could become much less reliable as the demand grows, the fraction of distributed generation grows, and the capacity margin falls back to historical, mandated levels.

Toward a Metric for Overall Criticality

The power transmission system has a fundamental open question in common with other complex systems that exhibit extreme events and other characteristics of systems near a critical point: namely, whether a metric exists that can capture the proximity to the critical point. The project has developed a new metric, Lambda-gaga, which seems to do a good job capturing this proximity in an overall sense. Using this modified version of the cascade propagation parameter λ, it has been shown that systems that are pushed to the critical point have a lambda-gaga of near 1 while systems that are backed away from the critical point have a lambda-gaga of significantly less than 1. When the technique was applied to the line-trip data available, the result was a lambda-gaga of approximately 1 (Figure 20) suggesting a system sitting at its critical point. Because this metric requires multiple events to calculate the value, it is not suitable for real-time analysis; however it is suited for long-term system evaluation, for investigating the evolution of the system character (and perhaps even subparts of the system), and for validation of models.

Figure 20: Lambda-Gaga for Real Line Trip Data Showing a Value of 1 After Stage Number k=2, Consistent with a System At or Near Its Critical Point



It would be of great interest to apply this technique to more real data.

Monitoring and Processing Real and Simulated Disturbance Data with Branching Processes

Monitoring Cascading Transmission Line Outages from Standard Utility Data

This section summarizes the project results for power system monitoring. Details are given in Appendix C1.

The number of transmission lines outaged is one measure of the extent of a cascading disturbance. Any initial number of lines outaged can lead to a cascading propagation of further outages. The amount by which line outages propagate can be estimated from standard utility data that is reported annually to NERC by transmission owners for the Transmission Availability Data System (TADS). Given an assumption about the initial line outages, the distribution of the total number of outages after cascading can be estimated from the amount of propagation and a probabilistic branching-process model of the cascading. This is a new method developed in this study for monitoring power system reliability with respect to cascading failure.

Transmission line outages are useful diagnostics in monitoring the progress and extent of blackouts. One common feature of large blackouts is the successive failure of transmission lines, and the number of transmission lines outaged is a measure of the extent of the blackout. The transmission line outage data includes both outages that lead to load shed (that is, blackout) and outages that do not lead to load shed. The outcome in terms of load shed is not given in the data. The primary interest is in the transmission line outages that do lead to load shed, but the transmission line outages that do not lead to load shed could be regarded as precursor data for the transmission line outages that do lead to load shed.

Transmission owners in the United States of America are required to report transmission- line outage data to NERC for TADS. The TADS data for each transmission line outage includes the outage time to the nearest minute. The transmission line outage data set used in this report is TADS data recorded by a North American utility over a period of ten years. The 8864 line outages in the data are automatic trips and most of the outages are of lines rated 115 kV or above.

The analysis supposes that the cascading line outages occur in generations following some initial line outages. That is, the initial line outages are generation zero, and then cascading produces further line outages in generation one, and then in generation two, and so on. The utility line outage data is processed in a simple way by separating the line outages into distinct cascades and then separating each cascade into generations or stages. This is done according to the timing of the line outages; line outages in quick succession are in the same generation of a cascade, and a succession of line outages with no gaps of an hour or more are in the same cascade. It is then easy to obtain statistics of the number of line outages in the generations. For example, propagation from generation zero to generation one is defined to be the average number of line outages in generation one per outage in generation zero. In the utility data set, there are 6254 outages in generation zero of a cascade and 1143 outages in generation one of a cascade. Therefore the generation one propagation is estimated to be 1143/6254 = 0.18. The propagation for each generation is calculated in a similar way for the subsequent generations and is shown in Table 3.

Table 3: Propagation in Each Generation Estimated from Utility Data

Generation Number	1	2	3	4	5 or more
Propagation	0.18	0.38	0.52	0.68	0.75

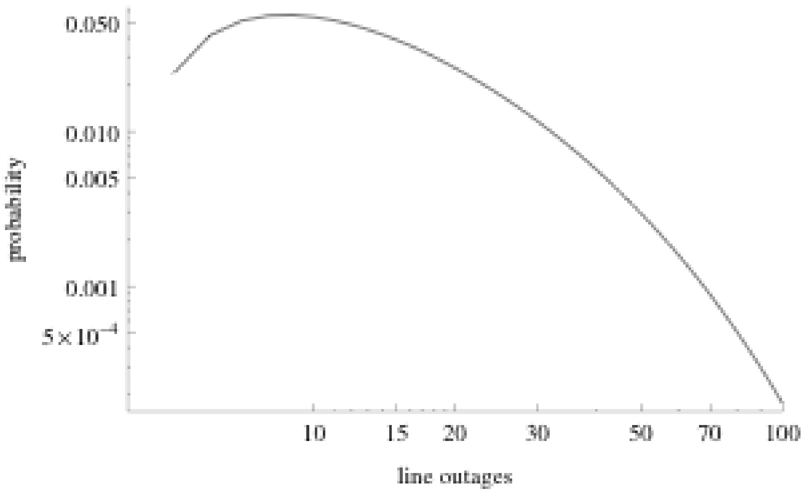
In Table 3, the amount of propagation increases with the generation number as the cascade proceeds, starting from 0.18 at generation one to about 0.75 at generation five and subsequent generations. This increase in propagation as the cascade proceeds is a significant observation. It would be worthwhile to find out whether this observation is typical for other utility data sets, if these could be made available for analysis.

Branching-process models are bulk statistical models of the cascading process. Branching-process models for cascading line outages are analytically and computationally tractable. For example, computer algebra can be used to estimate the distribution of the total number of line outages from assumed initial outages and estimates of the propagation. Calculating the effects of cascading by evaluating formulas is much faster than simulation approaches, and gives valuable insights into the cascading process.

Branching-process models are largely consistent with observed and simulated data for the purpose of estimating the distribution of the final blackout size. In particular, given the propagation estimated for each generation and the initial distribution of line outages from the utility data, a branching process can estimate a distribution of the total number of line outages that is consistent with the empirical distribution of the total number of line outages. That is, for the utility data set studied, a branching process model that accounts for the varying propagation as the cascade progresses can give a good prediction of the distribution of the total number of line outages from the initial number of line outages. Branching processes have also been used historically to model cascading processes in many subjects outside risk analysis, but their application to cascading failure is recent.

A significant outcome of the estimation of propagation from the utility data is the ability to estimate the consequence after cascading of some assumed initial line outages. For example, suppose there are five initial line outages and the propagation is estimated from the utility data set. Then the branching process model can be used to estimate the distribution of the total number of line outages as shown in Figure 21.

Figure 21: Probability Distribution of Total Line Outages Assuming Five Initial Line Outages; Estimated by the Branching-Process Model Using the Estimated Propagation from the Utility Data



Instead of assuming some initial line outages, conventional risk analysis and observational methods could be used to give the distribution of the initial number of line outages. Cascading failure can be thought of as initial outages that then propagate in generations. Many of the initial outages are due to external stresses such as weather or component reliability, whereas the propagation of outages is more related to the overall resilience of the system. To mitigate cascading failure, it is necessary either to limit the initial outages or reduce the ensuing propagation.

One benefit of quantifying the propagation in generations and the resulting distribution of total line outages is that the relative effectiveness of mitigating propagation at different generations can be evaluated. For the utility data set, it appears that to mitigate long cascades it is more effective to reduce the amount of propagation at the early stages of cascading.

It would also be useful to compare the effect of limiting the initial outages with the effect of limiting propagation. Little is known about whether propagation can effectively be changed to improve cascading performance, but the quantification of propagation and its impact on blackout extent discussed here is a first step toward this goal.

Why not simply estimate the distribution of the total number of line outages empirically? The reason is that accumulating enough data to get statistically accurate estimates takes too long, especially for the larger cascades that are rare. A preliminary analysis based on the utility data suggests that it requires an order of magnitude more data to estimate the distribution of total number of line outages empirically than to estimate the propagation using the branching process. That is, to estimate, say, the probability of a total of 10 line outages to a given accuracy with the branching process requires less than one tenth of the data required for empirical estimation. The number of line outages that have to be observed to get sufficiently accurate estimates of the distribution of the total number of line outages is a key quantity that determines the practicality of monitoring the power system with these methods.

The statistical accuracy of the estimated distribution of the total number of line outages can be increased either by gathering line outage data over a larger region or observing the line outage data for a longer time. Of course the resulting estimation applies as a bulk analysis averaged over both the chosen region and the chosen time span. Note that although the distribution of the total number of line outages is estimated, there is no information about which line outages will occur. This implies that there is no conclusion directly from the analysis itself of how to best to improve the cascading performance of the power system, although there is clearly scope for studying this relationship and learning how to do this. If the initial failures are not assumed, the statistical accuracy of the total number of failures is also affected by any uncertainty in the estimates of the initial failures. The goal is to estimate the distribution of the total number of line outages with useful accuracy from one year of data. Initial results based on the utility data suggest that this goal can be achieved for the Western Interconnection of North America and some large sub-regions of the Western Interconnection.

In summary, based on an observed utility data set and branching process model, we demonstrate a new capability to quantify the propagation of cascading line outages from standard utility data and estimate the distribution of the total number of line outages due to cascading from known or assumed initial line outages. It is a significant advance to be able to predict the extent of cascading in terms of the statistics of number of line outages based on observed data.

Post-Processing Simulation Output to Determine Propagation and Distributions of Blackout Size

This section summarizes the project results for determining propagation and distribution of blackout size from simulation outputs. Appendices F and G and [Dobson et al. 2010, Kim and Dobson 2010, Kim et al.] give details.

The cascading failure outputs produced by the OPA or TRELSS simulation are processed to estimate the initiating events and the propagation. Then a branching process model is used to predict the distribution of blackout size. The predicted distribution is compared with the distribution obtained by running the simulation for a long time. A good match validates the use of the branching process model for predicting the distribution of blackout size. The advantage of estimating the initiating events and the propagation, and then using the branching process model to predict the distribution of blackout size is that this works with a much shorter simulation run. This is not surprising, since determining the propagation from a relatively short simulation run has better statistical properties than running a simulation for a long enough time to get enough hits on rare events to get good statistics for the empirical distribution of blackout size. Moreover, propagation is a useful metric of resilience to cascading, and can be used to interpret and understand the simulation results.

The project considered two measures of blackout size: the number of transmission lines outaged and the load shed. The branching processes used in the project count (integer) number of failures, so it was necessary to discretize the load shed into “chunks” of load that could be counted.

The results are:

- In most cases tested to date, the branching process can give a reasonable match to distributions of blackout size obtained by exhaustive simulation for both number of lines outaged and load shed. (There are some discrepancies at highly stressed simulation cases.) The method can now be readily applied to post-process results from any cascading failure simulation, and the method should be validated for each such application and power system grid before being deployed.
- Given knowledge of the initiating events, a simulation run at least an order of magnitude shorter is needed to estimate the probability of the extreme events by first estimating the propagation and then using the branching process. Note that there is also uncertainty in estimating the initiating events, and this also affects the estimation of the probabilities of the rare events.

The results of processing OPA line trips and load shed on the Institute of Electrical and Electronics Engineers (IEEE) 300-bus test system are described in [Dobson et al. 2010, Kim and Dobson 2010, Kim et al.]. The results of processing TRELSS load shed on an industry case is described in [Kim et al.] and results on the uniform WECC model with 1328 buses for both lines outaged and load shed are described in Chapter 6.2 of the Phase 1 report.

The project developed the post-processing methods by statistically analyzing the post-processing of line outages, developing a new method of discretizing and analyzing the load shed, and testing the methods.

In summary, based on a branching-process model, the project tested and developed ways to estimate from shorter simulation runs the probability of rare events and the propagation of the cascades.

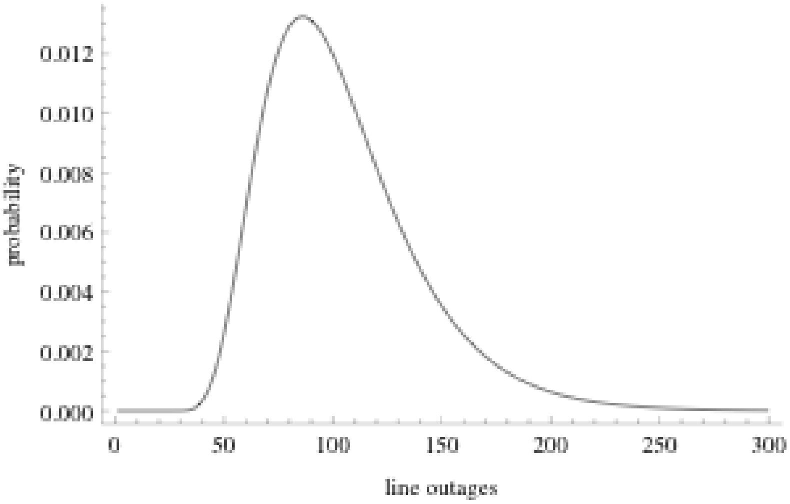
Predicting Extent of Blackout Triggered by an Earthquake

This section summarizes the project results about the size of blackouts triggered by earthquakes. Chapter 6.5.5 of the Phase 1 report gives details.

If there is a large initial shock to the power system such as from an earthquake, what is the risk of the failure cascading to other regions of the WECC? This is an important question because the time required to restore electric power and other infrastructure in the region that experienced damaging ground motion depends on how far the blackout extends. Long restoration times would multiply the consequences of the direct devastation not only to conventional measures such as load loss but to restoration of lifeline services. Since earthquakes can produce orders of magnitude more costly damage than a blackout, any prolongation of earthquake restoration due to the blackout cascading beyond the shaken region has a significant effect.

The project made an illustrative calculation of the blackout extent as measured by number of lines tripped as a result of a large shock to the system in which initially 26 lines outaged based on a real earthquake scenario. The calculations assumed and applied the branching-process model and observed propagation. (Figure 22) shows an initial estimate of the distribution of the total number of lines tripped due to the combined effect of the earthquake and subsequent cascading. The most likely extent is about 90 lines tripped, but there is a one-in-ten chance that more than 150 lines would trip. (The chance of more than 150 lines tripped is the sum of the chances of 151, 152, 153, ... lines out.) This initial estimate is illustrative of probable outage scenarios. A detailed examination of actual earthquake initiating failures and line-trip propagation data would be required to improve it. Similar calculations would be feasible for other large disturbances such as extreme weather events, wildfires or floods.

Figure 22: Probability Distribution of Total Line Outages After Cascading Assuming 26 Initial Line Outages Caused by an Earthquake. Estimated by the Branching-Process Model Using the Propagation Estimated from the Utility Line Outage Data



Comparison of Results

Compare OPA with Historical Data

Understanding and quantifying the risk of extreme events in the power transmission grid requires studying the rarest events in a very complex system. Developing confidence in the behavior and results from the models used to study these events requires validation against real data. The project compared the results of the OPA simulation to the historical blackout data of the WECC to validate the OPA simulation. OPA has a small number of input parameters that summarize overall aspects of the grid upgrading process and the cascading. The project found that these parameters could be assigned realistic values based on general information about the WECC and the line trip data. Appendix B2 contains a variety of types of analysis of WECC historical data and a validation study with one of the WECC grid models used in this work.

While the project has used a variety of WECC models, the WECC 1553-bus network is the basic reference model for the present calculations. (See Appendix C for details on network models). The discussion of most details of the modeling with OPA centers on this network, with the results then compared to the results from other network models.

A range of useful results have come from this validation and comparative study:

1. The set of OPA input parameters appropriate for the study of the dynamics of the Western Interconnection
2. New characteristics of NERC blackout data as well as some of the available outage data. These new characteristics are crucial for the validation of models
3. An examination of the results of the dynamical studies for the WECC 1553-node network in comparison with the data. This allowed for improved understanding of the models and the real network and guided improvements that led to better agreement between the models and reality.
4. A basis for the scaling of parameters and results for the different size models of the Western Interconnection. This lays some groundwork for the required grid-model level of detail to be determined and meaningful simulations to be done on reduced (and therefore more tractable) models of the WECC.

As can be seen from the figures, using the WECC 1553-node network a fairly remarkable agreement is obtained between the statistical data on blackouts from the Western Interconnection and the model calculation from OPA. Figure 23 shows a comparison of the cumulative distribution functions (CDF), (the cumulative probabilities) of the normalized load shed between the real WECC data and the 1553-bus OPA model. Excellent agreement is found for the substantial blackouts with more than one percent of load shed. Likewise, in Figure 24 the Probability Distribution Function (PDF) of the line outages is compared between the data and the OPA model and again excellent agreement is found. As discussed in Appendix B2, the way that the propagation of line outages increases as the cascade proceeds is not a close match, and this discrepancy may be resolved in larger grid models.

Figure 23: The CDF of the WECC Historical Load Shed Data and the OPA Load Shed Results with the 1553 Bus WECC Model

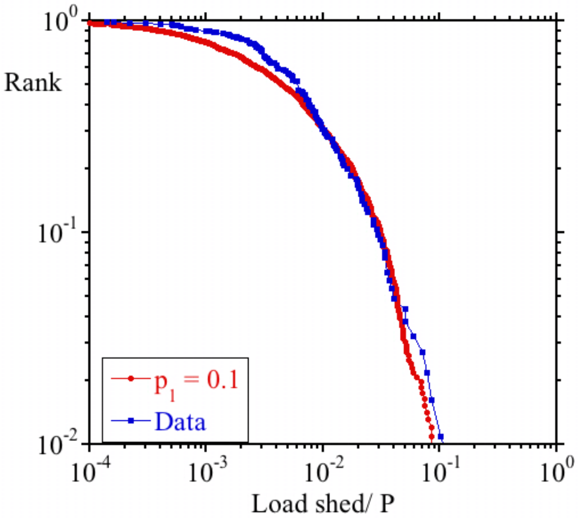
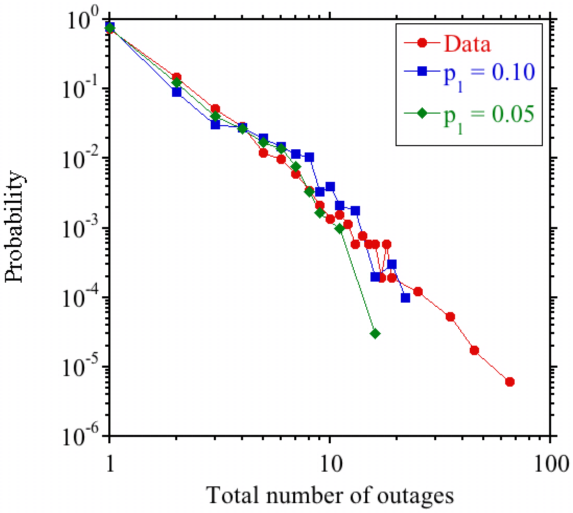


Figure 24: The PDF of the Number of Line Outages from Observed Utility Data and from OPA Results for Two Values of the Propagation Parameter



With these results, a set of parameters has been found giving sufficient agreement with the data to allow the determination of a Phase 2 reference case for the WECC 1553-node network. Reproducing quite closely observed WECC data with the OPA simulation (with all its modeling approximations) on a reduced WECC model is a significant result. Using this model and these parameters, it is now possible to determine the more vulnerable lines during a cascading event and the regions more likely to black out. It is also possible to identify the dominant blackout patterns and the sector of the grid that they affect.

TRELSS Results Validation

TRELSS performance is confirmed following two paths. The first path investigated several actual WECC disturbance cases by simulating these in TRELSS. The sequences in the cascading failure from TRELSS simulation results are then compared with the actual sequence. The second path extracts TRELSS simulation results for a few severe cases in which a significant amount of load was curtailed. The two cases chosen were sent to experts for feedback to determine whether, in their expert opinions, these are significant initiating events for their systems.

Compare TRELSS with Historical Blackouts

The disturbance selected for comparison occurred in the Northwest region of the WECC; it resulted in approximately 338 MW of load and 138 MW of generation loss and affected approximately 16,000 customers. This disturbance was triggered by two events within a few minutes of each other. The first trigger (Event #1) was caused by a construction crane hitting a transmission tower, causing a fault on the 144-kV line. The substation for this line was served by a 240/144-kV transformer to two 240-kV lines. The misoperation of the transformer, caused by incorrect transformer differential relay settings when the transmission line fault occurred, caused the outage of the two 240-kV lines that were serving the area and resulted in increased loading on the other 144-kV line (Line A) serving the load. The second trigger (Event #2) occurred when Line A hit a tree, resulting in a fault. The voltage decay caused the line protection to operate and trip the line. During the time before the Line A could be brought on line, other 144-kV lines' distance protection operated due to voltage decay, resulting in a blackout. The generation tripped due to the decaying frequency, resulting in a total load loss of 338 MW and generation loss of 138 MW.

The above disturbance was simulated in TRELSS. The initiating event outaged a 240/144-kV transformer, two 240-kV lines, and line A. The actual sequence of events could not be fully simulated in TRELSS due to limited information on the initial conditions and sequence of events. The simulation results show the total load loss of 223 MW. The first cascade in the disturbance, caused a load loss of 16 MW. Similar load loss of 14 MW at the same location was observed as a results from TRELSS simulation.

The simulation differed from the actual event in several ways:

- The actual disturbance was caused in the Spring 2010 spring as opposed to the 2009 heavy-summer base case used by TRELSS which can explain the changes in topology, line loadings and so forth.
- Actual breaker locations are not known for the WECC system; this can cause incorrect PCG outages resulting in different outage sequences as compared to reality.
- TRELSS is a steady-state cascading failure analysis tool and has no capability to capture the dynamics caused in the actual disturbance.
- Relay actions and frequency events cannot be captured in TRELSS in its current version.

However, TRELSS does help the planners and investors to identify the potential system vulnerabilities and weak points in their system in a worst-case scenario. This information can assist system-protection engineers, substation designers, planners, and operators to perform a further detailed investigation of those areas, provide a better solution and increase robustness if needed.

Compare TRELSS with Experience

Two cases with high load loss were extracted from simulation results. The cases were chosen within two Project Advisory Committee members' utilities to exchange results with them and get their feedback.

Case I

One severe contingency selected in the WECC system is the loss of six transmission lines connected to an important 230-kV substation in the initiating event. In the simulation, following the loss of the six branches, the remaining transmission lines connecting to the same substation become severely overloaded. One has a loading of 157 percent of its thermal rating, which is well beyond the PCG action threshold set in TRELSS (120 percent), so this line is tripped for protection. Although tripping this line can protect it from further damage, the surrounding lines at a lower kV level are further overloaded, especially the 138-kV lines. At the same time, low voltages are observed on the connected buses causing a large amount of load curtailment. As the cascading failure proceeds, tripping the overloaded 138-kV lines further stresses the remaining network again and more lines are tripped with an even larger amount of load loss. The cascading failure continues until a sufficient amount of load is shed and the system finally enters a new steady state. In this extreme event, the initial loss of six elements causes a total amount of 1280 MW of load loss and three cascading failures. This case is being verified by the WECC members using their engineering expertise.

Case II

Another severe contingency is identified in the southern part of the WECC system, in which six branches connected to a 230-kV substation are lost in the initiating event. There are 14 branches connected to this substation prior to the contingency. After the contingency, two branches out of the eight remaining ones are overloaded and therefore tripped for protection. This action furthers stresses the surrounding lines in the vicinity and causes the tripping of one 115-kV line. However, due to the PCG configuration, tripping the 115-kV branch also disconnects four other 115-kV lines. Low voltage magnitudes were observed on these buses and 116.9 MW of load was lost. As the disturbance continues, seventeen 60-kV branches are tripped with a load loss of 120.9 MW following a similar pattern. Before the system finally settled into a new operating condition, 16 cascading outages occurred in the system with a total amount of 3594.8 MW of load loss. This case is also being verified by the WECC members to validate the simulation results against expectations.

Effect of Model Reduction

A comparison was performed between simulation results of reduced models and the full WECC models to examine the effect of model reduction on results.

The reduced WECC model used in Phase 1 and the full WECC model show differing results. Further investigations show this mismatch is due to several reasons such as the use of equivalent generators and corrupted PCG structure.

Comparison of results of the reduced California-centric model and full WECC model show that cascading sequences for the reduced California model and the full WECC model are similar to a large extent. The reason is that the reduced California model maintained most of its original elements (generation units, transmission lines and PCGs). The California model is not capturing the other events beginning or ending outside the study area.

CHAPTER 6:
Discussion of Results and Path Forward

The Overall Approaches to Extreme Events

The team pursued two overall approaches to extreme events. No single approach addresses all the challenging questions that can be posed about extreme events.

The first overall approach extends the state-of-the-art engineering practices to systematically analyze cascading outages in the WECC system. A 16,000-bus model of the WECC, a simplified protection system model, and a large and exceptionally comprehensive list of multiple severe initiating contingencies were prepared to assist practical cascading failure analyses in California and Western Interconnection. The TRELSS simulation approach was used to compute the deterministic response of the WECC system to each contingency from the proposed extended list. This approach enables WECC engineers to find the most critical contingencies in terms of the possible load loss and number of cascading steps, and rank the contingencies based on their severity index and load loss incurred. The resulting cascades were analyzed to find commonly recurring sequences of events (critical-events corridors). The concept of critical events corridors helps to identify the most important and frequently occurring sequences of events that need to be addressed with appropriate system enhancements, protection and controls. The first overall approach pursues realism and detail for the engineering modeling and is conceived in a mostly deterministic context that is consistent with the current NERC/WECC reliability standards. The benchmarking relies mainly on expert judgment of sufficient realism in the engineering modeling and an appropriate choice of contingencies.

The second overall approach pursues the risk analysis of extreme events. Multiple approaches to this risk analysis were developed and compared, including analysis of historical data, a variety of models and simulations at varying degrees of approximation, and new methods of data analysis. Historical data was matched with approximate simulations, methods to detect critical components and conditions were proposed, complex systems effects were studied, statistical limitations were determined, new metrics and monitoring were developed, and problems of blackout risk were framed. The second overall approach is mostly in a probabilistic context and pursues understanding of the processes involved in cascading outages and the development of meaningful diagnostics. The benchmarking relies mainly on comparison with observed data.

The two overall approaches have considerable and useful overlap as well as some differences in context and perspective. For example, the first overall approach constructed detailed grid models that were approximated for use in the second overall approach, and both approaches find it useful to study large grid models. The first overall approach is explained in the first section of Chapter 6 and the second overall approach is explained in the second section of that chapter. There are also project findings common to both overall perspectives. Examples include:

- The project shows the value of studying cascading outages on large-size grid models over a large area. Developing these models paid off in results that are different from those obtained on smaller models.
- The project proposes several new methods of examining recurring patterns of simulated events that can suggest weak system elements that require more attention from the California and WECC practicing engineers.

The approaches developed in this project add both an opportunity to run multivariate simulations needed to enforce the requirements of the Category D reliability standard and foundational methods to quantify, monitor and mitigate extreme event risk.

Overall Approach 1: Evaluating Extreme Events and Their Possible Improvements

Post-research analysis revealed insights into the strengths and weaknesses of the approaches used in this project. These are described below to provide input to those who wish to extend the work done thus far, leveraging the lessons learned by this research team. Subsequent subsections will discuss suggested improvements to the approaches to fill identified research gaps and to exploit opportunities to advance the industry's ability to perform these studies and meet regulatory requirements, such as Category D studies.

Approach 1: Strengths and Weaknesses

Approach 1 to cascading events analysis in the WECC system was based on the static power flow model, where the initial system state, the state after the initiating event, and the cascading steps were simulated as subsequent deterministic power flow conditions. The approach revealed both strengths and weakness in either the methodology, assumptions used, or the information available for use.

Strengths

Interconnection-wide steady-state cascading-events models have been developed that can be deployed to run practical simulations and analyses. These types of models can assist California and WECC utilities and balancing authorities to enforce the existing NERC/WECC standard for extreme (Category D) events.

The project developed an extended list of initiating events that allows for much more in-depth analysis of extreme events in the WECC system.

The proposed and demonstrated concept of critical-events corridors is a significant step that, given further validation, could give the transmission planning engineer a tool that could determine places in the system where system enhancements could be most effective.

Weaknesses

Approach 1 uses a static system model whereas many of the major disturbances in the WECC system are dynamic processes that require dynamic models and simulations.

The risk of cascading events is greatly determined by their probabilities, which are not captured well using Approach 1.

The approach does not model remedial action schemes (RAS) or human intervention.

Severity indexes, which can ultimately be an important tool for industry, would benefit from additional research and from industry input.

The methodology should be expanded to include variants of possible cascading events for the same initiating event. It is important to note that, based on actual blackout and disturbance investigation experience, line trips were observed on lines that were not loaded to their rating (for instance, due to a tree contact).

Divergent cases create "gray areas" in the cascading event analysis. The key difficulty here is the inability to distinguish the cases where a power flow solution does not exist from those cases where the divergence is caused by deficiencies in the numerical solution algorithms.

Near-Term Enhancements to Approach 1

The work done in Phase 2 of this project demonstrated the ability of a tool based on a steady-state power flow model, along with the methodology enhanced in this project, to provide in-depth analyses of extreme events in the full WECC system. At the same time, it has become clear that immediate opportunities exist for near-future improvements. They are:

The breaker location information is critically important for producing an adequate structure of protection and control groups in the WECC system, and ultimately for an accurate modeling of cascading events. The WECC-wide state estimation model uses a system model in the common information model (CIM) format [EPRI 2001] that includes the actual breaker location information [Chung et al. 2010]. Access to this information as well as to the other similar data sets maintained by WECC utilities and system operators is one of the most significant near-term improvements needed for the deterministic extreme events simulation methodology.

The substation design and configuration have significant impact on PCG structure and ultimately on the system reliability and cascading sequences. The configuration affects the consequences of a fault as well as substation reconfiguration flexibility after a permanent fault. The system model used for cascading-failure analyses should reflect the variety of substation configurations as well as the differences in their behavior after disturbances.

The transmission components' protection-system model that was used includes overcurrent, impedance, and remote (Zone 3) relaying as part of the modeled protection scheme and should be included in a system model.

Selection of appropriate base cases for simulation is an important factor to consider.

The WECC system is equipped with multiple remedial action schemes that help to prevent or restrict extreme events in this system [AESO 2010]. Future models used to perform these studies should reflect the actual RAS actions and settings.

The sensitivity-based approach for selecting initiating events, along with the probability-based approach used in the initiating-events selection process, could help to dramatically increase the number of initiating events without making the analysis computationally unacceptable.

The Approach 1 algorithm follows only one variant of cascading process by selecting the most significant voltage reduction or transmission overload, and by addressing only one element (generator or transmission facility) at a time. In real life, the cascading sequences do not necessarily develop this way; less-affected elements can be disconnected before those most affected. Therefore, there is a need to diversify the cascading processes by following all variants of their development.

Roadmap for the Future Using Approach 1: Long-Term Advancements

Dynamic Models for Cascading Processes Simulations

Many major disturbances in the Western Interconnection are dynamic in nature; that is, they involve system parameters changing dynamically over time. The dynamic nature of these processes influences the operation of the protection systems and the cascading sequences. Future simulation models would benefit from capturing system dynamics.

Additional Types of Initiating Events

There is an evident need to expand the list of initiating events to reflect the complexities of modern power systems as well as new factors such as the increasing penetration of variable renewable generation resources, demand-side load management, virtual and actual consolidation of balancing authorities, new performance standards, and other factors.

Probabilistic Approach

Probabilistic reliability assessment methodologies and tools are available for generation, transmission, and composite reliability analyses. These tools are already used by a number of transmission system operators. These tools are usually based on contingency enumeration or Monte Carlo methods.

Multiple factors that contribute to the cascading failures can be considered as random variables. These random factors influence all phases of a blackout process development, including variable system conditions before the blackout, random initiating events, development of the cascading process (branching), as well as the final highly dynamic stages of a system blackout. These random factors can have the following characteristics:

- Combinations of discrete and continuous random factors (for instance, line and generator trips plus variations in wind generation or load).
- Combinations of random initiating events located in different parts of the system.

- Combinations of events with more-or-less known or identifiable characteristics (such as forced outage rates of generators or transmission lines) and events with probability characteristics that are hard to quantify (such as human errors).

Nevertheless, the probabilistic approach promises abundant opportunities for grid planning and control in terms of quantifying the risk of blackouts and making decisions on system reinforcements and controls to help reduce this risk.

Predictive and Actionable Blackout Indices

This report proposes a set of indices that help to evaluate the risk and consequences of cascading failures. This approach should be continued to develop a robust and practically acceptable cascading risk index (or risk indices). The index should be predictive from both grid planning and operational perspectives. The index should also provide information to help select the most effective system reinforcements and make the best control decisions to reduce the risk and potential consequences of cascading events. Ultimately, the index can be used to establish a standard mandating certain acceptable thresholds for the risk of system blackouts.

Periodic Deep-Dive Screening of the U.S. Interconnections for Cascading Events

The primary objective of this work is to reduce the risk of extreme events and to support actions that enhance grid resiliency. Secondarily, this research can reinforce approaches and processes that meet the intent of the current NERC/WECC Category-D event analyses. The research team recommends more generic approaches that lead to actual quantification of the risk and consequences of system blackouts. Clearly one approach could be the use of large-scale computations involving static and dynamic interconnection-level system models.

Overall Approach 2: Extreme Event Risk

Discussion of Approaches

Anatomy of Cascading

Suppose that the power system is in a particular operational state. Cascading failure starts with some initial outages and then subsequent outages happen in stages. When the cascading stops, the total number of outages and the load shed can be assessed. A particular cascade results from a particular combination of operational state, initial outages, and the particular way the subsequent outages proceed. In real power systems, there is considerable variability in all these factors. For all but the shortest cascades, it is impossible to fully enumerate all the myriad possibilities. Each cascade of failures that happens can be thought of as one sample from these possibilities. This view of cascading crystallized while the project developed the following approaches to quantify and mitigate extreme event risk.

Observed Data

Cascading outage or blackout data is observed over decades and statistics are accumulated. Particular blackouts can also be observed.

The project analyzed decades of data collected by NERC for WECC load shed. Analysis of this data, together with a rough assumption about blackout cost, implies that there is a substantial risk of large blackouts that exceeds the risk of medium-size blackouts. This is a consequence of the "heavy tail" behavior of blackout size statistics. The heavy tail implies that the extreme event of a large cascading blackout, although rarer than a smaller blackout, is expected to happen occasionally. In other words, large blackouts are not "perfect storms" that are vanishingly unlikely. The substantial risk of large blackouts justifies the project focus on extreme events, notwithstanding the difficulties of their analysis. Another consequence of the "heavy tails" is that blackout indices based on mean values or summing show high variability and should be used with caution.

The project analyzed a decade of line outage data from one utility. This is standard data reported to NERC under the Transmission Availability Data System. This data benchmarks the statistical distribution of line outages and proved to be of great value in understanding propagation of line outages, validating the OPA model, and developing monitoring methods.

The strength of observed data is its reality. The weaknesses are discrepancies, omissions, or incomplete coverage in the data, and the long time (decades) needed to gather statistically valid results, especially for the much less frequent extreme events. It is difficult to obtain observed data for research purposes because of data confidentiality. The observed data is a bulk measurement over the given areas and time periods over which it was gathered, and it may not be statistically valid to reduce the area or the time period to get finer resolution in space or time. "What if" experiments are impossible with observed data, and it is hard to associate changes in the data with changes in the power system. Nevertheless, observed data provides an important benchmark for other approaches to extreme event risk. As explained below, there are some ways to use shorter observed data records if the form of the data is understood.

Deterministic Simulation

A deterministic power system model always gives the same result for a given input. The deterministic framework for extreme event simulation computes the response of a deterministic power system model to a list of contingencies that stress the power system to a certain extent. The contingencies in the list are judged to be credible worst cases in the sense that they are severe contingencies that have some significant chance of occurring. Examining responses of the power system to all the contingencies can give insights into credible cascades of failure and their mitigation. Moreover, since many of the current NERC reliability rules are deterministic, a deterministic simulation can be used to check compliance with NERC rules.

The project has constructed, for the first time, a detailed 16,000-bus model of the WECC power system that can be used for deterministic analysis of cascading failure. The project constructed a large WECC contingency list that advances well beyond single failure cases. Running TRELSS on the contingency list gives the response of the WECC power system to a much larger set of contingencies. For NERC Category D events ("Extreme event resulting in two or more (multiple) elements removed or Cascading out of service" [WECC 2008]), this is relevant to the NERC standard to "Evaluate for risks and consequences...A number of extreme contingencies that are listed under Category D" [WECC 2008].

An approach to overall reliability based on the deterministic N-1 criterion and variants has been successful on the historical power system, and this project approach is a deterministic generalization for cascading failure. It seems clear from industry experience that if an expert selects the contingencies beyond the N-1 criterion, and examines the simulated responses of the power system, then this stress testing yields useful information on potential failure modes and weak points. The stress testing procedure itself is clear, but there remain open questions about which cases are examined, how to choose the level of stress and the requirements for the power system response, and the effects on risk of requiring the power system to respond to the stress within the requirements.

The strength of deterministic simulation is that it corresponds to current WECC/NERC rules. The weakness of the deterministic approach is the difficulty of objectively determining which contingencies are credible, insufficient sampling of power system states and possible outcomes, and the inability to compute event probabilities or risk within the framework. Another weakness common to all simulation approaches is that only a selection of all the possible cascading mechanisms are represented, and the representation is approximate. Finally there is the intrinsic problem with all contingency lists, namely the "looking under the lamp" problem. That is, we are looking under the lamp, see what is there and prepare for what we see, but the failures that will ultimately cause the most damage are the ones that are not under the lamp and that we have not prepared for. The existence of these unforeseen failure sequences is absolutely inevitable.

Probabilistic Simulation

A probabilistic simulation samples from all the possible cascades to be able to evaluate event probabilities and risks. Different samples are selected in different runs of the model so that the outcomes can be different. If the sampling is done properly, the results can be interpreted probabilistically and conclusions about risk can be made.

The project advanced several aspects of probabilistic simulation:

- Observed statistics of WECC blackout data can be well approximated by OPA-type models, which have a greatly simplified model of a cascading mechanism, but represent complex system dynamic feedbacks by which the grid slowly upgrades. This is a long-term risk analysis that accounts for the power system patterns of flow adjusting to any changes made.
- The modeling of the complex system dynamic feedbacks by which the grid slowly upgrades requires computation of a large number of cascades, but may be an important factor in making the results robust to the modeling of the detail of the cascade.
- For evaluation of blackout risk, the simulation needs to sample from both the network condition and the initiating events as well as the way that the cascade unfolds.
- The required number of "hits" on a simulated event for statistically valid estimates of the probability of the event was determined. This requirement can have a large influence on the event definition, model detail, and simulation run time.

The strength of probabilistic simulation is that it yields probabilities of events and hence enables quantitative risk analysis. Risk analysis accounts in an objective way for both the frequency and impact of cascades. The weakness of probabilistic simulation is that it is slower, and its application requires more knowledge. Because of that, some people are uncomfortable with or disagree with a probabilistic approach. Another weakness common to all simulation approaches is that only a selection of all the possible cascading mechanisms are represented, and the representation is approximate.

While current NERC reliability rules are in a deterministic framework, the impact of blackouts on our society depends on their risk. Planners intrinsically understand that it is risk they are trying to minimize and therefore they need the tools to accurately assess this risk. If risk can be quantified, an interesting next step to consider as reliability rules evolve is to evaluate deterministic reliability rules for their effectiveness in mitigating the risk of the various sizes of blackouts.

Branching Processes

Branching processes are high-level probabilistic models that describe the spreading of the cascading failure, but do not represent any details. The branching process tracks, at each stage of the cascade, the number of transmission lines outaged or the load shed. The project tested and applied branching processes for both observed and simulated cascading data.

- Cascading results from an initial event and a tendency for the outages to propagate. The amount of propagation is a parameter of the branching process model and a new metric of cascading failure.
- The propagation in transmission line outages can be quantified from the TADS utility data reported to NERC and used to predict the distribution of the total number of line outages from given initial outages using a branching-process model. This conclusion has been tested for one observed utility data set. It appears that useful conclusions can be drawn from about one year of TADS data over a sizable sub-region of WECC. The project has also opened up the possibility of monitoring the overall power system criticality from the TADS data.
- The new ability to predict the distribution of the total number of line outages from given initial outages was also applied to a sample calculation of the effect of a large initial disturbance, such an earthquake. Restoration after an earthquake depends on electricity and it is important to know the chances that a small blackout initiated by the earthquake could cascade into large blackout over a much wider area.
- The propagation in transmission line outages can be estimated from a short run of simulated cascade data. The branching process can then be used to predict the statistics of the total number of lines outaged. The idea is to estimate extreme events without a long simulation run. The approach has been extended to predict the distribution of load shed with OPA for a 300-bus system and with TRELSS for a larger system. Further testing the extension to load shed for large systems is recommended, because increasing the model detail at the load buses may affect how the load is shed.

- The strength of branching processes is their simplicity and tractability. The weakness of branching processes is that they do not represent any of the detail of the cascading. For example, it is useful to be able to compute with a branching process the chance of, say, 50 lines outaged in a cascade, since this helps to describe the likely extent of the cascading. But the branching process does not specify which 50 lines outage.

Brittleness

Brittleness is the susceptibility of the power system to large-scale disturbances. The project has developed highly efficient ways to compute brittleness in simplified power system models that account for system topology and operating conditions, but do not model the components' dynamic characteristics. The project computed the vulnerability frontier, which is the maximum amount of power that would be disrupted for a specific number of lost lines. Furthermore, the analysis identifies the specific lines involved in this worst-case scenario. These worst-case scenarios are candidate sets of outages to be monitored or further analyzed by more detailed methods. NERC reliability rules for Category D extreme events require worst-case contingencies to be analyzed. The strength of the brittleness algorithms is their ability to quickly compute a worst case extracted from a huge space of possibilities with minimal system data. The potential weakness of the brittleness approach is that this computational capability is achieved by simplification of the modeling. The project work on brittleness is documented in Chapter 3.4 of the Phase 1 project report.

Assessing Critical Elements and System Conditions

Cascading failure results from a combination of factors: the power system state, the initial outages, and the subsequent propagation of the cascade. Therefore, the project developed new methods to detect critical elements or conditions in each of these factors that influence the outcome of the cascading. Of particular interest in the outcome was the probability of large blackouts. The methods were developed using the OPA simulation.

- The project identified lines that are critical to initiating large blackouts. These are the multiple line outages that initiate many large blackouts.
- The project identified clusters of lines in the propagation of cascading failure. These are combinations of line outages that appear together in the same cascade much more often.
- The project also found that the lines critical for the initiation are often not in the set of lines in the propagation, leading to the interesting result that it is important to look at both trigger vulnerabilities and propagation vulnerabilities.
- The project identified several parameters of the system state that correlated with probability or size of large blackouts. The parameters included initial line outages, average and variance of line loading, and fraction of lines with high loading.

In each case, critical elements or critical system conditions have been identified. The next step is to check which of these identifications are statistically valid, and relate possible upgrades or changes to the critical elements to the change in risk.

Impact of Distributed Generation

The project studied the impact of increased distributed generation on cascading failure risk with the OPA simulation. The results of this work suggest that a higher fraction of distributed generation with no generation variability improves the system characteristics. However, if the distributed generation has variability in the power produced (and this is typical of distributed generation sources such as wind or solar), the system can become significantly less robust with the risk of a large blackouts becoming much larger. It is possible to find an optimal value of the fraction of distributed generation that maximizes the system robustness. Further investigations with different models of the reduced reliability of the distributed generation power and different distributions of the distributed generation would be worthwhile, as would the extension of this work to the larger WECC models.

Approach 2: Road Map for Extreme Event Risk

The project has defined new metrics for cascading outages. An important goal for both real and simulated data is to monitor meaningful and actionable quantities. Therefore the road map develops the new metrics further so that they can be applied by industry.

Metrics Goal: Establish, validate and implement new cascading-risk metrics:

- Improve understanding of criticality and metrics for criticality.
- Find relationships of different blackout size measures.
- Analyze conventional reliability metrics in the context of extreme event risk.
- Test propagation monitoring of line outages from standard data at utilities.
- Improve large blackout cost estimation.
- Improve risk computations.

The project has advanced simulation methods for cascading failure by sampling all the sources of variation, making larger grid models, validating approximate models with real data, detecting critical components and conditions, and assessing statistical validity of results. The new methods are substantial advances in particular aspects of simulation, but they are not coordinated together. The road map integrates these advances to design a practical simulation.

Simulation Design Goal: Design a multi-scale, practically feasible, probabilistic simulation approach with justifiable trade-offs when assessing specific questions in cascading risk. The trade-offs, together with what has to be studied to make the trade-off, are:

- Actionable and statistically valid results (extend and apply statistical tests for statistical validity; define which reliability questions have valid answers, find ways to generate robust results, formulate mitigation actions whose effects on cascading risk can be robustly computed)

- Cascading mechanisms modeled (understand impact of modeling complex systems feedback, find ways to generate robust conclusions from partial modeling of cascading mechanisms)
- Model detail (study how model detail affects results and their application)
- Model size (continue to study scaling with system size)
- Simulation speed (apply and develop fast simulation methods as needed.)
- Data requirements (this checks the availability of data for the simulation in an industry context; the study itself can mostly use typical values)
- Uniform sampling (includes joint sampling of system state, initiating events, and progress of cascades)

Now the road map applies the new metrics and simulation.

Applications Goal: Applications of the simulation approach and new metrics:

- Systematically determine vulnerable clusters (for both triggers and propagation).
- Monitor and assess reliability of power system with increased penetration of renewable resources, adding local storage, climatological variability and dispatch.
- Investigate impact of various smart-grid technologies on grid dynamics, resilience and robustness.
- Assess effects of applying various remedial actions to vulnerable clusters on system characteristics and overall risk of extreme events.
- Assess risk performance of deterministic reliability criteria.

Emerging Tech Transfer Opportunities

Evaluating Extreme Events

The work conducted for overall Approach 1 in this project was ultimately oriented to practical industry needs. It addressed the models, methodologies, and tools to help practical enforcement of the requirements mandated by NERC and WECC for extreme events analyses (Category D events). The work is already in place to transfer to industry the methodologies and know-how created during this work. In January 2011, the project team made a presentation to the WECC Reliability Subcommittee members and received a positive evaluation of the work done as well as some critical comments and suggestions that would help to improve the proposed methodologies.

The intent of the future work is to:

- Improve the proposed methodology in close cooperation with industry organizations in California and in the Western Interconnection. The objective will be to further verify the methodologies and make adjustments, including the ones above listed in this section and ones based on industry inputs.
- Develop a Category D Events Planning Guide in cooperation with the WECC Reliability Subcommittee and California grid planning engineers. The Guide will include recommendations, methodologies, and other relevant information to help understand, set up, and run extreme-events studies.
- Obtain and regularly update information from WECC on enforcing extreme event analyses. The information needed includes:
    - Breaker location information
    - Protection system information
    - Remedial action schemes
    - Outage rates for transmission lines, transformers, and generators
    - Breaker failure information
    - Information on the observed initiating events that result in cascading, and so forth
- Gather information needed for more precise extreme-events analyses. The gaps in the available data have been identified. Additional data such as breaker location information, extended lists of initiating events, descriptions of remedial action schemes, and relay protection information could be made available as part of the WECC extreme events system model regularly published by WECC for its members and used throughout the system to run transmission planning studies.
- Concentrate longer-term work around the probabilistic extreme events research methodology and using dynamic system models for simulating such events. This work will result in developing a high-fidelity model for extreme events analyses. Bearing in mind the complexity and computational effort involved in the analysis, and that many tasks in extreme events analysis are naturally parallel, supercomputer applications could be developed and used for the analysis.

Processing Utility Line-Outage Data to Quantify Cascading

The project developed a new method to process standard utility line-outage data to quantify the propagation of line outages. The propagation determines how much line outages spread on average and is a new metric of cascading. If some initial line outages are assumed, the chances of various outcomes of the cascading in terms of total numbers of lines outaged can be calculated. The calculations use approximately one year of the automatic line outage data that is required to be reported to NERC under the TADS. The method has been developed and tested on one decade of data from one utility as explained in Chapter 5.

The next steps to develop this processing into a useful tool are:

1. Rewrite the current research software to make a trial software package that can be run onsite at a utility or system operator using their TADS data. This approach allows the line outage data to remain at the utility.
2. Make the trial package available to industry for testing and invite feedback.
3. If there is interest in the results and the test results are good, develop the package further based on the industry feedback.

CHAPTER 7:
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CHAPTER 8: Glossary

BA	balancing authority: organization with responsibility for controlling the high voltage electric transmission grid within a geographical boundary to ensure reliability and security; there are ~140 BAs in the North American grid.
blackout	a power system disturbance in which customer load is shed
branching process	a high-level probabilistic model that describes in an overall way how failures propagate similarly to generations on a family tree
brittleness	susceptibility of the power system to large-scale disturbances
CAISO	California Independent System Operator
cascading failure	a sequence of dependent failures in which the power system progressively weakens
CDF	cumulative distribution function
CIEE	California Institute for Energy and the Environment
CIM	common information model: the CIM/XML language is a language for representing power system models; it has been adopted by the utility industry body, NERC, as the standard for exchanging models between transmission system operators
CLP	COIN-OR linear programming solver; COIN-OR is Computational Infrastructure for Operations Research
complex system	a system that adjusts or self-regulates its behavior when changes are made to it
convergence	the condition in which mismatch tolerances for all buses and/or the whole network are met
divergence	the condition in which the iterative solution shows rapidly increasing mismatches (also referred to as "blow-up")
EOP	emergency operations planning
EPRI	Electric Power Research Institute
extreme event	an event that is much larger than usual or expected
GE	General Electric Company

heavy tail	describes statistics in which extreme events are likely enough that they are not impossible and will happen occasionally; "tail" indicates the large or extreme events in a probability distribution of event size, and "heavy" means that the probability of a large-size event decreases very slowly as the size increases-more precisely, "very slowly" means slower than any exponential decrease
IEEE	Institute of Electrical and Electronics Engineers; non-profit professional association dedicated to advancing technological innovation related to electricity
initiating event	events that happen at the beginning of a power system disturbance; "trigger" events together with any immediately following events
IOU	investor-owned utility
model	mathematical or algorithmic representation of some aspects of the power system
MVA	megavolt ampere; a unit of measure of apparent power
N-1, N-2, contingency lists	N-1 is the loss of one element in the power grid, such as a single transmission line or a generating unit, while N-2 is the simultaneous loss of two elements; balancing authorities usually have a list of critical N-1 and N-2 events with the remedial actions they should take in case of their occurrence
NERC	North American Electric Reliability Corporation
NERC Category D events	a contingency category in NERC standards that covers extreme events resulting in two or more elements removed or cascading out of service, such as three-phase faults with delayed clearing, loss of tower line with three or more circuits, loss of all transmission lines on a common right of way, loss of substation or switching station, loss of all generating units in a station, failure or misoperation of fully redundant special protection systems and the impact of severe power swings or oscillations
OPA	Oak Ridge/PSERC/Alaska. Research-grade computer simulation of cascading transmission line outages that includes complex system effects
outage	a power system component is outaged if it is not available to generate or transmit power
PCG	protection and control group
PDF	probability distribution function
PIER	Public Interest Energy Research

PNNL	Pacific Northwest National Laboratory
power law	heavy-tailed statistics of a particular form that shows up as a straight line when logarithm of probability is plotted against logarithm of size
PSERC	Power Systems Engineering Research Center
PSLF	Positive Sequence Load Flow; commercial software product by General Electric for power systems modeling
PSS/E	Siemens PSS®E, Power System Simulation for Engineering
RAS	remedial action scheme: "Special Protection System (Remedial Action Scheme) - An automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability. Such action may include changes in demand, generation (MW and MVAr), or system configuration to maintain system stability, acceptable voltage, or power flows" [NERC 2008].
risk	risk accounts for both severity and frequency; risk is cost times probability
RD&D	research, development and demonstration
ROW	right of way
TADS	Transmission Availability Data System
transmission line	high-voltage power line (supported by the large towers) that transmits bulk electricity usually above 138 kV
TRELSS	Transmission Reliability Evaluation of Large-Scale Systems; industry-grade computer simulation of cascading outages
trigger event	first event at the beginning of a power system disturbance; often due to natural or random causes
UAF	University of Alaska-Fairbanks
UCB CIEE	University of California, Berkeley California Institute for Energy and Environment
UWM	University of Wisconsin-Madison
WECC	Western Interconnection, administered by the Western Electricity Coordinating Council