ARRA: Reconfiguring Power Systems to Minimize Cascading Failures — Models and Algorithms

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2 Executive Summary

Building on models of electrical power systems, and on powerful mathematical techniques including optimization, model predictive control, and simluation, this project investigated important issues related to the stable operation of power grids. A topic of particular focus was cascading failures of the power grid: simulation, quantification, mitigation, and control. We also analyzed the vulnerability of networks to component failures, and the design of networks that are responsive to and robust to such failures. Numerous other related topics were investigated, including energy hubs and cascading stall of induction machines.

3 Summary of Project Activities

- Quantification of cascading failures from real and simulated data.
- Fast simulation of cascading outages.
- Cascading stall of induction machines.
- Capacity enhancement strategies to defend the electrical power grid against terror attacks and earthquakes.
- Complex systems aspects of blackouts and their implications for small and large blackouts.
- Solution of semidefinite programming formulations of AC power flow equations.
- Optimal blackouts: Demand reduction strategies to minimize disruption to the grid in response to disturbances.

- Vulnerability analysis of electrical power grids: Modeling optimal attacks as bilevel optimization problems.
- Network design using stochastic integer programming models to avoid cascading failures.
- Evaluating linear models for energy hubs.
- Model predictive control approaches for cascade mitigation.
- Model predictive control approaches for overload prevention.

In the following sections, we provide more details and citations for our work on these topics.

4 Advances in Cascading Failure Analysis

Cascading failure is the main mechanism of large blackouts. The project made substantial progress on advancing several aspects of cascading failure analysis, as explained in the following subsections. In addition, advice on formulation of power system problems was provided to the rest of the team.

The project work by co-PI Ian Dobson was performed initially at University of Wisconsin-Madison and completed at Iowa State University. Some parts of work was leveraged by multiple collaborations with Cornell University, Zhejiang University, University of Vermont, BACV Solutions Inc., and the University of Alaska-Fairbanks.

4.1 Quantifying cascading outages from real data

Cascading outages can be thought of as an initial outage followed by propagation to a series of following outages. While there is a substantial body of risk analysis that can quantify the chance of the initial outage, it is only recently feasible to quantify the tendency for the outages to propagate. To mitigate cascading one should consider ways to reduce both the initial outages and their propagation. Indeed, the average amount of propagation can be understood as describing the grid's resilience: in a resilient grid, regardless of the initial outages, there will little propagation of outages following the initial outage.

We showed [9, 8] that the average amount of propagation can be estimated from standard utility data about transmission line outages that is reported to the government (this is the data in the TADS Transmission Availability Data System). Then the average amount of propagation can be used to quantify the effect of cascading, and in particular, estimate the distribution of the total number of outages given some initial outages. This procedure can estimate the probability of the rare, larger cascades from about one year of TADS data in a large utility. This procedure uses a high-level probabilistic branching process model of cascading (a Galton-Watson branching process with Poisson offspring distribution with generation dependent average propagation) that has been validated for this purpose.

4.2 Quantifying cascading outages from simulated data

The objectives here are similar to quantifying cascading outages from real data, except that instead of counting line outages, we extended the method to the harder problem of estimating the amount of load shed. We used the 'open loop" version of the OPA simulation to produce the simulated cascades and also collaborated with a large utility to process their cascades produced with the commercial-grade cascading failure simulation TRELSS. The load shed data is discretized so that the discrete units of load shed can be counted with a Galton-Watson branching process. The average amount of propagation can be estimated from the simulated cascades. Then the average amount of propagation can be used to quantify the effect of cascading, and in particular, estimate the distribution of the total amount of load shed [15]. We found some arbitrariness with choosing the discretization in an ad hoc manner, so we analyzed the problem and were able to propose a principled way to choose the discretization that is consistent with the Poisson offspring distribution assumption [17].

4.3 Fast simulation of cascading outages

Simulation of cascading blackouts poses many challenges, including fast simulation of long series of rare interactions in large grid models. In particular, simulation speed is a key barrier in assessing the risk of large cascading blackouts. The splitting method advances the simulation by stages, resampling from each stage to advance to the next stage. We apply the splitting method to the simulation of cascading blackouts to efficiently determine the probability distribution of blackout size. Testing on a blackout simulation shows that splitting can quickly compute large blackouts inaccessible to other methods [14]. The splitting method is a very promising method for significantly improving the performance of cascading failure simulations. The splitting method is well aligned with and takes advantage of the structure of the cascading processes. This appears to be a breakthrough in the capability of cascading failure simulations.

4.4 Cascading stall of induction machines

After an initial fault lowers bus voltage, induction motors connected to the bus can successively stall in a cascading process that can lead to a voltage collapse or delayed voltage recovery. There are typically many induction motors connected to the bus, and models that aggregate the motors do not capture the cascading stall. We study the cascading stall in a simple power system with many induction motors using a quasistatic assumption and randomization of some motor parameters, and hence efficiently estimate the distribution of the number of motors stalled. This approach is also extended to a simple 4-bus system and a simple motor dynamics and similar results are obtained. These distributions can often be fit with a high-level and generic probabilistic model of cascading failure, showing a commonality between cascading motor stall and other cascading processes [22].

After this work that discovered how the cascading stall could be fit with a cascading model, we went further to demonstrate the connection analytically. We analyze a single line power system supplying a bus with many induction motors. Variation and uncertainty in the motor load is modeled probabilistically. We describe an analytic method to estimate the parameters of a model of cascading failure from system parameters, and hence estimate the probabilities of the number of motors stalled. The analytic method gives insights into cascading stall and relates system parameters to the risk of cascading stall [23].

This thrust of work derives a new class of probabilistic load models that can quantify a cascading phenomenon of concern to utilities, especially in the Southwest USA. This work was done in collaboration with Prof. Hao Wu of Zhejiang University, China.

4.5 Complex system aspects of blackouts

Electric power transmission systems are a key infrastructure, and blackouts of these systems have major consequences for the economy and national security. Analyses of blackout data suggest that blackout size distributions have a power law form over much of their range. This result is an indication that blackouts behave as a complex dynamical system. We use a simulation of an upgrading power transmission system to investigate how these complex system dynamics impact the assessment and mitigation of blackout risk. The mitigation of failures in complex systems needs to be approached with care. The mitigation efforts can move the system to a new dynamic equilibrium while remaining near criticality and preserving the power law region. Thus, while the absolute frequency of blackouts of all sizes may be reduced, the underlying forces can still cause the relative frequency of large blackouts to small blackouts to remain the same. Moreover, in some cases, efforts to mitigate small blackouts can even increase the frequency of large blackouts. This result occurs because the large and small blackouts are not mutually independent, but are strongly coupled by the complex dynamics.

We validate the OPA cascading blackout simulation on a 1553 bus WECC network model by establishing OPA parameters from WECC data and comparing the blackout statistics obtained with OPA to historical WECC data. This serves to substantially validate the OPA model for estimating the statistical distributions of blackout size in terms of lines outaged and load shed on this 1553 bus network. A set of parameters has been found giving sufficient agreement with WECC data to allow the use of the 1553 bus network case as a reference case to study the long-term WECC blackout statistics. Validation of cascading failure models is necessary to find out which aspects of real blackouts are reproduced by the various models, and is crucial in determining what sort of conclusions can reasonably be drawn from model results, and what are the model limitations. In the case of cascading failure models, validation is particularly important, because it is currently infeasible, and perhaps inherently infeasible, to model and simulate all the mechanisms of cascading failure in great detail.

We gave some simple rules for getting sufficiently good statistics from blackout data t encourage good practice in the field [10].

This was joint work with Dr. Ben Carreras of BACV solutions and Prof. David Newman of University of Alaska-Fairbanks.

We found a way to encode the dependencies of cascading line outages in an influence graph [12]. This is a good start on describing how cascades spread in power grids. This work was joint with Prof. Paul Hines of University of Vermont.

5 Advances in Mitigation and Control of Cascading Failures

The research undertaken through this project brought together ideas from power systems, optimization, and control theory to improve the utility of existing and future energy infrastructures, by developing practical, yet rigorously justified solutions that mitigate the effects of overloads in power systems.

There are signs that cogeneration (i.e. the recovery of previously wasted heat) is on the rise in central energy plant settings, such as universities. These venues provide a starting point for the application of *energy hub* ideas. The tools developed in the project allow for quick analysis of arbitrary energy hub systems under relatively mild assumptions. In addition, the formulation developed for energy hub systems is linear (and convex), which enables computationally tractable and globally optimal solutions to multi-energy system problems.

Electric grid operation seeks to ensure safety from common and predicted disturbances, but blackout prevention falls largely on ad-hoc safety guidelines and human operators. As experienced in 2003, this does not always provide a sufficient safety guarantee, and the human and economic costs can be severe. This motivates the need to consider automated and verifiable methods to minimize the impact of disturbances. The project developed a *bilevel model-predictive control (MPC) scheme* to mitigate the effect of cascading failures. A centralized linear receding-horizon MPC cascade mitigation scheme incorporates a simple but sufficient model of an electric transmission system into an MPC formulation and considers the system response on a minute-by-minute timescale. Importantly, this MPC scheme combines and balances economic and security objectives and is shown to significantly improve system reliability by leveraging the temporal nature of storage and conductor temperatures.

Simultaneous overnight charging of plug-in electric vehicles (PEVs) may cause severe overloading of distribution transformers in the near future. A non-centralized incentive-based demand-scheduling scheme was derived as a solution to this issue. It was based on a dynamical model of a small PEV fleet that is served by a single temperature-constrained transformer. The solution is obtained with an iterative MPC scheme in which the individual PEVs can autonomously respond to incentives provided by a coordinator that is responsible for secure transformer operation.

5.1 Linear Models for Energy Hubs

A strictly linear formulation of the energy hub model was derived. Importantly, it is consistent with the nonlinear models developed in the literature. A concise ASCII-based format and a set of Matlab tools were developed, allowing seamless simulation, optimization, and analysis of multi-energy systems with more than 100 energy hubs. This allows users to address questions about the economical role of renewables and energy storage in a multi-energy setting, such as a university campus or military base. See [1].

5.2 Model Predictive Control for Cascade Mitigation

An MPC cascade mitigation scheme was developed for multi-energy systems. It highlights the importance of energy storage and balancing of economic and security constraints in power systems. Specifically, it was shown that without coupling economic and security objectives, an automated cascade mitigation scheme may become too greedy and place the system in a worse position long-term. See [3]

A receding-horizon MPC cascade mitigation scheme was established for electric power systems. It alleviates temperature overloads on transmission lines and prevents cascading failures. The scheme uses a simple, but sufficient, model of the power system, and balances economic and security constraints. Using a case-study of a standard IEEE test system, it was shown that this MPC scheme can mitigate the effect of severe disturbances and return the system to economically optimal set-points under uncertainty and model inaccuracies. See [4, 5].

A convex relaxation of AC line losses was derived and proven to be tight for the receding-horizon MPC scheme when line temperatures exceed their limit. This was crucial in the development of the MPC line overload model. The relaxation provides a superior approximation of losses in an AC transmission system compared with standard Taylor approximations. See [6]

5.3 Model Predictive Control and Optimization for Preventing Overloads

A non-centralized incentive-based robust MPC scheme was developed for preventing distribution transformer overloads. The scheme employs distributed load control of PEVs and a centralized coordinator to balance the charging objectives of the PEVs subject to network constraints. To achieve this overload prevention scheme, a dual ascent algorithm was applied. Simulations highlight that even with finite iteration limits enforced, the performance of the scheme is near-optimal and overloads are prevented robustly. See [11].

6 Advances in Vulnerability Analysis

6.1 Terror attacks, earthquakes and blackouts

We analyzed the interaction between a defender and a terrorist who threatens the operation of an electric power system. The defender wants to find a strategic defense to minimize the consequences of an attack. Both parties have limited budgets and behave in their own self-interest. The problem is formulated as a multi-level mixed-integer programming problem. A Tabu Search with an embedded greedy algorithm for the attack problem is implemented to find the optimum defense strategy. We apply the algorithm to a 24-bus network for a combination of four different defense budgets, three attack budgets, and three assumptions as to how the terrorists craft their attacks [21].

We developed a two-stage stochastic program and solution procedure to optimize the selection of capacity enhancement strategies to increase the resilience of electric power systems to earthquakes. The model explicitly considers the range of earthquake events that are possible and, for each, an approximation of the distribution of damage to be experienced. This is important because electric power systems are spatially distributed; hence their performance is driven by the distribution of damage to the components. We test this solution procedure against the nonlinear integer solver in LINGO 13 and apply the formulation and solution strategy to the Eastern Interconnect where the seismic hazard primarily stems from the New Madrid Seismic Zone. We show the feasibility of optimized capacity expansion to improve the resilience of large-scale power systems with respect to large earthquakes [19, 20].

This work was joint with Prof. Linda Nozick of Cornell University and her student Dr. Natalia Romero.

6.2 Restoring Feasibility

After a disturbance to a power grid, such as elimination of a transmission line in a deliberate attack or an "act of God," the network can sometimes be restored to feasibility by decreasing the demands at some nodes, and possibly also altering generator output. These actions can potentially be implemented by means of a controlled blackout, and would be far preferably to allowing a cascading failure to develop. We formulate the problem of determining the minimum set of adjustments — an "optimal blackout" — to demands and generation capabilities that can restore feasibility of the grid. We formulate this problem as a nonlinear program in which the AC power flow equations are the constraints, along with voltage magnitude constraints on the buses. The objective is a weighted sum of loads shed at demand nodes and changes to generation output at generator nodes. We proposed a sequential linear programming algorithm for solving the nonsmooth penalty function form of this nonlinear program, and showed that our approach has good global convergence properties (accumulation points satisfy first-order conditions) along with superlinear local convergence on nondegenerate problems. Our efficient implementation makes use of active-set heuristics and matrix factorization updates. It was shown to perform better than standard interior-point solvers. The method and application are described in [16, Chapter 2] and are currently being prepared for publication.

6.3 Vulnerability Analysis

We use a bilevel optimization framework eveals potential vulnerabilities to attack in a grid. At the top level of the bilevel formulation, a hypothetical attacker disrupts the system by degrading the capability of transmission lines (by increasing their impedance, in our model). The capability of the attacker to disrupt lines is limited by some budget on the impedance increases. (No network can be invulnerable to an unlimited attack.) At the lower level of the bilevel optimization problem, the system operator responds by shedding load and changing generator capability so as to restore feasibility of the grid. The optimal attack — the solution to the bilevel problem — is the set of impedance changes that causes maximum disruption to the grid, the one that requires the most changes to demands and power generation to restore viability. The lower-level problem is solved with the techniques of Section 6.2.

Bilevel optimization problems are notoriously difficult to solve, particularly when (as here) the upper-level problem is nonconvex and high-dimensional. There is the additional difficulty in this problem that many attacks can be dealt with without any load modifications, that is, the upper-level objective is zero over large parts of the feasible region. We have devised effective heuristics that identify the most vulnerable lines, and confine the search for optimal attack initially to these lines. A Frank-Wolfe scheme is applied in the vulnerable subspace, and the subspace is expanded progressively on later iterations. We have found the approach to be quite effective even for large grids; we tried a 2383-bus example. This work is described in [16, Chapter 3] and is currently being prepared for publication.

7 Advances in Network Design

In this section we discuss progress on designing power networks that are robust against cascades.

7.1 Stochastic Integer Programming Approaches

A cascading blackout is a random process with multiple stages. We embed Dobson's OPA simulation model for estimating load shed into a multi-stage stochastic mixed integer program. Using this model, we build a transmission expansion optimization problem that can guide planning decisions in power systems to ensure the system is robust with respect to cascading failure against a set of contingencies. A distinguishing feature of the uncertainty in the model is that the line failures are not completely random, but rather, they can be affected by the power flows injected into the network. This *decision-dependent uncertainty* severely complicates the modeling and solution process. We believe that our modeling of this decision dependent uncertainty is novel in that it allows for *a priori* sampling of scenarios of the cascading process. Our computational results indicate that even with a moderate amount of sampling, our model builds networks that are significantly more robust that competing ad-hoc methods. This work has been described in [7, Chapter 2], and a journal version of the paper is under preparation.

7.2 Simulation-Based Approaches

We have also attacked the transmission expansion design problem from a simulation-based optimization approach. Here, scenarios are not sampled beforehand. Rather, network design decisions are made, and distributions for the initial power demands, an initial trigger condition, and the cascade evolution are then (repeatedly) sampled. This process gives an accurate estimation of the distribution of the load shed via simulation for a fixed design decision.

From a mathematical perspective, optimizing the function that is the expected value (or any other statistic) of the load shed is extremely complicated. We have demonstrated with extensive numerical computation that the function is not convex, differentiable, continuous, or even monotone in its arguments. (It is well known that adding capacity to a network can increase the size of blackouts.)

Our work has to date resulted in a number of novelties in a simulation-based approach for this problem, including the embedding of *problem specific*, power-grid system information into well-known algorithms. Exploiting the problem structure has allowed us to more quickly find improving search directions and to perform a fast line search in this direction. Variance reduction techniques have also been explored and show significant promise in reducing the computation time to achieve a high quality solution and to verify its accuracy. This work has been described in [7, Chapter 3], and a journal version of the paper is under preparation.

8 Education

The grant contributed to the education of Co-PI Dobson's advisee Janghoon Kim PhD UW-Madison [13] and the ongoing education of his MS student Lingyun Ding and PhD student Atena Darvishi at Iowa State University. Co-PI Dobson also advised student Natalia Romero about electric power system modeling for her PhD in Civil Engineering under Prof. Linda Nozick at Cornell University [18]. The grant also supported ongoing research by PI Wright's advisee Taedong Kim, Co-PI Linderoth's student Eric Andersen, and Co-PI Hiskens' advisee Mads Almassalkhi.

9 Publications

A list of publications resulting from this project appears in the bibliography below.

10 Conclusions

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