Modeling and Optimization Techniques for Critical Infrastructure Resilience

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The resilience of critical infrastructure, such as water distribution systems and power systems, is critical for both the economy and public safety and health. However, methods and tools for evaluating and improving the resilience of these systems must be able to address the large network sizes, nonlinear physics, discrete decisions, and uncertainty. This dissertation focuses on the development of modeling and optimization techniques that address these difficulties, enabling the evaluation and improvement of power and water distribution system resilience.

In Part I, we present novel stochastic optimization models to improve power systems resilience to extreme weather events. We consider proactive redispatch, transmission line hardening, and transmission line capacity increases as alternatives for mitigating the effects of extreme weather. Our model is based on linearized or "DC" optimal power flow, similar to models in widespread use by independent system operators (ISOs) and regional transmission operators (RTOs). Our computational experiments indicate that each of these strategies can play a major role in power systems resilience.

We then extend the resilience formulations to investigate the role chemical process facilities, as industrial energy consumers, can play in improving electric grid resilience through demand response (DR). For process facilities to effectively negotiate demand response (DR) contracts and make investment decisions regarding flexibility, they need to quantify their additional value to the grid. We also reformulate the DR problems using the more accurate nonlinear alternating current power flow model to investigate the effect of the linear DC approximation. Our numerical results demonstrate that the linearized model often underestimates the amount of DR needed, motivating scalable solution algorithms for Mixed-Integer Nonlinear Programming (MINLP) problems in power systems.

An important step in many MINLP algorithms is the global solution of a Nonlinear Programming (NLP) subproblem. For power systems applications, this involves global solution of NLP's containing the alternating current (AC) power flow model. This thesis presents several advances to aid in global optimization of AC power flow equations. We show that a strong upper bound on the objective of the alternating current optimal power flow (ACOPF) problem can significantly improve the effectiveness of optimization-based bounds tightening (OBBT) on a number of relaxations. Furthermore, we investigate the effect

of the reference bus on OBBT. We find that, if reference bus constraints are included, relaxations of the rectangular form significantly strengthen existing relaxations and that the effectiveness of OBBT at a given iteration is directly related to the distance of the corresponding bus from the reference bus.

Ultimately, with OBBT alone, we are able to reduce the optimality gap to less than 0.1% on all but 5 NESTA test cases with up to 300 buses. However, the compuational expense required for OBBT grows rapidly with the size of the network. We present a decomposition algorithm based on graph partitioning to drastically improve this performance. Our numerical results demonstrate that our decomposed bounds tightening (DBT) algorithm results in variable bounds nearly as tight as those obtained with traditional, full-space OBBT. Furthermore, the compuatational expense of the DBT algorithm scales far more favorably with problem size, resulting in drastically reduced wallclock times, especially for large networks.

In Part II, we describe the Water Network Tool for Resilience (WNTR), an new open source Python package designed to help water utilities investigate resilience of water distribution systems to hazards and evaluate resilience-enhancing actions. The WNTR modeling framework is presented and a case study is described that uses WNTR to simulate the effects of an earthquake on a water distribution system. The case study illustrates that the severity of damage is not only a function of system integrity and earthquake magnitude, but also of the available resources and repair strategies used to return the system to normal operating conditions. While earthquakes are particularly concerning since buried water distribution pipelines are highly susceptible to damage, the software framework can be applied to other types of hazards, including power outages and contamination incidents.