Research Statement
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The National Academy of Engineering has classified widespread electrification as one of the greatest engineering accomplishments of the 20^{th} century. The ubiquity of electricity access in much of the world masks the challenges facing electric power systems in the 21^{st} century; reliability and economic efficiency improvements are needed for future power systems. Achieving these improvements requires the development of new optimization and control algorithms.

Motivation

Improving reliability is a major challenge facing electric power systems. Since electric power systems are intimately connected to modern society, service interruptions are extremely burdensome; a Lawrence Berkeley National Laboratory study estimated that the annual cost of power interruptions in the United States is $79 billion. Wide-scale blackouts are particularly disruptive and costly. For instance, the August 2003 blackout affected 50 million people in the Eastern United States and cost between $4 billion and $10 billion. Integrating large penetrations of intermittent renewable generation and operating power systems close to their limits further challenges electric reliability.

Economic operation of electric power systems is another major concern. Advanced optimization techniques have proven capable of improving power system economics. As one example, the Federal Energy Regulatory Commission (FERC) estimates that the recent adoption of modern mixed-integer optimization tools saves more than $1 billion annually in the US electricity markets.

Enhancing the reliability and economics of power systems are important research emphases that are amenable to improvements using new optimization and control algorithms. For instance, advances in convex optimization techniques, such as semidefinite programming, provide significant potential for achieving such improvements. Prior to these advances, the non-convexity of many power systems problems precluded obtaining solutions that were guaranteed to be globally optimal. By convexifying these problems, a semidefinite programming relaxation finds the global optima for many problems relevant to power system reliability and economics. Further research is necessary to fully exploit the potential of this approach as well as other advanced optimization and control algorithms.

Research Emphasis 1: Power System Reliability

Advances in optimization and control algorithms can be applied to enhance power system reliability. My previous work in this area focuses on the power flow equations, which are at the heart of many power system optimization and control problem. These equations relate the power injections and voltage phasors in an electric power system. Leveraging advances in semidefinite optimization and sum-of-squares programming, specific previous work includes developing algorithms that yield margins of the distance to power flow infeasibility, which is associated with power system instability. These margins help power system engineers ensure reliable operation and prevent blackouts. Related research with experts in demand response is developing an algorithm for using controllable loads to quickly improve stability following a disturbance.

Other current work relevant to power system reliability includes theoretical analyses that characterize the solutions to the power flow equations. An ongoing collaboration with mathematicians studying algebraic geometry has yielded new insights, particularly regarding the "low-voltage" power flow solutions that inform so-called "Unstable Equilibrium Point" analyses of transient stability.

In addition to investigating the power flow equations, previous work includes a partnership with FERC that developed new algorithms for identifying the transmission facilities that are most important to system reliability. Specific work in this area includes development of the Topological and Impedance Element Ranking (TIER) methodology. TIER uses tools from graph theory and power system engineering to identify facilities that should be considered part of the "bulk power system" and thus subject to federal regulations concerning system reliability. Other related work with FERC has provided methodologies for determining the transmission facilities that are most essential for the reliability of a specified location (e.g., ensuring service to a military base or hospital complex) and identifying the most important locations for reliability of the entire transmission network.

Another example partnership relevant to power system reliability is a current project with the Chicago utility company ComEd. This project analyzes off-line simulations to enable on-line detection of potentially destabilizing contingencies via appropriate warning thresholds for system instability based on real-time Phasor Measurement Unit (PMU) data. Future work aims to apply new signal processing techniques to PMU data in order to improve state estimation and topology identification algorithms.

Alongside existing stability-related challenges, cyberattacks are emerging as a major reliability concern. Algorithms that detect, characterize, and ameliorate cyberattacks are therefore of increasing interest. Relevant ongoing work includes developing algorithms for network parameter validation using historical operational data in order to identify and mitigate cyberattacks at control centers.

Research Emphasis 2: Power System Economics

Optimal power flow (OPF) is one of the main problems in power system economics. Electricity market operators solve OPF problems every five to fifteen minutes to minimize operating costs while satisfying network constraints and engineering limitations (e.g., requirements on voltage magnitudes and transmission line flows). Due to the OPF problem's non-convexity, traditional solution techniques do not guarantee obtaining the globally optimal solution. However, a convex relaxation in the form of a semidefinite optimization problem lower bounds the optimal objective value; certifies problem infeasibility; and, for many OPF problems, yields the global solution.

My previous work includes advances in theoretical aspects, computational speed, and modeling flexibility of this semidefinite relaxation. Ongoing research leverages recent developments in polynomial optimization theory to construct hierarchies of stronger convex relaxations that are appropriate for a broader class of OPF problems. Related algorithms globally solve OPF problems using the Lasserre hierarchy along with novel variants that exploit sparsity and complex variable structures. Promising research directions include further improving speed and flexibility as well as determining when these relaxations will globally solve an OPF problem (versus providing a strict lower bound on the objective value). Other ongoing research related to OPF algorithms uses a continuation method to escape local optima by finding multiple local extrema. In collaboration with experts in stochastic optimization, additional work studies an analytical reformulation of a chance-constrained OPF problem. With a particular focus on optimizing electric distribution networks, current efforts also include cataloging and numerically comparing various power flow representations as well as developing rigorous error bounds on linear power flow approximations.

Improving OPF algorithms requires a better understanding of the associated feasible spaces. Recent work has developed a new computational tool that is guaranteed to compute the entire feasible space for small OPF problems to within a specified discretization tolerance. This tool is being applied to understand what physical characteristics of a power system result in "difficult" versus "easy" problems. In addition to its theoretical interest, this will inform the development of challenging power system test cases for benchmarking optimization and control algorithms.

There is also much promise in the application of newly developed techniques to other problems. Relevant problems in electric power systems include unit commitment, where generators are dedicated for day-ahead operation; transmission switching, where the network topology is economically optimized; determining optimal locations for siting new facilities; and extending related optimization and control techniques to jointly analyze electric and natural gas networks.

Plans for Future Research and Collaboration

With increasing penetrations of controllable devices, renewable generation, sensors, and communication equipment at both the utility and consumer levels, electric power systems are undergoing significant changes. My intermediate- to long-term research plans include developing techniques to leverage the capabilities of future “smart grids” in order to improve power system reliability and economics. Creation of future smart grids will require collaborations among a wide variety of researchers in such fields as automatic control, signal processing, communications, cybersecurity, power electronics, electric machines, computer science, economics, and policy analysis.

I look forward to continuing to work with researchers and practitioners in these and other fields to conduct meaningful and practical research. Examples of collaboration opportunities that are related to my ongoing work include leveraging new signal processing techniques to improve the accuracy and computational speed of state estimation algorithms, using machine learning to identify the physical characteristics and related mathematical parameters that lead to challenging optimization problems, and applying emerging stochastic control algorithms to account for uncertainties in non-linear systems.

Conclusion

Economic and reliable operation of electric power systems are important goals for the 21st century. The development of new optimization and control algorithms is necessary for achieving these goals. With a solid basis of research experience and broad network of collaborators, I have a strong foundation for continued work in addressing the challenges faced by future power systems.

There is considerable interest in these research topics; the prior and ongoing work described in this statement has been funded by the Department of Energy, FERC, the National Science Foundation, and the Laboratory Directed Research and Development program at Argonne. In addition to previous competitive graduate and postdoctoral fellowships, research support includes three ongoing projects for which I am the lead investigator at Argonne as well as partnerships with faculty colleagues in which I currently serve as a co-advisor for three graduate students.