Research Statement
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The National Academy of Engineering 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 power systems in the 21^{st} century; future electric systems require reliability and economic improvements. Application of tools from the fields of optimization and policy are essential for achieving these improvements.

Motivation

Since electric power systems are intimately connected to modern society, service interruptions are extremely burdensome and expensive; a Lawrence Berkeley National Laboratory estimate placed the annual cost of power interruptions in the United States at $79 billion. Of these interruptions, 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 the increasing need to operate power systems close to their physical limits will further challenge electric reliability.

Economic operation of electric power systems is another major concern. Application of advanced optimization techniques has significant potential impact on power system economics. For instance, the Federal Energy Regulatory Commission (FERC) indicates that adoption of mixed-integer optimization will save more than $1 billion annually by 2015. Policies related to electricity markets and environmental requirements also have significant impacts on power system economics. Wind generation subsidies, for instance, have the unintended consequence of negative electricity prices in transmission constrained regions during periods of low demand.

Improving the reliability and economics of power systems are important research emphases that are amenable to improvements using both optimization and policy tools. 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. A semidefinite programming relaxation convexifies these problems and therefore finds globally optimal solutions for many problems relevant to power system reliability and economics. Further research is necessary to fully exploit the potential of these advanced optimization techniques. Power system reliability and economics also stand to benefit from investigations into such policies as the continuing transition from vertically integrated utilities to an electricity market paradigm and environmental policies encouraging distributed renewable generation and demand response.

Research Emphasis 1: Power System Reliability

Optimization: Advances in optimization can be used to enhance power system reliability. Previous work in this area includes a semidefinite optimization problem yielding margins of the distance to power system instability. This work helps power system engineers ensure reliable operation and prevent blackouts. Continuing work includes applying optimization techniques, real analytic geometry, and sum-of-squares programming to further investigate power system reliability. These approaches hold great promise for both developing better measures of power system stability and improving the computational and modeling aspects of existing techniques.

Policy Analysis: Previous policy-related research conducted with FERC identifies the transmission facilities most important to system reliability. Identification enables regulation and enhanced protection of these facilities. Specific work in this area includes development of the Topological and Impedance Element Ranking system to identify facilities that should be considered part of the "bulk power system" and thus subject to federal regulations concerning system reliability. Other work with FERC provides 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) and identification of the most important locations for reliability of the entire transmission network.

Future work includes investigating the design of rules and incentives in electricity markets to improve reliability. One question of interest regards the use of demand response resources such as controllable charging of plug-in electric vehicles. By balancing intermittent renewable generation sources, demand response resources can contribute to power system reliability. Unlocking the potential of these resources requires researching appropriate policies and institutional structures.

Research Emphasis 2: Power System Economics

Optimization: The optimal power flow (OPF) is one of the main problems in power system economics. This problem minimizes the operating cost of a power system within physical network constraints and engineering limitations (e.g., requirements on voltage magnitudes and transmission line flows). Electricity market operators solve OPF problems every five minutes to minimize power system operating costs. Due to the OPF problem's non-convexity, traditional solution techniques do not guarantee obtaining the globally optimal solution.

A recent relaxation in the form of a semidefinite optimization problem obtains the global solution to many OPF problems, thus enabling optimal power system operation. Previous work includes advances in theoretical aspects, computational speed, and modeling flexibility of this semidefinite relaxation. Future work in power system economics includes further investigation of the OPF problem. One open question of interest is determining when the semidefinite relaxation can and cannot be successfully applied to an OPF problem. Another promising research direction is leveraging developments in polynomial optimization theory to form better convex relaxations appropriate for a larger class of OPF problems and to incorporate stochastic renewable generation.

There is also much promise in the application of new optimization techniques to other power systems problems. Relevant problems include unit commitment, where generators are dedicated for day-ahead operation; transmission switching, where the network topology is economically optimized; and determining optimal locations for siting new power system assets.

Policy Analysis: Analyzing electricity market policies is also essential for improving power system economics. Previous policy-related work includes the analysis of speculation in electricity markets. Since market participants are not limited to producers and consumers of electricity, speculators, such as financial institutions, transact in these markets. In a study undertaken with the Public Service Commission of Wisconsin, a statistical analysis of the MidwestISO's financial transmission rights market showed evidence of significant speculator activity. By analyzing the liquidity benefits as well as the profits extracted by speculators, this study informs future debate on the appropriateness of speculator participation in this market. Further policy analyses are needed to ensure that these and other electricity markets operate in the public interest.

Policy analysis also has an important role in studying the institutional structures needed for integration of distributed generation and demand response resources. For instance, aggregation of distributed generators for participation in electricity markets could encourage more widespread adoption of small-scale renewable energy production. Determining the best institutional structures and policies for such aggregation is an important research topic.

Long-Term Research Vision

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. Longer-term research goals include developing techniques to leverage the capabilities of future power systems. In addition to the optimization and policy communities, creation of future "smart grids" will require collaboration with a wide variety of researchers and practitioners in such fields as cyber-security, signal processing, communication, dynamical systems, power electronics, electric machines, and economics. I look forward to working with experts in these and other fields to conduct meaningful and practical research that is relevant to future electric power systems.

Conclusion

Economic and reliable operation of electric power systems are important societal goals for the 21st century. The fields of optimization and policy analysis have crucial roles to play in achieving these goals. With interdisciplinary training in optimization and policy analysis along with previous research experience, I have a strong foundation for continued work in addressing the challenges faced by future electric power systems.

There is considerable interest in these topics at the national level; the prior work described in this statement has been funded by the Department of Energy and the Federal Energy Regulatory Commission. In addition to these funding sources, I intend to seek research support from the National Science Foundation and engagement with state public service commissions.