Research Statement

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MAIN CONTRIBUTIONS

The electric power and energy field is currently undergoing comprehensive and unprecedented changes. On the power supply side, extensive investments are being made into renewable generation systems, with the goal of achieving a cleaner energy structure. On the power consumption side, the deployment of smart meters, distributed generation and storage units, and home management systems has resulted in the power demand that is more flexible than ever before. In the middle, modern transmission and distribution grids benefit from advanced devices and theories, which allow system operators to dispatch their assets and operate their regional markets with much greater accuracy, thereby minimizing both generation costs and transmission losses. Along with the ongoing changes, countless opportunities and challenges have merged, necessitating dedicated research efforts that would allow the future world to be fueled in a cleaner and smarter manner.

My research endeavors have been driven by these challenges and have resulted in publications on a wide range of topics in the field of modeling and optimization of electric power systems. However, I dedicate this statement to one particular research direction: *state estimation, economic dispatch,* and *interregional power transactions in multi-area power systems*.

The power system in North America is jointly operated by multiple operators, whose operating areas are connected by tie-lines. Large scale power systems in Europe and China have similar structures. The optimal operation of the entire power system necessitates efficient local energy management with a given boundary state, which has been relatively mature, along with interregional coordination that specifies boundary states. The focus of my research is on the latter problem.

MULTI-AREA STATE ESTIMATION

In addressing the issue of interregional coordination, I started with the problem of state estimation, which is the cornerstone of today's energy management systems. The aim of state estimation is to extract the static state of the power system, represented by nodal voltage magnitudes and phase angles, from collected measurements by solving a weighted-least-square problem. Traditionally, each system operator separately estimated the state of the designated operating area. However, this approach would typically yield a sub-optimal solution because measurements at the remote side of tie-lines are usually inaccessible to system operators.

Moreover, separate and asynchronous state estimations by system operators may lead to discrepancies in boundary state estimates. Presence of these issues may compromise the accuracy of state estimates and hinder the area control error controlling.

The aforementioned shortcomings can be overcome by an effective multi-area state estimation method, which has been a subject of an extensive body of research. Multi-area state estimation is a distributed solution of a non-convex and unconstrained optimization. Numerous approaches have been proposed in this field, typically relying on system operators exchanging their intermediate boundary state estimates or pseudo-measurements. However, achieving the globally optimal state estimate with moderate computation and communication burdens is still an open question.

Thus, in approaching this challenge, I adopted a novel perspective, whereby only the most representative information pertaining to optimal conditions of local estimators is exchanged. For this purpose, I approximated optimal values of local objective functions as quadratic functions with respect to boundary states. These functions highly represent the relation between optimalities of local state estimators and the boundary state. Exchanging these functions ensures a rapid rate of convergence of the multi-area state estimator, which is proved to be equivalent to that achieved by the Gauss-Newton iteration. Owing to the improved rate of convergence, computation and communication efficiencies are also enhanced.

The paper describing this work has been published in *IEEE Transactions on Power Systems* in January 2017 [1]. I was also invited by Professor Mohamed E. El-Hawary to contribute a chapter on the same topic in the book "*Advances in Electric Power and Energy Systems*".

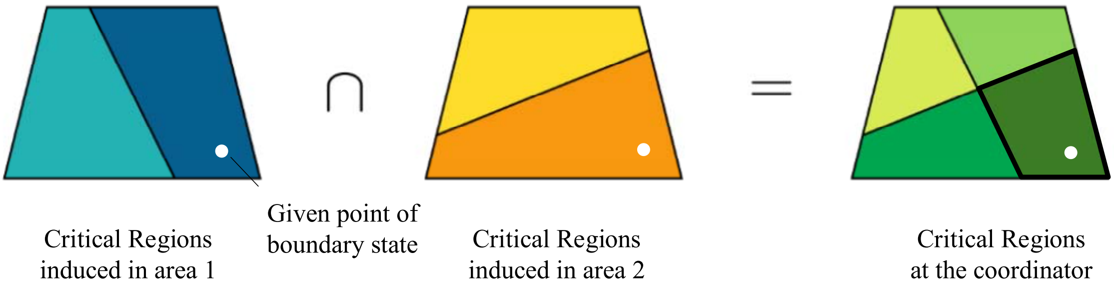
MULTI-AREA ECONOMIC DISPATCH

Inspired by the outcome of my work on the multi-area state estimation, I focused my research endeavors on a closely related and extremely attractive problem, that of multi-area economic dispatch.

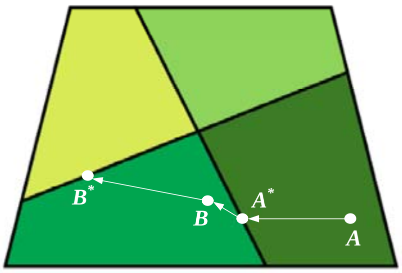
Economic dispatch is a quadratic or linear programming problem, depending on the characterization of generation cost functions. It is the key requirement for ensuring the optimal dispatch of controllable assets in electricity markets.

The problem of multi-area economic dispatch was introduced by the deregulation of electric power systems. Inefficient interchange power flow scheduling has resulted in substantial economic losses, estimated at $784M for 2006-2010 for the interface between ISO-NE and NYISO [2]. Multi-area economic dispatch optimizes the boundary state such that local economic dispatches also minimize the total cost of the entire system. It is essentially a distributed linear or quadratic optimization problem.

In addressing this issue, once again, I commenced with exchanging the most representative information among system operators. In this endeavor, I drew upon the multi-parametric programming theory, which described properties of parameterizations of local economic dispatches. More specifically, the optimal cost in each area is a piecewise affine/quadratic and convex function of the boundary state. The boundary state space is partitioned into polyhedral *critical regions*, representing the change of active constraint sets in sub-problems with the boundary state. Accordingly, I designed a strategy to search for the optimal boundary state based on local parameterizations in current critical regions and explorations of new critical regions. The resultant procedure is illustrated via the example with two areas and quadratic cost functions shown in Figure 1. The iteration procedure generates a sequence with decreasing costs.



(a) Local parameterization: The bolded polytope is the critical region containing the given boundary state



(b) Exploration: Initial boundary state A → optimum A^* in the current critical region → explore point B in a new critical region → optimum B^* in the new critical region

Figure 1 Illustration of parameterizations of local problems and explorations of critical regions [3]

I formally proved that the procedure described above could reach the global optimum in a finite number of steps, owing to the finiteness of the number of critical regions. The optimization is achieved by constructing only the critical regions identified in the exploration procedure. The method yields outstanding computation and communication efficiency. It is also noteworthy that it does not require sharing of any confidential information such as prices, system topologies and parameters, or operating states.

The method based on quadratic costs was described in a paper that has been accepted for publication in *IEEE Transactions on Power Systems* [4]. A robust solution of the tie-line scheduling with linear cost functions has been submitted to the same journal [3].

INTERREGIONAL POWER TRANSACTIONS

The multi-area economic dispatch solution provides a basis for interregional transaction scheduling. However, the results yielded are not directly applicable, as independent system operators are usually not permitted to trade directly. Therefore, interregional power transactions must rely on interface bids from external market participants. This results in the emergence of the cleared interface bid concept, which is a financial contract as a part of which the market participant will purchase and sell the same amounts of electricity at a pair of specified boundary locations in the two regional real-time markets. As market participants act as intermediaries, they do not physically generate or consume electricity.

In line with this prevalent market practice, I generalized the existing model of interface bids so that they could be incorporated into the formulation of multi-area economic dispatch. Of particular relevance are the two crucial properties I established for system operators with optimally cleared interface bids. First, all system operators achieve their revenue adequacies, whereby their net revenue from all internal and external bids are non-negative and are equal to the congestion rent. Second, under reasonable assumptions, system operators are expected to achieve lower costs relative to those achieved by the conventional separate clearing of interface bids. These two properties are critical when system operators are independent and primarily responsible for the performance of their respective operating areas.

The research paper describing this work has been submitted to *IEEE Transactions on Power Systems* [5].

RESEARCH PLAN

Going forward, I plan to expand my research on multi-area power systems. I aim to develop a general solution of the distributed optimization problem with the idea of critical region exploration. I will also seek collaborations with suitable industrial partners to implement my work in real power systems.

In addition, I plan to commence new research directions on modeling and dispatch of multi-energy systems and active distribution networks. These problems are of paramount importance in the transformation of power systems and I have distinctive potential to make valuable contributions in these fields.

Modeling and Dispatch of Multi-energy systems: I plan to focus on the coordinated state estimation and optimal dispatch for a complex energy system comprised of electricity, gasoline, heat, etc. These different energy types are increasingly being incorporated into unified systems via interfaces such as combined heat and power production and electric heat pumps. A coordinated operation of multi-energy systems can fundamentally change the existing approach to energy management and propel the defossilization of the entire energy system [6]. A key challenge is the fact that different types of energy have heterogeneous characteristics and are operated by different utilities. This issue can be handled by distributed optimization, whereby each utility would continue to operate its subsystem, subject to coordination driven by algorithms that optimally set the boundary states.

I have extensive research experience in the state estimation and dispatch of electric power system, which is at the core of many multi-energy systems. Moreover, my research pertaining to multi-area power systems provides me with a sturdy foundation for addressing the key challenge of distributed optimization in multi-energy systems. I believe that I can make valuable theoretical and practical contributions in this area.

My plan is to establish an inter-disciplinary research group with experts on different energy types, as this would allow investigating the modeling and operation methods in various energy systems. Moreover, drawing on my extensive research experience in the field of multi-area power systems, I would develop algorithms for coordination among different utilities. In addition, I would consider the market structure and clearing mechanisms for energy transactions in energy hubs.

Modeling and Dispatch of Active distribution networks: I am particularly interested in the distribution network, as it is at the forefront of the smart grid innovation focusing on the increasing integration of distributed generations, storage, and electric vehicles.

As I have been working on topics associated with distribution networks since my undergraduate research training program, I am in an excellent position to make a valuable contribution in this area. I am aware that the excessive number of buses is the main hindrance to efficient distribution network operation. Therefore, my prior work on distributed optimization for multi-area power systems is pertinent to distribution networks after proper adaption.

In addressing this issue, I will commence with the state estimation in distribution networks, wherein the lack of measurements is the key obstacle. Subsequently, I will extend my research effort to the dispatch of distributed generators and storages. Thereafter, the coordination among multiple distribution networks will be considered, as well as that between transmission and distribution networks.

To realize my research plans in practice, I will apply for external funding from National Science Foundation, Department of Energy, and industrial and international partners.

REFERENCE

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