

## DOCTORAL THESIS

# Computational methods and mechanisms for evaluating and enhancing the robustness of energy distribution systems

Shi, Benyun

*Date of Award:*  
2012

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Computational Methods and Mechanisms for  
Evaluating and Enhancing the Robustness of  
Energy Distribution Systems

SHI Benyun

A thesis submitted in partial fulfillment of the requirements  
for the degree of  
Doctor of Philosophy

Principal Supervisor: Professor LIU Jiming

Hong Kong Baptist University

August 2012

# Abstract

Energy distribution systems, such as pipeline networks and electric power systems, are complex due to not only the connectivity of distribution infrastructures but also the interactivity of their associated heterogeneous stakeholders. Historical data has shown that accidents, whether natural or man-made hazards, can severely damage the distribution systems, and potentially create various social and economic impacts. When this happens, disruptions on one part of a distribution system can spread to other parts, and even cause cascading failures in the system. Therefore, in order to take preventive measures, it would be desirable to evaluate, and if necessary to enhance, the robustness of energy distribution systems. Here, by robustness we mean the ability of maintaining system-level performances in the face of the disruptions. By leveraging the local-global relationships between interactions among the stakeholders at the microscopic (local) level and the desired performance of the systems at the macroscopic (global) level, this thesis further addresses the problem of how to enhance the robustness of distribution systems from a self-organizing systems perspective.

Specifically, this work adopts a network approach to modeling energy distribution systems by taking into consideration the energy flow dynamics in the systems and the connectivity of distribution infrastructures. On such networks, there exist two major types of disruptions, i.e., (i) supply disruptions and (ii) structural disruptions. With respect to supply disruptions, the thesis introduces the functional robustness of a distribution network to reflect its ability of maintaining a supply-demand balance on individual nodes. To computationally evaluate the functional robustness, here

we present a notion of network entropy to macroscopically characterize the energy flow dynamics on the network, based on a random walk theory. In addition, we look into how microscopic evaluation based on a failure spreading model helps us further determine the extent to which disruptions on one node may affect the others. In this work, we take the interstate natural gas distribution network in the U.S. as an example to demonstrate these concepts and methods.

Based on the macroscopic evaluation, we are then able to solve the problem of how to enhance the functional robustness of a distribution network by controlling energy flows on the network. From a self-organizing systems perspective, we propose a decentralized computational pricing mechanism, where each node needs only to communicate with its distribution neighbors by sending a “price” signal to its upstream neighbors and receiving “price” signals from its downstream neighbors. By doing so, each node can determine its outflows (i.e., distribution strategy) by maximizing its own payoff function. In this work, we carry out simulations on the U.S. natural gas pipeline network to validate the convergence and effectiveness of our proposed mechanism.

With respect to structural disruptions, the thesis addresses the problem of how to prevent cascading failures in an electric power system in the face of line contingencies. Specifically, we present two decentralized load-shedding algorithms. The coercive load-shedding algorithm is designed to secure the system by quickly shedding a necessary amount of loads and generation, while the fair load-shedding algorithm is to compute the shed amount of individual participants by taking into consideration the heterogeneity of their shed costs. Moreover, an embedded feedback mechanism in the fair load-shedding algorithm enables the real-time adjustment of compensations for each load-shedding participant based on the proportional fairness criterion. The properties of the two load-shedding algorithms are demonstrated by carrying out simulation-based experiments on the IEEE 30 bus system.

In summary, this thesis focuses on the development of computational methods and mechanisms for evaluating and enhancing the robustness of energy distribution

systems from a self-organizing systems perspective. The demonstrated results will offer policy makers, planners, and system managers with further insights into, as well as new tools for, emergency planning and design improvement for energy distribution infrastructures.

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