Understanding Complex Systems

Springer : COMPLEXITY

Rush D. Robinett III
David G. Wilson

Nonlinear Power Flow Control Design

Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis

Springer

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Understanding Complex Systems

Founding Editor: J.A. Scott Kelso

Future scientific and technological developments in many fields will necessarily depend upon coming to grips with complex systems. Such systems are complex in both their composition—typically many different kinds of components interacting simultaneously and nonlinearly with each other and their environments on multiple levels—and in the rich diversity of behavior of which they are capable.

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Dr. Rush D. Robinett III
Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185
USA

Dr. David G. Wilson
Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185
USA
dwilso@sandia.gov

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R & D Exploration:

"3 man fire team only."
"Prepare to deploy."
KANE 607
"Sounds reckless."
"3 against 50."
"I can tell these men have no combat experience."
"The old ones."
"The Veterans."
"They would have called for support, just in case."
CAPTAIN
Recommendation:
"Load them up with heavy artillery . . . pound that place with mortars, rockets, and cannons."
"Everything we've got."
"From a safe distance."
"It ain't fancy, but it will sure take care of your hostile military force."
CAPTAIN
"Alright do it."
"Withdraw the men."
COLONEL

SOLDIER
Excerpts from, ©1998 Warner Bros. and Morgan Creek Productions, Inc

Sandia
Z Division
1*st Battalion*
RECON
Three Man Fire Team

The authors dedicate this book to the memory
of J. Arlin Cooper

Foreword

Common problems and challenges that the United States and other countries must deal with involve integration of their green renewable resources on an existing aging electric power grid infrastructure. Faced with quickly approaching deadlines, many countries are trying to retrofit and patch in renewables in the best way possible. Given this, many of the proposed “future” smart grids are overlaying/marrying information networks with existing electric power grid infrastructure. What is needed is a paradigm shift in current practices in power engineering. At the heart of the electric power grid is the coordination and control of generation to meet customer loads.

Globally, there is awareness of the challenges associated with realization of the next generation of green grid. In the U.S., much work is being planned to achieve high penetration (more than 20 percent) of renewable resources by 2030. Some key issues are how to best take advantage of the high-wind corridors and transmission (currently nonexistent) of the power in the Midwest, where to install solar, how best to use storage, and what incentives can be offered. In some local cases, penetration can be greater than 40 percent, a serious technical challenge to overcome.

Traditionally, this has consisted of large portions of generation that is called on in an “open-loop” fashion to be dispatched to service random load needs. The grid of the future will require much improved automation with an efficiently integrated “closed-loop” configuration.

New breakthroughs and advances in our tools and methodologies based on sound scientific and engineering practices will need to be developed to meet these challenges and problems. A new approach will be required to formally address the green grid of the future with distributed variable generation, buying and selling of power (bidirectional flow), and decentralization of the electric power grid.

Many researchers are attempting to address this problem. While I was at the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy, a key program I led to address issues associated with increasing the role of renewable energy on our grid was the Solar Energy and Grid Integration Systems (SEGIS) program. The concepts developed under the SEGIS program are key to achieving high penetration of photovoltaic (PV) systems into the utility grid. Advanced, integrated inverter/controllers will be the enabling technology to maximize the benefits of residential and commercial solar energy systems, both to the system owners and to the utility distribution network as a whole. The value of the energy provided by these solar systems will increase through advanced communication interfaces and controls, while the reliability of electrical service, both for solar and nonsolar customers, will also increase.

In my current role as the Research and Development Program Manager in the Office of Electricity Delivery and Energy Reliability, I have further developed programs directed at integration of renewable energy into our electric grid with concentration on the perspective of the electric grid. In both my SEGIS program and Office of Electricity renewable to grid activities, Sandia National Laboratory has provided a leadership role in developing and demonstrating the all important control system architectures necessary to increase the role of renewable energy penetration on our electric grid with respect to stability and performance.

The goal of this book is to present a step toward addressing the integration of renewable resources into the electric power grid by applying new nonlinear power flow control techniques to the analysis of renewable generators connected to the electric power grid.

Washington, DC, USA
March 2011

Dan T. Ton

Program Manager
Office of Electricity Delivery & Energy Reliability
Smart Grid Research & Development

Preface

This book presents an innovative control system design methodology that is based on the latest research and development results at Sandia National Laboratories within the renewable energy electric power grid integration program. The inspiration for these research and development results are from three problems. The first problem is to find a unifying metric to compare the value of different energy sources to be integrated into the electric power grid such as coal-burning power plants, wind turbines, solar photovoltaics, etc., instead of the typical metric of costs/profits. The unifying metric of choice turns out to be exergy which is effectively negative entropy since price, in economic terms, has too many unaccounted for externalities. The second problem was to develop a new nonlinear control tool that applies power flow control, thermodynamics, and complex adaptive systems theory to the energy grid in a consistent way. The third problem is mathematically formulating how a person effectively navigates a time, spatially varying environment from a robotic engineer's point of view such that collective robotic theories can be used to create optimal individuals and high-performance teams of people. This problem is far from solved, however many of the basic concepts in this book are a result of how a person regulates power flows. These insights will be used in the future to account for the effects of individuals and groups of people that will be controlling and selling power into a distributed, decentralized electric power grid. In addition, these problems have several key concepts in common: exergy flow, limit cycles, and balance between competing power flows.

The main goal of the research effort was to develop a methodology that provides a unique set of criteria to design nonlinear controllers for nonlinear systems. This methodology addresses both stability and performance as well as seamlessly integrating information theory concepts instead of following the typical linear controller zero-sum design trade-off process between stability and performance. It works by combining concepts from thermodynamic exergy and entropy, Hamiltonian mechanics, Lyapunov's direct method and Lyapunov optimal analysis, electric AC power concepts, power flow analysis, and Fisher Information. The thermodynamic concepts are employed to allow the control design to be viewed as a power flow approach. This power flow approach balances power generation and power dissipation subject to the power storage (i.e., kinetic and potential energies) for a special class of dynamical systems called Hamiltonian natural systems and adiabatic irreversible work processes. This approach provides both necessary and sufficient conditions for stability while simultaneously allowing for performance specifications.

This book has been subdivided into three parts; theory, applications, and advanced concepts. In the first part (Chaps. 1–5), the necessary theoretical developments are presented that include: nonequilibrium thermodynamics, Hamiltonian mechanics, stability principles, and advanced control design concepts. In part two (Chaps. 6–13), the methodology is demonstrated through multiple case studies ranging from control design issues, collective plume tracing, nonlinear aeroelasticity and wind turbine control, fundamental power engineering, renewable energy microgrid design, robotic manipulator control, to satellite reorientation control. In part three, Chap. 14, advanced concepts are introduced that employ the fundamental theory, from part one as a foundation, and demonstrates how to extend it sustainability of self-organizing systems.

Research scientists, practicing engineers, applied mathematicians, physicists, and engineering students with a background in and basic understanding of thermodynamics, dynamics, and controls will be able to develop and apply this methodology to their particular problems. Considerable emphasis is placed on the necessary design steps for which the concepts are introduced and explained with numerous examples and a variety of case studies. The organization of the book makes it possible to be used as a first-level graduate course on nonlinear control design or as a reference or supplemental textbook for a special topic in support of a broader control theory course. In addition, the book has been developed in such a fashion that the interested reader, through self-study, could broaden their understanding of the analysis, design, and synthesis of nonlinear control systems.

Several distinctive features that are developed in this book are:

- Our approach provides both necessary and sufficient conditions for stability of a class of nonlinear systems while simultaneously allowing for performance specifications.
- Our approach provides seamless connections between information theory and nonlinear control by demonstrating the equivalence of physical and information exergies by applying nonlinear equilibrium thermodynamics, Hamiltonian mechanics, quantum mechanics, and Fisher Information.
- The material has been subdivided into three parts: theory, applications, and advanced concepts. This allows the reader to progressively move through the material, such as in a classroom environment or selectively investigate chapters most related to their own interests, working at their own pace. Many of the case studies are provided with explicit design steps to illustrate the ideas and principles behind the nonlinear power flow control methodology.
- Several of the case studies have been selected surrounding advanced and future control system designs and issues associated with the current integration of renewable energies (wind and solar) and interlaced with conventional energy sources and operations.

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Sandia National Laboratories provides a unique atmosphere for the advancement of control research and the development of needed control tool sets through continued commitment and support. In particular, the Laboratory Directed Research and Development (LDRD) projects *Design Tools for Complex Dynamic Security Systems—Adaptive Complexity* and *Innovative Control of a Flexible, Adaptive Energy Grid* have very much facilitated the outcome of this research. Sandia is currently supporting a Grand Challenge LDRD project associated with our advanced microgrid control architectures. In addition, work completed for the following external projects: the Office of Force Transformation, Office of the Secretary of Defense, *Implementing the Power of the Collective* project and DARPA Mechanics Based Analogies for Swarms, *Collective Systems: Physical and Information Exergies* also played a key role.

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Rush D. Robinett III
David G. Wilson

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