

Understanding Complex Systems

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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

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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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Dynamic Stability, and Lyapunov Analysis



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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
1st 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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Albuquerque, NM, USA
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Rush D. Robinett III
David G. Wilson

Contents

Part I Theory

1	Introduction	3
1.1	Background	3
1.2	Thermodynamics	5
1.3	Hamiltonian Mechanics	6
1.4	Static Stability and Dynamic Stability	6
1.5	Limit Cycles	8
1.6	Information Theory	9
1.7	Chapter Summary	11
2	Thermodynamics	13
2.1	Introduction	13
2.2	First Law (Energy)	13
2.3	Second Law (Stability/Entropy/Available Work)	14
2.4	Equilibrium Thermodynamics (Reversible/Irreversible Processes)	18
2.5	Local Equilibrium (Nonequilibrium Thermodynamics; Energy, Entropy, and Exergy Rate Equations)	19
2.6	Chapter Summary	21
3	Mechanics	23
3.1	Introduction	23
3.2	Work, Energy, and Power	23
3.3	Energy Diagrams and Phase Planes	26
3.4	Hamiltonian Mechanics	27
3.5	Connections Between Thermodynamics and Hamiltonian Mechanics	29
3.5.1	Conservative Mechanical Systems	29
3.5.2	Reversible Thermodynamic Systems	29
3.5.3	Irreversible Thermodynamic Systems	30
3.5.4	Connections	30
3.6	Line Integrals and Limit Cycles	32

3.6.1	Linear Limit Cycle	32
3.6.2	Nonlinear Limit Cycles	39
3.6.3	Connection of Line Integrals and Limit Cycles to Thermodynamics	51
3.7	Chapter Summary	53
4	Stability and Control	55
4.1	Introduction	55
4.2	Static Stability and Dynamic Stability	56
4.3	Eigenanalysis	60
4.3.1	Integral Feedback Is an Exergy Generator—Comparison to a Lag Stabilized System	63
4.3.2	Integral Feedback Is an Exergy Generator—Investigation by Exergy/Entropy Control Stability Boundary	64
4.3.3	Integral Feedback Is an Exergy Generator—Routh– Hurwitz Stability Analysis	65
4.3.4	PID Control Design Numerical Example	66
4.3.5	The Power Flow Principle of Stability for Nonlinear Systems	71
4.4	Lyapunov Analysis	72
4.5	Energy Storage Surface and Power Flow: HSSPFC	77
4.6	Chapter Summary	93
5	Advanced Control Design	95
5.1	Introduction	95
5.2	Distributed Parameters/PDEs	95
5.3	Fractional Calculus	99
5.3.1	Sorting Power Terms: Generators, Storage, Dissipators	100
5.3.2	Compare Performance: PID, Lag-Stabilized, Fractional	107
5.4	Optimal Control	112
5.5	Robust/Tracking Control	116
5.6	Adaptive/Tracking Control	119
5.7	Chapter Summary	122
 Part II Applications: Case Studies		
6	Case Study #1: Control Design Issues	127
6.1	Introduction	127
6.2	Nonlinear Second-Order System with Sinusoidal Damping	127
6.3	An Extension of Eigenanalysis to MIMO Nonlinear Systems	132
6.4	Two-Mass Numerical Example	135
6.4.1	Linear MIMO System Controller Design	136
6.4.2	Nonlinear MIMO System Controller Design	144
6.5	Noncollocated Control	152
6.6	Chapter Summary	160

- 7 Case Study #2: Collective Systems and Controls 161**
 - 7.1 Introduction 161
 - 7.2 Equilibrium Collective Systems 163
 - 7.3 Kinematic Collective Control 173
 - 7.3.1 Kinematic Control Design 173
 - 7.3.2 Robot Description 175
 - 7.3.3 Information Flow: A Trade-off Between Processing,
Memory, and Communications 176
 - 7.4 Kinetic Collective Control 177
 - 7.5 Fisher Information and Equivalency 179
 - 7.6 Chapter Summary 184

- 8 Case Study #3: Nonlinear Aeroelasticity 185**
 - 8.1 Introduction 185
 - 8.2 Nonlinear Stall Flutter Model 187
 - 8.2.1 Linear Region 188
 - 8.2.2 Nonlinear Stall Flutter with Linear Dynamics 189
 - 8.2.3 Nonlinear Stall Flutter with Nonlinear Dynamics 189
 - 8.2.4 Controller Design 192
 - 8.3 Specific 5 MW Wind Turbine Control Design 197
 - 8.4 Chapter Summary 202

- 9 Case Study #4: Fundamental Power Engineering 207**
 - 9.1 Introduction 207
 - 9.2 Power Engineering Application 207
 - 9.3 Performance of Electric Power Grid System 211
 - 9.4 Linear Adaptive Power Engineering 214
 - 9.5 Nonlinear Adaptive Power Engineering 217
 - 9.6 Chapter Summary 222

- 10 Case Study #5: Renewable Energy Microgrid Design 225**
 - 10.1 Introduction 225
 - 10.2 HSSPFC Design for a Typical OMIB System 227
 - 10.3 HSSPFC Applied to UPFCs and Renewable Generators 230
 - 10.3.1 Example One—OMIB System with a UPFC 231
 - 10.3.2 Example Two—Swing Equation for a Wind Turbine
Connected to an Infinite Bus Through UPFC 232
 - 10.3.3 HSSPFC Applied to UPFC and Variable Generation 233
 - 10.3.4 Numerical Simulations 234
 - 10.4 Microgrid in Islanded Mode 236
 - 10.5 HSSPFC Applied to UPFCs for Conventional and Renewable
Generators 240
 - 10.6 Chapter Summary 243

- 11 Case Study #6: Robotic Manipulator Control Design 245**
 - 11.1 Introduction 245
 - 11.2 Evaluation of the Equations of Motion 246

- 11.2.1 Two-Link Robot Model 246
- 11.2.2 Evaluation of the Hamiltonian Surface Shaping 248
- 11.2.3 Evaluation of Power Flow 249
- 11.3 Tracking Controller: Perfect Parameter Matching 252
- 11.4 Chapter Summary 258
- 12 Case Study #7: Satellite Reorientation Control 259**
 - 12.1 Introduction 259
 - 12.2 Spacecraft Attitude Control Design 260
 - 12.3 Chapter Summary 267
- 13 Case Study #8: Wind Turbine Control Design 273**
 - 13.1 Introduction 273
 - 13.2 Wind Turbine Model 273
 - 13.3 Adaptive Power Flow Controller Design 276
 - 13.4 Simple Model Simulation Results 278
 - 13.5 Chapter Summary 279
- Part III Advanced Topics**
- 14 Sustainability of Self-organizing Systems 283**
 - 14.1 Introduction 283
 - 14.2 Simple Nonlinear Satellite System 286
 - 14.2.1 Conservation Equations for the Engine Component
(Control Volume 1) 287
 - 14.2.2 Conservation Equations for the Machine (Control
Volume 2) 289
 - 14.2.3 Conservation Equations for the Total System (Control
Volume 12) 291
 - 14.3 Lifestyle Definition 292
 - 14.3.1 Deformation of Potential Field with Information Flow . . . 294
 - 14.4 Exergy Sustainability: An Energy Surety Approach 296
 - 14.4.1 Optimality 297
 - 14.4.2 Scalability 303
 - 14.5 Chapter Summary 304
- References 307**
- Index 315**

List of Figures

Fig. 1.1 Flowchart describing mechanics based approaches for collective systems. Robinett III, R.D. and Wilson, D.G. [37], reprinted by permission of the publisher (Interscience Publishers) 10

Fig. 2.1 Equilibrium states (potential energy) 15

Fig. 2.2 Expansion of gas: adiabatic irreversible expansion 16

Fig. 2.3 Expansion of gas: reversible expansion 16

Fig. 2.4 Energy versus entropy curve 17

Fig. 2.5 Entropy changes 18

Fig. 2.6 Equilibrium thermodynamics 19

Fig. 2.7 Reversible cyclic work 19

Fig. 3.1 General mass, spring, damper system. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 26

Fig. 3.2 Paraboloid (*left*) and parabolas (*right*) 27

Fig. 3.3 Phase plane 27

Fig. 3.4 Time response for power in a general AC circuit with $\omega = 2\pi$, $\tilde{v} = 1.5$, $\tilde{i} = 2.0$, and $\theta = \pi/4$. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 32

Fig. 3.5 Linear limit cycle: Hamiltonian 3D surface (*left*) and phase plane plot (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 34

Fig. 3.6 Linear limit cycle mass–spring–damper system rising to higher energy state—generative with 3D Hamiltonian (*left*) and projected 2D phase plane (*right*) plots ($K_p = c = K_D = 0$, $K_I = 0.5$). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 35

Fig. 3.7	Linear limit cycle mass–spring–damper system falls to lower energy state—dissipative with 3D Hamiltonian (<i>left</i>) and projected 2D phase plane (<i>right</i>) plots ($K_P = c = K_I = 0$, $K_D = 1.0$). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	36
Fig. 3.8	Thevenin equivalent RLC circuit. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	36
Fig. 3.9	Linear limit cycle Hamiltonian 3D spiral transient (<i>upper-left</i>) with corresponding phase plane plot (<i>upper-right</i>). The next 3D plots present the linear, 10% variation in inductance, and 20% variation in capacitance, C steady-state responses (<i>lower-left</i>) with the corresponding phase plane plots (<i>lower-right</i>). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	38
Fig. 3.10	Van der Pol power flow (<i>left</i>) and energy (<i>right</i>) responses—generative case. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	41
Fig. 3.11	Van der Pol power flow (<i>left</i>) and energy (<i>right</i>) responses—neutral case. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	41
Fig. 3.12	Van der Pol power flow (<i>left</i>) and energy (<i>right</i>) responses—dissipative case. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	41
Fig. 3.13	Van der Pol responses: Hamiltonian 3D surface (<i>left</i>) and phase plane 2D projection (<i>right</i>). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	42
Fig. 3.14	Van der Pol reconstructed as controller inputs: power flow (<i>left</i>) and energy (<i>right</i>) responses—generative case (Note: DISS and \int DISS $d\tau$ are zero). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	43
Fig. 3.15	Van der Pol reconstructed as controller inputs: power flow (<i>left</i>) and energy (<i>right</i>) responses—dissipative case (Note: GEN and \int GEN $d\tau$ are zero). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandf.co.uk/journals)	43

Fig. 3.16 Van der Pol reconstructed as controller inputs responses: Hamiltonian 3D surface (*left*) and phase plane 2D projection (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 44

Fig. 3.17 Nonlinear limit cycles with nonlinear stiffness and damping effects. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 45

Fig. 3.18 Combined van der Pol and Duffing responses: Hamiltonian 3D surface (*left*) and phase plane 2D projection (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 45

Fig. 3.19 Case 1 stable phase plane plot (*left*) and kinetic/potential energy rate responses (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 46

Fig. 3.20 Case 2 power flow and energy responses (*left*) and system responses (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 47

Fig. 3.21 Case 3 power flow and energy responses (*left*) and system responses (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 47

Fig. 3.22 Case 4 power flow and energy responses (*left*) and system responses (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 48

Fig. 3.23 Cases 2–4: mass–spring–damper with Duffing oscillator/Coulomb friction model numerical results: Hamiltonian 3D surface (*left*) and total energy responses (*right*). Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 48

Fig. 3.24 Gain scheduling with the integral gain as a function of initial conditions. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 49

Fig. 4.1 Static stability. Robinett III, R.D. and Wilson, D.G. [56], reprinted by permission of the publisher (©2010 IEEE) 56

Fig. 4.2 Static margin 57

Fig. 4.3 Aerodynamic moment (*left*) and integral of aerodynamic moment with respect to angle of attack (*right*) 57

Fig. 4.4 Nonlinear mass, spring, damper system. Robinett III, R.D. and Wilson, D.G. [46], reprinted by permission of the publisher (Taylor & Francis Ltd, <http://www.tandf.co.uk/journals>) 60

Fig. 4.5 Case 1A: rotary mass–spring–damper model with PID control numerical transient responses. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 67

Fig. 4.6 Case 1A: rotary mass–spring–damper model with PID control numerical results. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 67

Fig. 4.7 Case 1: rotary mass–spring–damper model with PID control numerical transient responses. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 68

Fig. 4.8 Case 1: rotary mass–spring–damper model with PID control numerical results. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 68

Fig. 4.9 Case 2: rotary mass–spring–damper model with PID control numerical transient responses. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 68

Fig. 4.10 Case 2: rotary mass–spring–damper model with PID control numerical results. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 69

Fig. 4.11 Case 2: rotary mass–spring–damper model spring restoring and inertial effects numerical results. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 69

Fig. 4.12 Case 3: rotary mass–spring–damper model with PID control numerical transient responses. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 69

Fig. 4.13 Case 3: rotary mass–spring–damper model with PID control numerical results. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 70

Fig. 4.14 All cases: rotary mass–spring–damper model with PID control exergy transient responses. Robinett III, R.D. and Wilson, D.G. [13], reprinted by permission of the publisher (Interscience Publishers) 70