Large-Scale System Analysis under Uncertainty

Discover a comprehensive set of tools and techniques for analyzing the impact of uncertainty on large-scale engineered systems. Providing accessible yet rigorous coverage, this book showcases the theory through detailed case studies drawn from electric power application problems, including the impact of integration of renewable-based power generation in bulk power systems, the impact of corrupted measurement and communication devices in microgrid closed-loop controls, and the impact of components failures on the reliability of power supply systems. The case studies also serve as a guide on how to tackle similar problems that appear in other engineering application domains, including automotive and aerospace engineering.

This is essential reading for academic researchers and graduate students in power systems engineering, and dynamic systems and control engineering.

Alejandro D. Domínguez-García is a Professor in the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign, where he also holds Research Professor appointments with the Coordinated Science Laboratory and the Information Trust Institute.

“Uncertainty and reliability are of higher and higher priority as marginal costs go down and the number of components goes up. This book is comprehensive and rigorous, full of derivations and nuanced examples – an excellent reference for anyone seeking solid foundations.”

Josh Taylor, University of Toronto

“Professor Domínguez-García’s book should be required reading for all graduate students in electric power systems. It fills a critical gap by focusing on the dynamical systems and control engineering foundations that underpin power system analysis and control, rather than focusing on the application domain problems themselves.”

Johanna Mathieu, University of Michigan

“With climate change disruptions being a new normal, electric vehicles taking over our roads, and renewable energies being an existential matter for all of us, there is a considerable need for a reference book on power system analysis under uncertainties. This book is advantageous to both students and practitioners working in the planning and operation of the electric grid.”

Reza Argandeh, Western Norway University of Applied Sciences

Large-Scale System Analysis under Uncertainty

With Electric Power Applications

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**In memory of my father,
Ángel Domínguez Casás (1930 – 2020),
who instilled in me a passion for mathematics**

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Preface and Acknowledgments

This book presents a collection of uncertainty analysis techniques for systems whose behavior can be mathematically represented by a set of algebraic or differential equations describing the relation between certain variables of interest. The techniques included revolve around probabilistic and set-theoretic descriptions of some uncertain phenomena that drive the system response, for example, random load variations in an electric power system, or manifest themselves as changes in the system structure, such as a power line outage caused by a storm. The case studies used throughout the book draw heavily from electric power system applications; however, the techniques presented are general and can be used in other applications, such as aerospace and automotive.

Many of the techniques presented in the book were developed in the area of systems theory and control. These techniques are very powerful and universally applicable; however, it requires a certain level of mathematical sophistication to understand the theory behind them. The goal of the book is to make these techniques accessible to applied researchers and engineers across multiple domains while maintaining a certain level of rigor in the exposition. In doing so, I have tried to make the book as self-contained as possible by including a preliminaries chapter and a mathematical background appendix that reviews most fundamental concepts used throughout the book, namely probability, stochastic processes, set theory, and linear dynamical systems theory. Except for the introductory and preliminaries chapters, the structure of subsequent chapters is always the same. Specifically, the first part of each chapter presents the general theory for a particular analysis technique interspersed with small examples that illustrate its use. The second part of each chapter illustrates the application of the particular technique to the analysis of problems encountered in electric power applications.

The inspiration for this book came from the book by Fred C. Schweppe entitled *Uncertain Dynamic Systems*, which published in 1973. I first became familiar with the book while I was working on my PhD when Professor George Verghese, who was a member of my thesis committee, pointed it out to me because of the material it contained on set-theoretic techniques for uncertainty analysis of linear dynamical systems. This material ended up being very relevant for my graduate research work on reliability and performance analysis of fault-tolerant systems, and it formed the core of one of the chapters of my PhD thesis; thus, I am greatly indebted to Professor Verghese.

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Shortly after joining the University of Illinois, I developed a graduate-level course entitled Dynamic System Reliability. Early on in this course, I adopted Schweppe's aforementioned book as a reference. The book had been long out of print, but I was fortunate enough to get permission from the publisher to have the book reprinted locally for exclusive use in the course. As the course material evolved, over numerous offerings, it became apparent that Schweppe's book, while a fantastic reference, was not a perfect match for the course syllabus. As a result, I decided to develop a set of lecture notes that would align better with the course material; those notes eventually became the core material for this book.

Since my arrival at Illinois, I have worked with many undergraduate and graduate students – too many to name them all here – and I am grateful for having had the opportunity to work with a group of such talented individuals. Special thanks go to my former graduate students Stanton Cady, Sairaj Dhople, Christine Chen, Xichen Jiang, Eric Hope, and Madi Zholbaryssov as several of the application examples featured in the book are drawn from our joint research. I would also like to thank the students who have taken my graduate course and provided feedback on early versions of some of the book chapters. My former PhD student, Madi Zholbaryssov, read the whole manuscript very thoroughly and helped in fixing several issues; the end result is better because of him and I am very thankful for it. I am eternally grateful to my friend and long-term collaborator Christoforos Hadjicostis, who read early versions of the manuscript, providing encouragement and critical feedback early in the writing process, and also gave a thorough read to the final manuscript. Finally, I would like to thank my colleagues at the Department of Electrical Engineering at Illinois for providing a stimulating intellectual environment – George Gross, Daniel Liberzon, Pete Sauer, and Venu Veeravalli deserve a special mention for all the mentoring and encouragement they have provided over the years.

This book is dedicated to my father, Ángel, who unexpectedly passed away as I was applying the final touches to the manuscript. He and my mother, Vicenta, provided a nurturing environment when I was growing up and prioritized the education of their six children over all material things. They instilled in me a curiosity for learning and the importance of hard work that led me to pursue an academic career and ultimately resulted in the writing of this book. The final words are for the three loves of my life, my two daughters, Maia and Lia, and my wife, Cristina. Maia and Lia were both born in the six-year span that it took me to complete the book, and they brightened some difficult periods in the writing process. Cristina's appetite for learning, work ethic, and determination were a continuous source of inspiration during the writing process, and a constant reminder of values I hold dear.

Notation

Set Theory

$\mathbb{N}$	Set of natural numbers
$\mathbb{Z}$	Set of integer numbers
$\mathbb{R}$	Set of real numbers
$\mathbb{C}$	Set of complex numbers
$\mathbb{R}^n$	Set of n-dimensional real vectors
$\mathbb{R}^{n \times m}$	Set of $(n \times m)$-dimensional real matrices
$\mathbf{int}(\mathcal{X})$	Interior of the set $\mathcal{X} \in \mathbb{R}^n$
$\mathbf{cl}(\mathcal{X})$	Closure of the set $\mathcal{X} \in \mathbb{R}^n$
$\mathbf{bd}(\mathcal{X}),\ \partial\mathcal{X}$	Boundary of the set $\mathcal{X} \in \mathbb{R}^n$
$S_{\mathcal{X}}(\cdot)$	Support function of the set $\mathcal{X} \in \mathbb{R}^n$

Vectors and Matrices

$x^\top y$, $<x, y>$	Inner product of two vectors, x, y
$\|x\|_2$	Euclidean norm, or 2-norm, of a vector x
$\mathbf{0}_n$	All-zeros vector of dimension n
$\mathbf{1}_n$	All-ones vector of dimension n
$\mathbf{0}_{n \times m}$	All-zeros matrix of dimensions $n \times m$
I_n	Identity matrix of dimensions $n \times n$
$A^\top$	Transpose of a real matrix A
A^{-1}	Inverse of a nonsingular matrix A
$\mathbf{diag}(x_1, x_2, \ldots, x_n)$	$(n \times n)$-dimensional diagonal matrix whose (i, i) entry is equal to x_i
$\mathbf{rank}(A)$	Rank of a matrix A
$\mathbf{tr}(A)$	Trace of a square matrix A
$\mathbf{det}(A)$	Determinant of a square matrix A
$\mathbf{vec}(A)$	Column vector obtained by stacking the columns of a matrix A
$\mathbf{real}(\lambda)$	Real part of eigenvector λ
$\sigma(A)$	Spectrum of a square matrix $A \in \mathbb{R}^{n \times n}$, i.e., set of eigenvalues of A
$A \otimes B$	Kronecker product of matrices A and B.

Functions

$f\colon \mathcal{X} \to \mathcal{Y}$	A function mapping elements in $\mathcal{X}$ into elements in $\mathcal{Y}$
$f^{-1}\colon\ \mathcal{Y} \to \mathcal{X}$	Inverse function of $f\colon\ \mathcal{X} \to \mathcal{Y}$
$f, f(\cdot)$	Shorthand notation for $f\colon\ \mathcal{X} \to \mathcal{Y}$
$f\colon \mathbb{R}^n \to \mathbb{R}$	A function mapping n-dimensional real vectors into real numbers
$f\colon \mathbb{R}^n \to \mathbb{R}^m$	A function mapping n-dimensional real vectors into m-dimensional real vectors
$\nabla f(x)$	Gradient of a real-valued function $f(\cdot)$
$\frac{\partial f(x)}{\partial x}$, $J_f(x)$	Jacobian of a vector-valued function $f(\cdot)$ at x
$\left.\frac{\partial f(x)}{\partial x}\right\vert_{x=x_0}$	Jacobian of a vector-valued function $f(\cdot)$ at $x = x_0$

Probability and Stochastic Processes

$\Pr(A)$	Probability that event A has occurred
$F_X(\cdot)$	Cumulative distribution function (cdf) of random variable X
$p_X(\cdot)$	Probability mass function (pmf) of a discrete random variable X
$f_X(\cdot)$	Probability density function (pdf) of continuous random variable X
$F_{X,Y}(\cdot,\cdot)$	Joint cdf of random variables X and Y
$p_{X,Y}(\cdot,\cdot)$	Joint pmf of discrete random variables X and Y
$f_{X,Y}(\cdot,\cdot)$	Joint pdf of continuous random variables X and Y
$f_{X\,\vert\,Y}(\cdot\,\vert\,y)$	Conditional pdf of random variable X given $Y = y$
$\mathrm{E}[\cdot]$	Expectation operator
μ_X	Mean of random variable X
$c_{X,Y}$	Covariance of random variables X and Y
$r_{X,Y}$	Correlation of random variables X and Y
σ_X^2	Variance of random variable X
m_X	Mean of random vector X
Σ_X	Covariance matrix of random vector X
S_X	Correlation matrix of random vector X
$C_{X,Y}$	Covariance matrix of random vectors X and Y
$R_{X,Y}$	Correlation matrix of random vectors X and Y
$m_X[\cdot]$	Mean function of discrete-time stochastic vector process X
$C_X[\cdot,\cdot]$	Covariance function of discrete-time stochastic vector process X
$R_X[\cdot,\cdot]$	Correlation function of discrete-time stochastic vector process X
$m_X(\cdot)$	Mean function of continuous-time stochastic vector process X
$C_X(\cdot,\cdot)$	Covariance function of continuous-time stochastic vector process X
$R_X(\cdot,\cdot)$	Correlation function of continuous-time stochastic vector process X
$\delta(\cdot)$	Dirac delta function

Linear Dynamical Systems

$\Phi_{k,\ell}$	State-transition matrix of a discrete-time state-space model
$\Phi(t,\tau)$	State-transition matrix of a continuous-time state-space model

Power Networks

θ_i	Phase angle of the phasor associated with bus i's sinusoidal voltage
V_i	Magnitude of the phasor associated with bus i's sinusoidal voltage
p_i	Active power injected into a power network at bus i
q_i	Reactive power injected into a power network at bus i
$\overline{Y}_{ik}$	Shunt admittance of a transmission line linking bus i and bus j
$\overline{Z}_{ik}$	Series impedance of a transmission line linking bus i and bus j
X_{ik}	Imaginary part of $\overline{Z}_{ik}$
$\overline{Y}$	Power network admittance matrix
G	Real part of $\overline{Y}$
B	Imaginary part of $\overline{Y}$
$\overline{y}_{i,k}$	(i,k) entry of the power network admittance matrix
$g_{i,k}$	Real part of $\overline{y}_{i,k}$
$b_{i,k}$	Imaginary part of $\overline{y}_{i,k}$
M	Incidence matrix of the graph associated with a power network
p.u.	Per unit