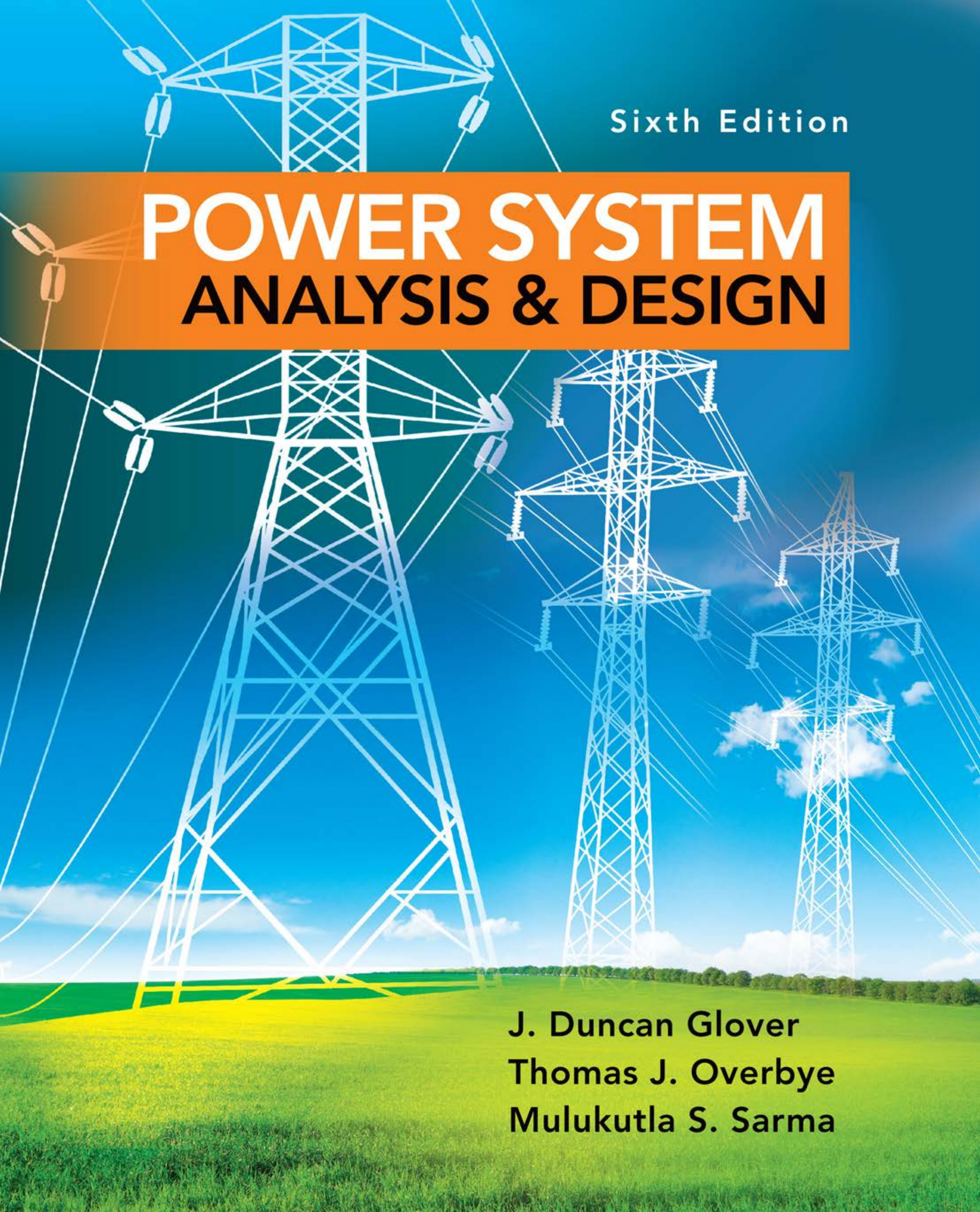

Sixth Edition

POWER SYSTEM ANALYSIS & DESIGN

J. Duncan Glover
Thomas J. Overbye
Mulukutla S. Sarma

POWER SYSTEM ANALYSIS & DESIGN

SIXTH EDITION

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***Power System Analysis & Design*, Sixth Edition**
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Cover Image: High voltage power lines and pylon, kstudija/ShutterStock.com; Picturesque Green Field and Blue Sky, AlinaMD/ShutterStock.com; Power high voltage tower, kstudija /ShutterStock.com

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WCN: 02-200-203

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Library of Congress Control Number: 2015956452

ISBN: 978-1-305-63213-4

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Printed in the United States of America
Print Number: 01 Print Year: 2015

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In loving memory of my mentors Professor Fred C. Schweppe [1933–1988] and Dr. Alexander Kusko [1921–2013]. You taught me, you guided me, you set the bar for which I continue to strive. You shall not be forgotten.

My Guardian Poet[s]

A guardian poet you have been to me
Much like an angel, there protecting me
When I was silent, lost in dark of night
You read my words and brought me back to light

You told me that my words were ever true
That in my writes were thoughts profound and new
You would not let me simply drift away
A word of hope you'd send to greet each day

Your name is there below each thing I write
To tear dimmed eyes you brought a vision bright
"The Queen of Passion," how I love the name
You gave to me and life is not the same

To you, my Guardian Poet, thanks I bring
You fool me not; I see your angel wing

Eileen Manassian Ghali

To Jo, Tim, Hannah, and Amanda

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Preface

The objective of this book is to present methods of power system analysis and design, particularly with the aid of a personal computer, in sufficient depth to give the student the basic theory at the undergraduate level. The approach is designed to develop students' thinking processes, enabling them to reach a sound understanding of a broad range of topics related to power system engineering, while motivating their interest in the electrical power industry. Because we believe that fundamental physical concepts underlie creative engineering and form the most valuable and permanent part of an engineering education, we highlight physical concepts while giving due attention to mathematical techniques. Both theory and modeling are developed from simple beginnings so that they can be readily extended to new and complex situations.

NEW TO THIS EDITION

New chapter-opening case studies bring principles to life for students by providing practical, real-world engineering applications for the material discussed in each chapter.

Comprehensively revised problem sets ensure students have the practice they need to master critical skills.

Updated Instructor Resources

These resources include

- Instructor's Solutions Manual with solutions to all problems
- Comprehensive Test Bank offering additional problems
- Annotated Lecture Note PowerPoint Slides
- Lesson Plans that detail how to most effectively use this edition
- Updated PowerWorld Simulator Software
- Student PowerPoint Notes

New design projects in this edition meet Accreditation Board for Engineering and Technology (ABET) requirements to provide valuable hands-on experience and to help ensure students are receiving an education that meets globally recognized accreditation standards.

The latest version of the valuable PowerWorld Simulator (version 19) is included and integrated throughout the text.

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KEY FEATURES

The text presents present-day, practical applications and new technologies along with ample coverage of the ongoing restructuring of the electric utility industry. It is supported by an ample number of worked examples, including illustrations, covering most of the theoretical points raised. It also includes PowerWorld Simulator version 19 to extend fully worked examples into computer implementations of the solutions. Version 19 includes power flow, optimal power flow, contingency analysis, short circuit, and transient stability.

The text includes a chapter on Power Distribution with content on Smart Grids.

It also includes discussions on modeling of wind turbines in power flow and transient stability.

Four design projects are included, all of which meet ABET requirements.

POWERWORLD SIMULATOR

One of the most challenging aspects of engineering education is giving students an intuitive feel for the systems they are studying. Engineering systems are, for the most part, complex. While paper-and-pencil exercises can be quite useful for highlighting the fundamentals, they often fall short in imparting the desired intuitive insight. To help provide this insight, the book uses PowerWorld Simulator version 19 to integrate computer-based examples, problems, and design projects throughout the text.

PowerWorld Simulator was originally developed at the University of Illinois at Urbana-Champaign to teach the basics of power systems to nontechnical people involved in the electricity industry, with version 1.0 introduced in June 1994. The program's interactive and graphical design made it an immediate hit as an educational tool, but a funny thing happened—its interactive and graphical design also appealed to engineers doing analysis of real power systems. To meet the needs of a growing group of users, PowerWorld Simulator was commercialized in 1996 by the formation of PowerWorld Corporation. Thus while retaining its appeal for education, over the years PowerWorld Simulator has evolved into a top-notch analysis package, able to handle power systems of any size. PowerWorld Simulator is now used throughout the power industry, with a range of users encompassing universities, utilities of all sizes, government regulators, power marketers, and consulting firms.

In integrating PowerWorld Simulator with the text, our design philosophy has been to use the software to extend, rather than replace, the fully worked examples provided in previous editions. Therefore, except when the problem size makes it impractical, each PowerWorld Simulator example includes a fully worked hand solution of the problem along with a PowerWorld Simulator case. This format allows students to simultaneously see the details of how a problem is solved and a computer implementation of the solution. The added benefit from PowerWorld Simulator is its ability to easily extend the example. Through its interactive design, students can quickly vary example parameters and immediately see the impact such changes have on the solution. By reworking the examples with the new parameters, students get immediate feedback on whether they understand the solution process.

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The interactive and visual design of PowerWorld Simulator also makes it an excellent tool for instructors to use for in-class demonstrations. With numerous examples utilizing PowerWorld Simulator instructors can easily demonstrate many of the text topics. Additional PowerWorld Simulator functionality is introduced in the text problems and design projects.

PREREQUISITES

As background for this course, it is assumed that students have had courses in electric network theory (including transient analysis) and ordinary differential equations and have been exposed to linear systems, matrix algebra, and computer programming. In addition, it would be helpful, but not necessary, to have had an electric machines course.

ORGANIZATION

The text is intended to be fully covered in a two-semester or three-quarter course offered to seniors and first-year graduate students. The organization of chapters and individual sections is flexible enough to give the instructor sufficient latitude in choosing topics to cover, especially in a one-semester course. The text is supported by an ample number of worked examples covering most of the theoretical points raised. The many problems to be worked with a calculator as well as problems to be worked using a personal computer have been revised in this edition.

After an introduction to the history of electric power systems along with present and future trends, *Chapter 2* orients the students to the terminology and serves as a brief review of fundamentals. The chapter reviews phasor concepts, power, and single-phase as well as three-phase circuits.

Chapters 3 through 5 examine power transformers including the per-unit system, transmission-line parameters, and steady-state operation of transmission lines. *Chapter 6* examines power flows including the Newton-Raphson method, power-flow modeling of wind generation, economic dispatch, and optimal power flow. These chapters provide a basic understanding of power systems under balanced three-phase, steady-state, normal operating conditions.

Chapters 7 through 10, which cover symmetrical faults, symmetrical components, unsymmetrical faults, and system protection, come under the general heading of power system short-circuit protection. *Chapter 11* examines transient stability, which includes the swing equation, the equal-area criterion, and multi-machine stability with modeling of wind-energy systems. *Chapter 12* covers power system controls, including generator-voltage control, turbine-governor control, and load-frequency control. *Chapter 13* examines transient operation of transmission lines including power system overvoltages and surge protection.

Chapter 14 introduces the basic features of primary and secondary distribution systems as well as basic distribution components including distribution substation transformers, distribution transformers, and shunt capacitors. We list some of the major distribution software vendors followed by an introduction to distribution reliability, distribution automation, and smart grids.

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ADDITIONAL RESOURCES

Companion websites for this book are available for both students and instructors. These websites provide useful links and other support material.

Student Website

The **Student Companion Site** includes a link to download the free student version of PowerWorld and Student PowerPoint Notes.

Instructor Resource Center

The **Instructor Companion Site** includes

- Instructor's Solutions Manual
- Annotated PowerPoint Slides
- Lecture Notes
- Test Banks

To access the support material described here along with all additional course materials, please visit https://sso.cengage.com.

MINDTAP ONLINE COURSE AND READER

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap have access to the book's multimedia-rich electronic Reader and are able to complete homework and assessment material online, on their desktops, laptops, or iPads. Instructors who use a Learning Management System (such as Blackboard, Canvas, or Moodle) for tracking course content, assignments, and grading, can seamlessly access the MindTap suite of content and assessments for this course.

With MindTap, instructors can

- Personalize the Learning Path to match the course syllabus by rearranging content or appending original material to the online content
- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student engagement, progress and comprehension
- Promote student success through interactivity, multimedia, and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes in the digital Reader, study from and create their own Flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and automatically-graded homework.

ACKNOWLEDGMENTS

The material in this text was gradually developed to meet the needs of classes taught at universities in the United States and abroad over the past 35 years. The original 13 chapters were written by the first author, J. Duncan Glover, *Failure Electrical LLC*,

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who is indebted to many people who helped during the planning and writing of this book. The profound influence of earlier texts written on power systems, particularly by W. D. Stevenson, Jr., and the developments made by various outstanding engineers are gratefully acknowledged. Details of sources can only be made through references at the end of each chapter, as they are otherwise too numerous to mention.

Chapter 14 *(Power Distribution)* was a collaborative effort between Dr. Glover (Sections 14.1-14.7) and Co-author Thomas J. Overbye (Sections 14.8 & 14.9). Professor Overbye, *University of Illinois at Urbana-Champaign* updated Chapter 6 *(Power Flows) and* Chapter 11 *(Transient Stability)*. He also provided the examples and problems using PowerWorld Simulator as well as three design projects. Co-author Mulukutla Sarma, *Northeastern University,* contributed to end-of-chapter multiple-choice questions and problems.

We commend the following Global Engineering team members at Cengage Learning: Timothy Anderson, Product Director; Mona Zeftel, Senior Content Developer; and Kristiina Paul, Freelance Permissions Researcher; as well as Rose Kernan of RPK Editorial Services, Inc. for their broad knowledge, skills, and ingenuity in publishing this edition. We also thank Jean Buttrom, Content Project Manager; Kristin Stine, Marketing Manager; Elizabeth Murphy, Engagement Specialist; Ashley Kaupert, Associate Media Content Developer; Teresa Versaggi and Alexander Sham, Product Assistants.

The reviewers for the sixth edition are as follows: Ross Baldick, *University of Texas at Austin*; François Bouffard, *McGill University*; Venkata Dinavahi, *University of Alberta*; Seyed Pouyan Jazayeri, *University of Calgary*; Bruno Osorno, *California State University at Northridge*, Zeb Tate, *University of Toronto*; and Mahyar Zarghami, *California State University at Sacramento.*

Substantial contributions to prior editions of this text were made by a number of invaluable reviewers, as follows:

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In conclusion, the objective in writing this text and the accompanying software package will have been fulfilled if the book is considered to be student-oriented, comprehensive, and up to date, with consistent notation and necessary detailed explanation at the level for which it is intended.

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List of Symbols, Units, and Notation

Symbol	Description
a	operator 1/120°
a_t	transformer turns ratio
A	area
A	transmission line parameter
A	symmetrical components transformation matrix
B	loss coefficient
B	frequency bias constant
B	phasor magnetic flux density
B	transmission line parameter
C	capacitance
C	transmission line parameter
D	damping
D	distance
D	transmission line parameter
E	phasor source voltage
E	phasor electric field strength
f	frequency
G	conductance
G	conductance matrix
H	normalized inertia constant
H	phasor magnetic field intensity
i(*t*)	instantaneous current
I	current magnitude (rms unless otherwise indicated)
I	phasor current
I	vector of phasor currents
j	operator 1/90°
J	moment of inertia
l	length

Symbol	Description
P	real power
q	Charge
Q	reactive power
r	radius
R	resistance
R	turbine-governor regulation constant
R	resistance matrix
s	Laplace operator
S	apparent power
S	complex power
t	time
T	period
T	temperature
T	torque
v(*t*)	instantaneous voltage
V	voltage magnitude (rms unless otherwise indicated)
V	phasor voltage
V	vector of phasor voltages
X	reactance
X	reactance matrix
Y	phasor admittance
Y	admittance matrix
Z	phasor impedance
Z	impedance matrix
α	angular acceleration
α	transformer phase shift angle
β	current angle

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Symbol	Description
l	length
L	inductance
$\mathbf{L}$	inductance matrix
N	number (of buses, lines, turns, etc.)
p.f.	power factor
$p(t)$	instantaneous power
λ	magnetic flux linkage
λ	Penalty factor
Φ	magnetic flux
ρ	resistivity
τ	time in cycles
τ	transmission line transit time

Symbol	Description
β	area frequency response characteristic
δ	voltage angle
δ	torque angle
ε	permittivity
Γ	reflection or refraction coefficient
θ	impedance angle
θ	angular position
μ	permeability
υ	velocity of propagation
ω	radian frequency

SI Units

A	ampere
C	coulomb
F	farad
H	henry
Hz	hertz
J	joule
kg	kilogram
m	meter
N	newton
rad	radian
s	second
S	siemen
VA	voltampere
var	voltampere reactive
W	watt
Wb	weber
Ω	ohm

English Units

BTU	British thermal unit
Cmil	circular mil
ft	foot
hp	horsepower
in	inch
mi	mile

Notation

Lowercase letters such as v(t) and i(t) indicate instantaneous values.
Uppercase letters such as V and I indicate rms values.
Uppercase letters in italic such as *V* and *I* indicate rms phasors.
Matrices and vectors with real components such as **R** and **I** are indicated by boldface type.
Matrices and vectors with complex components such as ***Z*** and ***I*** are indicated by boldface italic type.
Superscript T denotes vector or matrix transpose.
Asterisk (*) denotes complex conjugate.
PW highlights problems that utilize PowerWorld Simulator.

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1 Introduction

Blundell geothermal power plant near Milford, UT, USA. This 38-MW plant consists of two generating units powered by geothermal steam. Steam is created from water heated by magma at depths up to 6100 meters below Earth's surface. (Courtesy of PacifiCorp.)

Electrical engineers are concerned with every step in the process of generation, transmission, distribution, and utilization of electrical energy. The electric utility industry is probably the largest and most complex industry in the world. The electrical engineer who works in that industry encounters challenging problems in designing future power systems to deliver increasing amounts of electrical energy in a safe, clean, and economical manner.

The objectives of this chapter are to review briefly the history of the electric utility industry, to discuss present and future trends in electric power systems, to describe

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the restructuring of the electric utility industry, and to introduce PowerWorld Simulator—a power system analysis and simulation software package.

CASE STUDY

The following article describes the deregulation of the electric utility industry that has been taking place in the United States, including the benefits and problems that have been encountered with deregulation. During the last two decades, deregulation has had both good and bad effects. It has changed the mix of fuels in the U.S. generation fleet, shifting it away from coal and nuclear power toward natural gas and has opened the door to greener forms of electricity generation. It has also made many companies that provide electricity more efficient by increasing the reliability of power plants and reducing labor costs. However, wholesale prices of electricity have increased dramatically in some areas of the United States, market-based investments in transmission have been problematic, and rolling blackouts have been encountered [8].

How the Free Market Rocked the Grid*

Seth Blumsack Pennsylvania State University

It led to higher rates and rolling blackouts, but it also opened the door to greener forms of electricity generation.

Most of us take for granted that the lights will work when we flip them on, without worrying too much about the staggeringly complex things needed to make that happen. Thank the engineers who designed and built the power grids for that—but don't thank them too much. Their main goal was reliability; keeping the cost of electricity down was less of a concern. That's in part why so many people in the United States complain about high electricity prices. Some armchair economists (and a quite a few real ones) have long argued that the solution is deregulation. After all, many other U.S. industries have been deregulated—take, for instance, oil, natural gas, or trucking—and greater competition in those sectors swiftly brought prices down. Why not electricity?

Such arguments were compelling enough to convince two dozen or so U.S. states to deregulate their electric industries. Most began in the mid-1990s, and problems emerged soon after, most famously in the rolling blackouts that Californians suffered through in the summer of 2000 and the months that followed. At the root of these troubles is the fact that free markets can be messy and volatile, something few took into account when deregulation began. But the consequences have since proved so

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chaotic that a quarter of these states have now suspended plans to revamp the way they manage their electric utilities, and few (if any) additional states are rushing to jump on the deregulation bandwagon.

The United States is far from being the only nation that has struggled with electricity deregulation. But the U.S. experience is worth exploring because it highlights many of the challenges that can arise when complex industries such as electric power generation and distribution are subject to competition.

Unlike many other nations grappling with electricity deregulation, the United States has never had one governmentowned electric utility running the whole country. Instead, a patchwork of for-profit utilities, publicly owned municipal utilities, and electric cooperatives keeps the nation's lights on. The story of how that mixture has evolved over the last 128 years helps to explain why deregulation hasn't made electric power as cheap and plentiful as many had hoped.

The 1882 opening of Thomas Edison's Pearl Street generation station in New York City marks the birth of the American electric utility industry. That station produced low-voltage direct current, which had to be consumed close to the point of production, because sending it farther would have squandered most of the power as heat in the connecting wires.

Edison's approach prevailed for a while, with different companies scrambling to build neighborhood power stations. They were regulated only to the extent that their owners had to obtain licenses from local officials. Municipalities handed these licenses out freely, showing the prevailing laissez-faire attitude toward competition. Also, politicians wanted to see the cost of electricity drop. (A kilowatt-hour in the late 1800s cost about U.S. $5.00 in today's dollars; now it averages just 12 cents.)

It didn't take long, though, before Samuel Insull, a former Edison employee who became a utility entrepreneur in the Midwest, realized that the technology George Westinghouse was advocating—large steam or hydroelectric turbines linked to long-distance ac transmission lines—could provide electricity at lower cost. Using such equipment, his company soon drove its competitors out of business. Other big utilities followed Insull's lead and came to monopolize the electricity markets in New York, New Jersey, and the Southeast. But the rise of these companies was ultimately a bane to consumers, who had to pay exorbitant prices after the competition had been quashed.

Angered by the steep rates, consumers formed electricity cooperatives and municipal utilities. That in turn led Insull and his counterparts to plead with state officials for protection from this "ruinous" competition. Politicians complied, passing laws that granted the large electric power companies exclusive franchises in their areas in exchange for regulation of their prices and profits. The municipal utilities and electricity cooperatives continued to operate but in most cases never grew as large as the regulated for-profit (investor-owned) utilities.

This basic structure remained in place until the oil shocks of the 1970s. Real electricity prices rose by almost 50 percent during that

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troubled decade, despite having fallen virtually every year since the opening of Edison's Pearl Street station. One culprit was the widespread use of imported oil. The United States then generated almost 20 percent of its electricity using fuel oil; today that figure is less than 1 percent. And many utilities had made some poor investments—primarily in nuclear power—which their customers had to pay for.

The 1970s also exposed problems in how the electric power industry was regulated. Power grids were growing in complexity as different utilities began interconnecting, and many regulators—particularly those whose appointments were political favors—didn't understand the technical implications of their decisions. The combination of rising prices and obvious mismanagement led many large industrial consumers of electricity to push for deregulation.

The Public Utility Regulatory Policies Act of 1978 was the first shot fired in the ensuing battle. The new federal law allowed nonutility companies to generate electricity from "alternative" fuel sources (mostly natural gas), and it required utilities to sign long-term supply contracts with these new generating companies. The Energy Policy Act of 1992 expanded the pool of players in the wholesale electricity market by allowing financial institutions—Morgan Stanley being the first—to buy and sell bulk electric power. Yet neither act was effective in curbing electricity prices.

Two states, California and Pennsylvania, then decided to take more drastic measures. They established centralized spot markets for electricity and allowed individual customers to choose their electricity suppliers. While Pennsylvania's experiment has largely run smoothly, California's experience was quite different. After two years of reasonably stable operation, wholesale prices exploded in 2000, from a few cents per kilowatt-hour to more than a dollar per kilowatt-hour. One reason for those astronomical prices was that power-trading companies like Enron Corp. had figured out how to game the system. With retail prices capped by law at 6.7 cents per kilowatt-hour, two of the state's three investor-owned utilities, Pacific Gas & Electric and Southern California Edison, ran out of money to pay for electricity. That triggered a second power crisis the following year, which forced the state to buy electricity from producers. The long-term contracts signed during that period of panic buying saddled California taxpayers with a debt of some $40 billion.

■ ■ ■ ■

For Californians, at least, deregulation had lost its gloss. This turned out to be temporary: The state recently reintroduced centralized wholesale markets modeled after Pennsylvania's. But has deregulation on the whole made things better or worse? Dozens of studies have attempted to answer that question. But you can't simply compare states that have aggressively deregulated with ones that haven't. That would ignore the fact that some states have built-in advantages that keep prices low: proximity to natural resources,

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a large base of generation capacity, and so forth. It also ignores what utilities and regulators would have done if deregulation had never happened.

To answer the question properly, you'd need to figure out what things would have been like in the absence of deregulation. And that's well-nigh impossible. Of the various studies that have attempted to assess the impacts of deregulation, most have come from groups with a stake in the outcome of the regulatory reform process. So they tend to be either strongly for deregulation or strongly against it. In reality, deregulation has had both good and bad effects.

Consider a simple variable like the price of electricity. That competition will lead to lower prices is about as close to a universal truth as economics gets. But electricity seems to be an exception.

Here's why: Under regulation, each generating plant is paid for its electricity based on its average cost plus some prescribed rate of return. In a competitive market, supply and demand set the price. That means that the last plant coming online to handle the load determines the wholesale price of electricity. All generators in the system are then paid that same amount for each kilowatt-hour they inject into the grid.

That might seem only fair, but you have to remember that not all electricity generators are created equal. In most places, coal and nuclear plants, which can't be ramped up and down easily, produce the roughly constant baseload power feeding the grid. If more is needed, natural gas turbines then kick in. So in deregulated markets, the price of gas, which has historically been higher than that of coal or nuclear fuel, ends up controlling the wholesale price of electricity—allowing the owners of nuclear plants and efficient coal plants to earn much higher profits than they did under regulation. That's why electricity prices in many places rose so sharply when natural gas prices skyrocketed at the turn of the millennium.

Other strange dynamics also come into play. For example, state political leaders realize that escalating or erratic electricity prices are bad for economic development (and their own chances of reelection). So they've fought hard to keep them low and stable by imposing rate caps and freezes. But many of these same states also compelled their electric utilities to divest themselves of generating capacity in an attempt to spur competition. And when electricity demand is high and the utilities don't have enough of their own generating capacity, they're forced to buy more on the spot market, where prices are volatile. The results have not been pretty. In 2000, one of California's two largest utilities went bankrupt, and the other nearly did. And when regulators in Maryland finally allowed retail electricity rates in Baltimore to float with wholesale electricity prices, the local utility immediately announced a rate increase of 72 percent, leading to consumer outrage and eventually to the summary firing of the entire public utility commission.

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DEREGULATION IS ALL OVER THE MAP
Countries have deregulated their electric power industries to different degrees, as these five examples show.

Argentina

Privatization of electricity generation in Argentina began in 1992, followed the next year by privatization of that nation's six transmission companies. Argentine law did not allow any of the resultant for-profit power companies to control more than 10 percent of the country's generation capacity, ensuring considerable competition among them.

United Kingdom

Electricity restructuring in the UK began under Margaret Thatcher, with the Electricity Act of 1983, which gave independent power producers access to the national grid. Government-owned generators were then fully privatized in the 1990s.

France

France began a very modest program of reform in 2001, but for the most part electricity supply remains completely dominated by the state electricity company, Électricité de France.

Germany

In response to a 1996 European directive, Germany abolished its law exempting electricity from competition in 1998. But most of that country's electricity still comes from just a few vertically integrated power companies, with comparatively little electricity trading on open exchanges.

Australia

The Australian state of Victoria privatized its electricity sector in 1994. Some other Australian states soon followed suit. And Australia established a national wholesale electricity market in December 1998.

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Clearly, deregulation hasn't been at all successful in bringing prices down. But has it made the companies that provide electricity more efficient? Very probably. Their labor costs have fallen, mostly through reductions in staff, while the reliability of their power plants has improved. The champions in this regard are the nuclear power stations, whose uptimes have risen from around 65 percent in the 1980s to over 90 percent today. This shouldn't be a surprise. Because the construction costs of most of these plants have been paid off and because nuclear generators have very low operating expenses, the plants have become extraordinarily profitable. So their owners strive to have them online as much as possible, investing as needed to keep them well maintained.

Maintaining some other parts of the grid infrastructure has, however, proved to be more of a struggle. In the old days, investments in transmission lines and generating stations were determined by consensus between each utility and its regulator. Deregulation's architects envisioned a different scenario—that entrepreneurial firms would automatically make the needed investments in hopes of profiting from them. That didn't exactly happen. One thing deregulation definitely did do, though, was to change the mix of fuels in the U.S. generation fleet, shifting it away from coal and nuclear power toward natural gas. That's because gas units are quick to build, and many are flexible enough to operate only when prices are high enough to warrant throwing their switches on. It helps, too, that natural gas is a cleaner fuel than coal and less controversial than nuclear power, which helps with public approval. Also, because companies generating electricity in a free market need to demonstrate a return on investment within 5 to 10 years, building big nuclear and coal plants, which usually take over a decade to complete, just isn't an option. So more and more of the grid's power comes from gas turbines, despite the high fuel costs.

The changing investment environment has also inflated the cost of building new infrastructure. The reason is obvious once you think about it. Regulated utilities can spread the burden of investment among all their customers, and the government guarantees that these companies can charge enough to recover their initial outlay and make a decent profit on it. So there's little financial risk in building a new plant or transmission line, allowing the companies to attract low-priced capital. Not so with unregulated utilities, whose fortunes depend on an uncertain market. The greater risk they face means they must offer higher returns to attract investors, and these increased financing costs make capital projects more expensive.

Depending on market-based investment in transmission lines has proved especially problematic. Deregulation's proponents believed that for-profit companies would recover the money they invested in transmission lines through "congestion

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pricing"—charging more when demand for these lines is high. Instead, lucrative congestion revenues have only given the owners of existing transmission lines an incentive *not* to build more capacity. And the general aversion people have to high-tension cables nearby—the "not in my backyard" effect—has made it almost impossible to construct new lines.

No great wonder, then, that investment in transmission lines and equipment has mostly been falling since the 1970s. Many people paid little notice to that fact, but the Northeast blackout of 2003 was a wake-up call. It began on a hot August afternoon with several seemingly trivial outages of transmission lines in Ohio, but by nighttime a series of cascading failures grew to plunge more than 50 million people in the Midwest, the Northeast, and Ontario into darkness. This episode convinced even skeptics that investment in the nation's electricity grid was lagging.

■ ■ ■ ■

Given deregulation's checkered record, you have to wonder how well competitive electricity markets will handle upcoming challenges. In particular, how will they reconcile the need for reliable, low-cost power with the environmental costs of producing it?

One much-discussed way to use markets to benefit the environment is to put a price on emissions of carbon dioxide and other greenhouse gases. Many countries have already done this. But unless the price is set a lot higher than in Europe, U.S. utilities and generating companies aren't going to be abandoning their carbon-spewing coal plants anytime soon—they're just too profitable. Putting a dollar value on greenhouse gases might encourage some generators to invest in less carbon-intensive power sources where they can, but only if proper laws and regulations are in place to lower the risk. And that won't happen overnight.

In the meantime, 32 of the 50 U.S. states are trying to boost the use of renewables by mandating "renewable portfolio standards." These standards force utilities to buy considerable quantities of wind and solar power but also give them the freedom to shop for the least expensive sources. Also, the U.S. Department of Energy wants 20 percent of the nation's electricity to come from wind power by 2030. Government bodies are taking these actions because consumer demand alone hasn't sparked much renewable generation. That's not surprising. The wind and sun are notoriously fickle, which forces system operators to maintain plants that can fill in when necessary. Those backup generators are expensive, as are the transmission lines needed to link most renewable resources, which are located in sparsely populated areas, to the people using electricity. So the cost of generating "green" electricity is generally higher than the price it can command.

Renewable portfolio standards create a not-so-free market (but a market nevertheless) for wind and solar power while also pressuring these producers to keep their prices down.

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Policymakers in both regulated and deregulated states are also hoping to harness other market-based approaches to reducing electricity consumption. Using less electricity not only helps the environment, it can be just as effective as increasing supply in maintaining the reliability of the grid. And it's less expensive to boot.

The most straightforward way to discourage electricity use is, of course, to charge a lot for it. But U.S. consumers, and the lawmakers who represent them, are never too keen on that. Another strategy now being explored—one that's less of a political hot potato—is to have utility operators offer their customers compensation for reducing their demand for electricity during times of peak use. A reduction in demand allows utilities to avoid having to buy so much electricity when wholesale costs are at their highest. This approach provides an enticement to consumers to react to market signals, even if they are not yet ready to face them squarely in the form of higher prices.

Another advance that probably wouldn't have come about without deregulation is the emergence of small-scale, distributed generation, particularly from renewable sources such as rooftop solar panels. What's happening in many places is that customers are producing some electricity on their own while still attached to the grid. So they can offset some of the electricity they would otherwise consume, perhaps even spinning their meters backward at times. Although this practice competes with the electricity that the utility sells, more and more utilities are nevertheless allowing it to a greater or lesser degree.

■ ■ ■ ■

In hindsight, the electricity crisis in California and the myriad problems with deregulation in other parts of the country could have been anticipated. Given the complex market rules, concentrated supply, and largely inelastic demand, it's really no wonder that Enron, other energy-trading companies, and the electricity suppliers themselves found clever ways to manipulate markets.

Would U.S. consumers have been better off if the industry had remained strictly regulated? It all depends. If your goal is low electricity rates, maybe the answer is yes—but don't forget that bad regulatory decisions helped drive up electricity prices in the first place. If, however, you want the ability to feed power from your rooftop solar panels into the grid, the answer is probably no.

The real question facing the United States now is whether it can maintain reliable electricity grids without building lots of new transmission lines and big power plants. The only realistic alternative to such massive construction projects is for the generation of electricity to become more widely distributed, coupled with substantial efforts in energy efficiency. Electricity markets will surely have to become more expansive and open to accommodate that inevitable evolution. And they will also require new technical standards and, yes, some new forms of regulation. ■

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