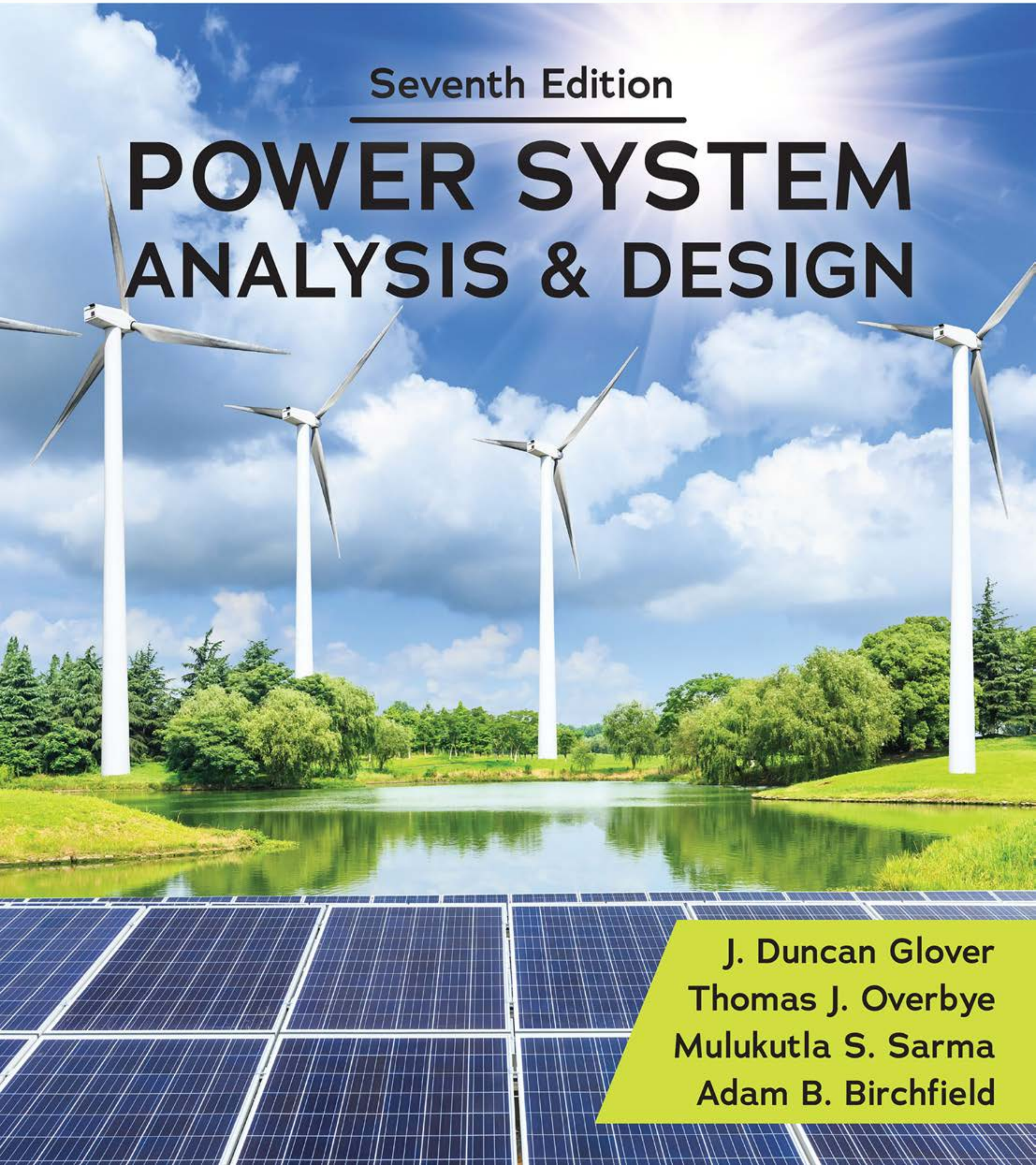
SI EDITION

Seventh Edition

POWER SYSTEM ANALYSIS & DESIGN



J. Duncan Glover
Thomas J. Overbye
Mulukutla S. Sarma
Adam B. Birchfield

CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Acceleration (linear)					
foot per second squared	ft/s^2	0.3048*	0.305	meter per second squared	m/s^2
inch per second squared	$in./s^2$	0.0254*	0.0254	meter per second squared	m/s^2
Area					
circular mil	cmil	0.0005067	0.0005	square millimeter	mm^2
square foot	ft^2	0.09290304*	0.0929	square meter	m^2
square inch	$in.^2$	645.16*	645	square millimeter	mm^2
Density (mass)					
slug per cubic foot	$slug/ft^3$	515.379	515	kilogram per cubic meter	kg/m^3
Density (weight)					
pound per cubic foot	lb/ft^3	157.087	157	newton per cubic meter	N/m^3
pound per cubic inch	$lb/in.^3$	271.447	271	kilonewton per cubic meter	kN/m^3
Energy; work					
foot-pound	ft-lb	1.35582	1.36	joule (N·m)	J
inch-pound	in.-lb	0.112985	0.113	joule	J
kilowatt-hour	kWh	3.6*	3.6	megajoule	MJ
British thermal unit	Btu	1055.06	1055	joule	J
Force					
pound	lb	4.44822	4.45	newton ($kg \cdot m/s^2$)	N
kip (1000 pounds)	k	4.44822	4.45	kilonewton	kN
Force per unit length					
pound per foot	lb/ft	14.5939	14.6	newton per meter	N/m
pound per inch	lb/in.	175.127	175	newton per meter	N/m
kip per foot	k/ft	14.5939	14.6	kilonewton per meter	kN/m
kip per inch	k/in.	175.127	175	kilonewton per meter	kN/m
Length					
foot	ft	0.3048*	0.305	meter	m
inch	in.	25.4*	25.4	millimeter	mm
mile	mi	1.609344*	1.61	kilometer	km
Mass					
slug	$lb\text{-}s^2/ft$	14.5939	14.6	kilogram	kg
Moment of a force; torque					
pound-foot	lb-ft	1.35582	1.36	newton meter	N·m
pound-inch	lb-in.	0.112985	0.113	newton meter	N·m
kip-foot	k-ft	1.35582	1.36	kilonewton meter	kN·m
kip-inch	k-in.	0.112985	0.113	kilonewton meter	kN·m

CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS (Continued)

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Moment of inertia (area)					
inch to fourth power	$in.^4$	416,231	416,000	millimeter to fourth power	mm^4
inch to fourth power	$in.^4$	0.416231×10^{-6}	0.416×10^{-6}	meter to fourth power	m^4
Moment of inertia (mass)					
slug foot squared	$slug\text{-}ft^2$	1.35582	1.36	kilogram meter squared	$kg{\cdot}m^2$
Power					
foot-pound per second	ft-lb/s	1.35582	1.36	watt (J/s or N·m/s)	W
foot-pound per minute	ft-lb/min	0.0225970	0.0226	watt	W
horsepower (550 ft-lb/s)	hp	745.701	746	watt	W
Pressure; stress					
pound per square foot	psf	47.8803	47.9	pascal (N/m^2)	Pa
pound per square inch	psi	6894.76	6890	pascal	Pa
kip per square foot	ksf	47.8803	47.9	kilopascal	kPa
kip per square inch	ksi	6.89476	6.89	megapascal	MPa
Section modulus					
inch to third power	$in.^3$	16,387.1	16,400	millimeter to third power	mm^3
inch to third power	$in.^3$	16.3871×10^{-6}	16.4×10^{-6}	meter to third power	m^3
Velocity (linear)					
foot per second	ft/s	0.3048*	0.305	meter per second	m/s
inch per second	in./s	0.0254*	0.0254	meter per second	m/s
mile per hour	mph	0.44704*	0.447	meter per second	m/s
mile per hour	mph	1.609344*	1.61	kilometer per hour	km/h
Volume					
cubic foot	ft^3	0.0283168	0.0283	cubic meter	m^3
cubic inch	$in.^3$	16.3871×10^{-6}	16.4×10^{-6}	cubic meter	m^3
cubic inch	$in.^3$	16.3871	16.4	cubic centimeter (cc)	cm^3
gallon (231 $in.^3$)	gal.	3.78541	3.79	liter	L
gallon (231 $in.^3$)	gal.	0.00378541	0.00379	cubic meter	m^3

*An asterisk denotes an *exact* conversion factor

***Note:* To convert from SI units to USCS units, *divide* by the conversion factor**

Temperature Conversion Formulas

$$T(°C) = \frac{5}{9}[T(°F) - 32] = T(K) - 273.15$$

$$T(K) = \frac{5}{9}[T(°F) - 32] + 273.15 = T(°C) + 273.15$$

$$T(°F) = \frac{9}{5}T(°C) + 32 = \frac{9}{5}T(K) - 459.67$$

POWER SYSTEM ANALYSIS & DESIGN

SEVENTH EDITION, SI

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From J. Duncan Glover:

To my grandchildren: Natalie, John, Brigid, Emily, Anna, and Owen

From Thomas J. Overbye:

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

We welcome Adam B. Birchfield as a co-author for this edition. Dr. Birchfield insures that the text will continue to be updated with the latest technological advances in power systems.

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.

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 22 to extend fully worked examples into computer implementations of the solutions. Version 22 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 22 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. 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.

The latest version of the valuable PowerWorld Simulator (version 22) is included and integrated throughout the text.

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, network equations, single-phase as well as balanced three-phase circuits and a brief discussion of energy conversion.

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, control of power flow, sparsity techniques, and power-flow modeling of wind and solar generation. Chapter 7 covers economic dispatch and optimal power flow, including coverage of unit commitment and markets. These chapters provide a basic understanding of power systems under balanced three-phase, steady-state, normal operating conditions.

Chapters 8 through 11, which cover symmetrical faults, symmetrical components, unsymmetrical faults, and system protection, come under the general heading of power system short-circuit protection. *Chapter 12* examines transient stability, which includes the swing equation, the equal-area criterion, and multi-machine stability with modeling of wind turbine and solar PV systems. *Chapter 13* covers power system controls, including generator-voltage control, turbine-governor control, load frequency control, and power system stabilizer control. *Chapter 14* examines transient operation of transmission lines including power system overvoltages, insulation coordinationand surge protection.

Chapter 15 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.

Preface to the SI Edition

This edition of *POWER SYSTEM ANALYSIS & DESIGN* has been adapted to incorporate the International System of Units (*Le Système International d'Unités* or SI) throughout the book.

Le Système International d'Unités

The United States Customary System (USCS) of units uses FPS (foot−pound−second) units (also called English or Imperial units). SI units are primarily the units of the MKS (meter−kilogram−second) system. However, CGS (centimeter−gram−second) units are often accepted as SI units, especially in textbooks.

USING SI UNITS IN THIS BOOK

In this book, we have used both MKS and CGS units. USCS (U.S. Customary Units) or FPS (foot-pound-second) units used in the US Edition of the book have been converted to SI units throughout the text and problems. However, in case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, it also encroaches upon the intellectual property of the source. Some data in figures, tables, and references, therefore, remains in FPS units. For readers unfamiliar with the relationship between the USCS and the SI systems, a conversion table has been provided inside the front cover.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units just before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, readers may contact the appropriate government agencies or authorities in their regions.

INSTRUCTOR RESOURCES

The Instructors' Solution Manual in SI units is available through your Sales Representative or online through the book website at http://login.cengage.com. A digital version of the ISM, Lecture Note PowerPoint slides for the SI text, as well as other resources are available for instructors registering on the book website.

Feedback from users of this SI Edition will be greatly appreciated and will help us improve subsequent editions.

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WebAssign Offers Engineering Instructors the Following

- The ability to create and edit algorithmic and numerical exercises.
- The opportunity to generate randomized iterations of algorithmic and numerical exercises. When instructors assign numerical WebAssign homework exercises (engineering math exercises), the WebAssign program offers them the ability to generate and assign their students differing versions of the same engineering math exercise. The computational engine extends beyond and provides the luxury of solving for correct solutions/answers.
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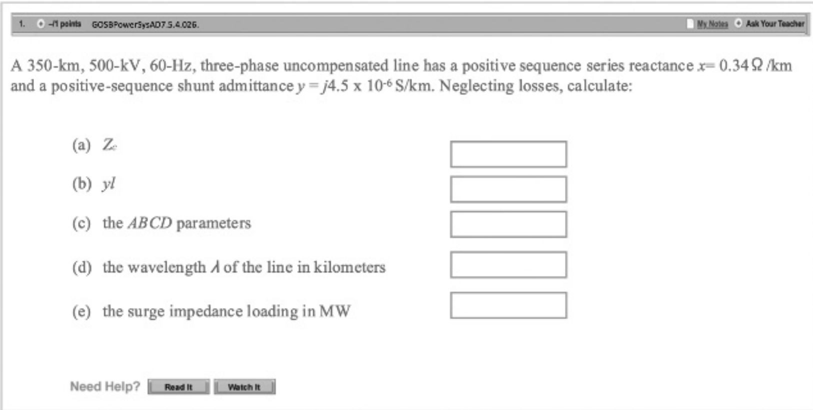

- **My Class Insights**
  WebAssign's built-in study feature shows performance across course topics so that students can quickly identify which concepts they have mastered and which areas they may need to spend more time on.
- **Ask Your Teacher**
  This powerful feature enables students to contact their instructor with questions about a specific assignment or problem they are working on.

MindTap Reader

Available via WebAssign and our digital subscription service, Cengage Unlimited, MindTap Reader is Cengage's next-generation eBook for engineering students. The MindTap Reader provides more than just text learning for the student. It offers a variety of tools to help our future engineers learn chapter concepts in a way that resonates with their workflow and learning styles.

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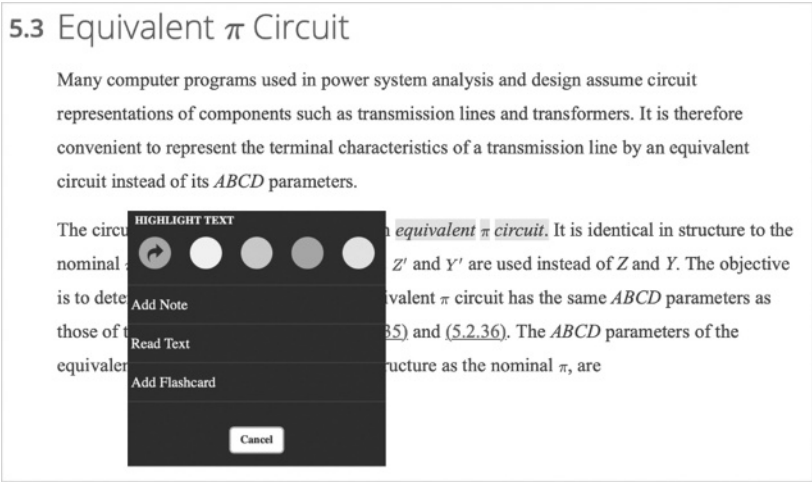

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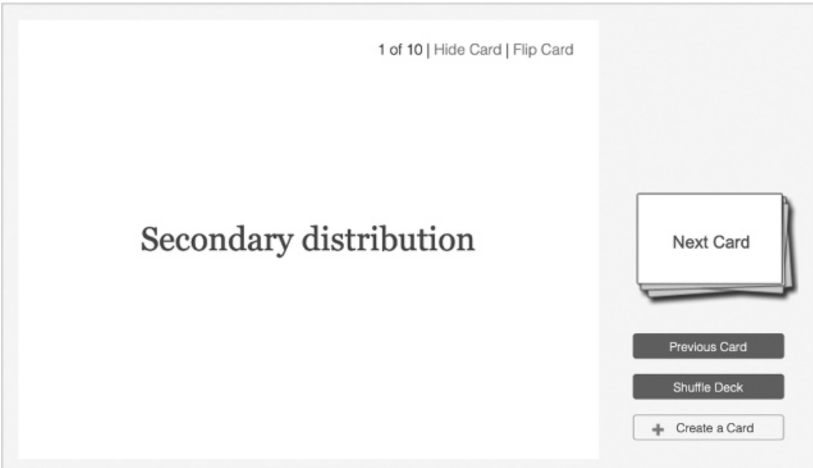

THE CENGAGE MOBILE APP

Available on iOS and Android smartphones, the Cengage Mobile App provides convenience. Students can access their entire textbook anyplace and anytime. They can take notes, highlight important passages, and have their text read aloud whether they are online or off.

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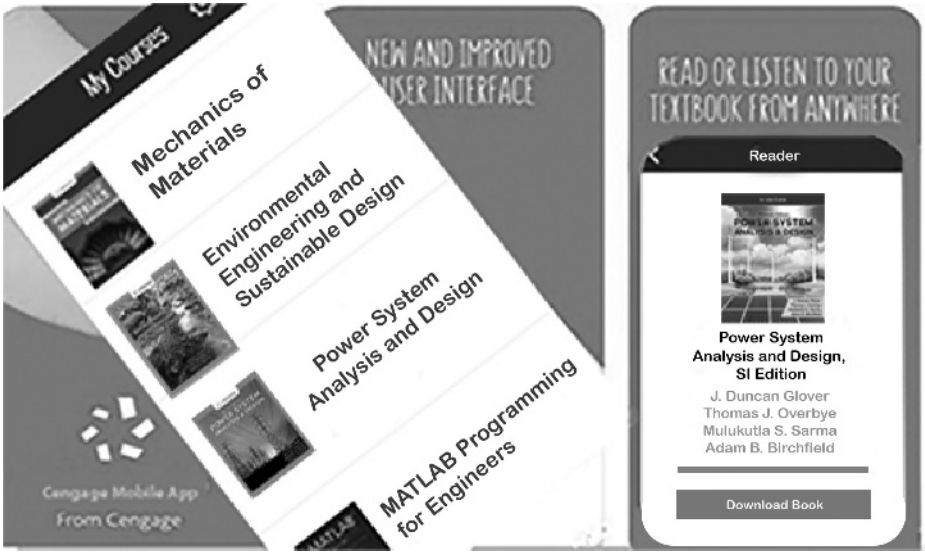

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SUPPLEMENTS FOR THE INSTRUCTOR

Supplements to the text include a Solution and Answer Guide that provides complete solutions to all problems, Lecture Note PowerPoint™ slides, and an image library of all figures in the book. These can be found on the password-protected Instructor's Resource website for the book at http://login.cengage.com.

SUPPLEMENTS FOR THE STUDENT

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

ACKNOWLEDGMENTS

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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.

J. Duncan Glover

Thomas J. Overbye

Adam B. Birchfield

Mulukutla S. Sarma

List of Symbols, Units, and Notation

Symbol	Description
a	operator 1/120°
a_t	transformer turns ratio
A	area
A	transmission line parameter
$\boldsymbol{A}$	symmetrical components transformation matrix
B	Susceptance
B	Susceptance 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 strengths
$\boldsymbol{f}$	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
$\boldsymbol{I}$	vector of phasor currents
j	operator 1/90°
J	moment of inertia
l	length
l	length
L	inductance
L	inductance matrix
N	number (of buses, lines, turns, etc.)
Q	reactive power
p.f.	power factor
$p(t)$	instantaneous power
P	real power
q	Charge
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
$\boldsymbol{V}$	vector of phasor voltages
X	reactance
X	reactance matrix
Y	phasor admittance

Symbol	Description
$\boldsymbol{Y}$	admittance matrix
Z	phasor impedance
$\boldsymbol{Z}$	impedance matrix
α	angular acceleration
α	transformer phase shift angle
β	current angle
β	area frequency response characteristic
δ	voltage angle
δ	torque angle
ϵ	permittivity
Φ	magnetic flux

Symbol	Description
λ	Penalty factor
Γ	reflection or refraction λ coefficient
θ	impedance angle
θ	angular position
μ	permeability
υ	velocity of propagation
ω	radian frequency
ρ	resistivity
τ	time in cycles
τ	transmission line transit time

	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	volt-ampere
var	volt-ampere 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.

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.)

LEARNING OBJECTIVES

At the conclusion of this chapter, you should be able to:

1. Briefly explain the history of the electric utility industry;
2. Discuss present and future trends in electric power systems;
3. Describe the restructuring of the electric utility industry;
4. Get up and running with PowerWorld Simulator, a power system analysis and simulation software package.

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.

CASE STUDY

The following article describes the impacts that Distributed Energy Resources (DERs) are having on bulk power systems in four of the United States: Hawaii, California, New York, and North Carolina; as well as in South Australia. As DERs continue to grow around the world, the aggregate amount of them is having impacts on bulk power system planning and operation. The power system industry is learning from prior experience and taking actions in anticipation of future DER penetration levels. The article also describes the ongoing efforts of the North American Reliability Corporation, in coordination with its stakeholders, to study the effect of increasing DER penetration on bulk power systems [8].

Transformation of the Grid*

Ryan Quint, Lisa Dangelmaier, Irina Green, David Edelson, Vijaya Ganugula, Robert Kaneshiro, James Pigeon, Bill Quaintance, Jenny Riesz, and Naomi Stringer

DISTRIBUTED ENERGY RESOURCES (DERs) are unlocking new opportunities, and the grid is undergoing a dramatic transformation with unprecedented change. Yet as DERs continue to grow in North America and around the world, it is apparent that the aggregate amount of them is having an impact on bulk power system (BPS) planning and operation. The effects of DERs can be attributed to the uncertainty, variability, and lack of visibility of these resources at the BPS level. From a BPS perspective, the key grid planning impacts generally include the following:

- transmission-distribution coordination and data exchange
- visibility, dispatchability, and controllability
- DER ride-through capability

* Transformation of the Grid, by Ryan Quint et al, © 2019 IEEE. Reprinted, with permission, from *Power & Energy Magazine* (November/December 2019), pp. 35–45.

- impacts to load-shedding programs
- aggregate DER modeling and changing reliability study approaches.

The industry is learning from prior experience and taking actions in anticipation of future DER penetration levels. Waiting for the effect of DERs to manifest before developing solutions may be extremely costly and even risk BPS reliability. However, the proactive development and coordination of requirements can ensure reliable operation of the BPS moving forward. The electric industry needs to address these challenges with innovative solutions earlier rather than later.

Distributed Energy Resource (DER) Impacts on Hawai'i's Grid Operation

The islands of Hawai'i, Oahu, and Maui have among the highest penetration levels of DERs in the United States, in terms of installed capacity relative to system size. Under favorable policies and the right economic circumstances, the rapid deployment of DERs can occur in an extremely short period of time. In only six years, the average distributed solar photovoltaic (D-PVs) contribution to meeting the gross peak daytime demand (net peak plus D-PVs) increased from 12 to 37% on Hawai'i island (see Figure 1). The instantaneous D-PVs penetration can exceed 71% of the daytime demand today, and it provides approximately 11% of the annual energy supply. With increasing DER penetration levels come rapidly rising levels of variability and uncertainty. Hawai'i is now seeing more D-PVs systems with battery energy storage systems (BESSs), and it is anticipating the effect that these combined systems will have on the island grid. Needless to say, the long-term planning studies performed 10 years ago never anticipated such a major change.

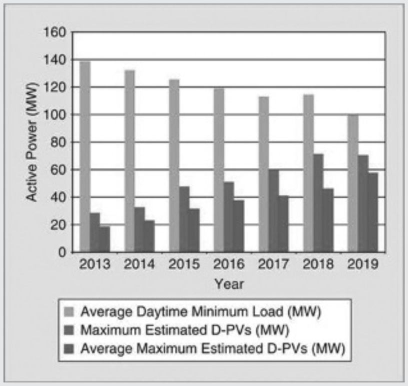


Figure 1 The rapid deployment of D-PVs for the island of Hawai'i.

The performance requirements needed for high DER penetration levels on the island grids were not initially supported by the requirements in IEEE Standards 1547-2003 and 1547a-2014. Hawai'i's DER interconnection standard (Rule 14 H) eventually deviated from IEEE Standard 1547 to support the continued integration of DERs. However, the new IEEE Standard 1547-2018 includes requirements that are beyond Rule 14 H and under consideration for inclusion in a revised Hawai'i standard. Based on Hawai'i's experience, robust interconnection requirements need to be in place well in advance of high penetration levels to support BPS reliability. It is extremely challenging and expensive to meet changing BPS needs by retroactively enhancing equipment that was installed with minimal performance requirements and capabilities.

For the Hawai'i grid, the following aspects of DER integration are top priorities:

- balancing solar PV variability with flexible energy resources that are capable of fast ramping and cycling and ensuring that regulation resources do not fall below minimum allowable dispatch levels
- managing frequency stability with sufficient frequency-responsive reserves and checking that newly installed DERs have active power-frequency controls enabled to assist the primary frequency response
- improving DER estimation techniques since nearly all DERs are behind-the-meter (BTM), with no visibility or control by the system operator; D-PVs output is estimated using field irradiance measurements provided to the operator via supervisory control and data acquisition
- ensuring effective system restoration with variable DER auto-reconnection and possibly adjusting reconnection criteria (although this will not address situations of high solar PV periods where DER control is necessary)
- studying the adverse impacts of DERs tripping during BPS faults and working with existing DER installations to modify trip settings and improve ride-through capability, where possible.

There are also two issues related to frequency stability that are worth highlighting: the use of fast-responding battery energy storage to mitigate legacy DER tripping and the development of an adaptive UFLS program to ensure system security during severe resource-loss events.

Storage to Mitigate DER Loss

Some legacy DERs do not have a robust ride-through capability and, therefore, are subject to aggregate loss during over/under frequency and voltage excursions. The behavior of D-PVs is determined by the standard requirements at the time of interconnection, with different possible aggregate losses during these frequency and voltage excursions. The largest contingency concern for Hawai'i island is the loss of legacy DERs tripping at 60.5 Hz, as a large majority of the existing D-PVs is subject to trip at or near that frequency. The second-largest vulnerability is the loss of DERs during large-voltage excursions. On an island system like Hawai'i's, 60.5 Hz is possible after delayed fault clearing (due to transient swings following fault clearing) and major loss-of-load events, which can occur with transmission outages (both N-1 and N-1-1). The potential aggregate loss of D-PVs during high solar-production periods is roughly double the largest single-generator contingency, resulting in severe underfrequency conditions and the possible risk of system failure.

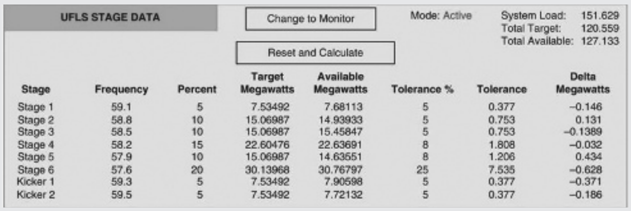
The loss of D-PVs also exacerbates other loss-of-generation events, with some additional D-PVs loss during the underfrequency situation. To address this concern, a battery energy storage study was conducted to analyze the effect of legacy DER tripping for low voltage during transmission faults, low frequency following generating-unit trips, and high frequency following a transmission line fault. The study found that retrofitting legacy DERs to full ride-through capability was the most effective solution, but that it was too costly and impractical. The study also found the following:

- Storage can replace DER energy lost during transient voltage and frequency conditions, preventing excessive underfrequency protection and reducing the risk of system failure for disturbances during high solar PV production.
- The size of the storage necessary to mitigate reliability issues depends on the number of legacy DERs installed.
- Increased numbers of spinning reserves could reduce the size of the necessary storage but not eliminate the need for it. Increasing reserves also exacerbates excess-energy concerns.
- D-PVs protection systems are not consistently implemented, and performing sensitivity studies around the uncertainty of this DER behavior is critical.

Based on the studies, a BESS with 18 MW of capacity and a 30-minute duration was able to arrest frequency excursions and provide sufficient time to bring standby generation online. Increasing the duration to 1 hour enabled the BESS to respond to over-frequency conditions. Studies showed that two BESSs geographically and electrically separated from one another provided the best performance and grid resilience.

Underfrequency Load Shedding

The reliable operation of the Hawai'i island systems heavily relies on underfrequency load shedding (UFLS) that trips distribution circuits at preestablished frequency thresholds. However, as the penetration of DERs rapidly increases, variability in net loading on any given feeder poses significant challenges to the conventional UFLS design, which means that static UFLS arming is no longer effective. An adaptive UFLS program has been implemented to address this variability. Figure 2 is a dashboard of the adaptive program, including six instantaneous stages of UFLS arming between 59.1 and



UFLS STAGE DATA

Change to Monitor

Mode: Active

System Load: 151.629
Total Target: 120.559
Total Available: 127.133

Reset and Calculate

Stage	Frequency	Percent	Target Megawatts	Available Megawatts	Tolerance %	Tolerance	Delta Megawatts
Stage 1	59.1	5	7.53492	7.68113	5	0.377	−0.146
Stage 2	58.8	10	15.06987	14.93933	5	0.753	0.131
Stage 3	58.5	10	15.06987	15.45847	5	0.753	−0.1389
Stage 4	58.2	15	22.60476	22.63691	8	1.808	−0.032
Stage 5	57.9	10	15.06987	14.63551	8	1.206	0.434
Stage 6	57.6	20	30.13968	30.76797	25	7.535	−0.628
Kicker 1	59.3	5	7.53492	7.90598	5	0.377	−0.371
Kicker 2	59.5	5	7.53492	7.72132	5	0.377	−0.186

Figure 2 The adaptive UFLS-arming dashboard.

57.6 Hz and two kicker stages that operate with time delays at 59.3 and 59.5 Hz. The target megawatt value is calculated based on system net loading at the time, and available distribution circuits are automatically armed every 15 minutes to achieve the target net load level. An arming tolerance percentage and value are depicted as well as the difference between the available megawatt arming and the target megawatt value. Stages 1–2 sum to 15% and stages 1–4 sum to 40% of the system net load based on the maximum allowable load shedding for N-1 and N-1-l unit trips, respectively. Each stage operates with an eight-cycle relay time plus breaker operation time. A rate-of-change-of-frequency (ROCOF) load shedding element was also included in stages 1 and 2, with a 0.5-Hz/s set point and nine-cycle relay time plus breaker operation time.

More than 40 substations were modified, including relay and communications upgrades, and 78% of customer circuits (up to 70% of peak load) are participating. The adaptive UFLS program has performed well during N-1 and N-1-1 events at various times of day and is an effective reliability improvement. Figure 3 provides an example of a severe N-1-1 generator-loss disturbance where stages 1–4 operated successfully to arrest the frequency and mitigate a potential large-scale outage.

Rooftop Solar PV Deployment

California has a state mandate that 33% of its annual energy must come from renewable sources by 2020, with a target of 60% by 2030, established by a bill, SB100, that took effect in September 2018. However, on some days, instantaneous output from the renewable sources already exceeds 50% of the total generation output. A large portion of that penetration consists of BTM D-PVs, and the rapid deployment of D-PVs is forcing changes in transmission planning, forecasting, and grid operations at the California Independent System Operator (CAISO).

Figure 4 provides an example of the effect that D-PVs are having

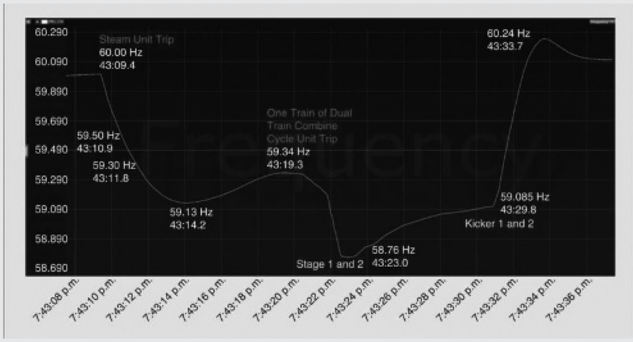


Figure 3 The operation of adaptive UFLS for a multiple-contingency event.

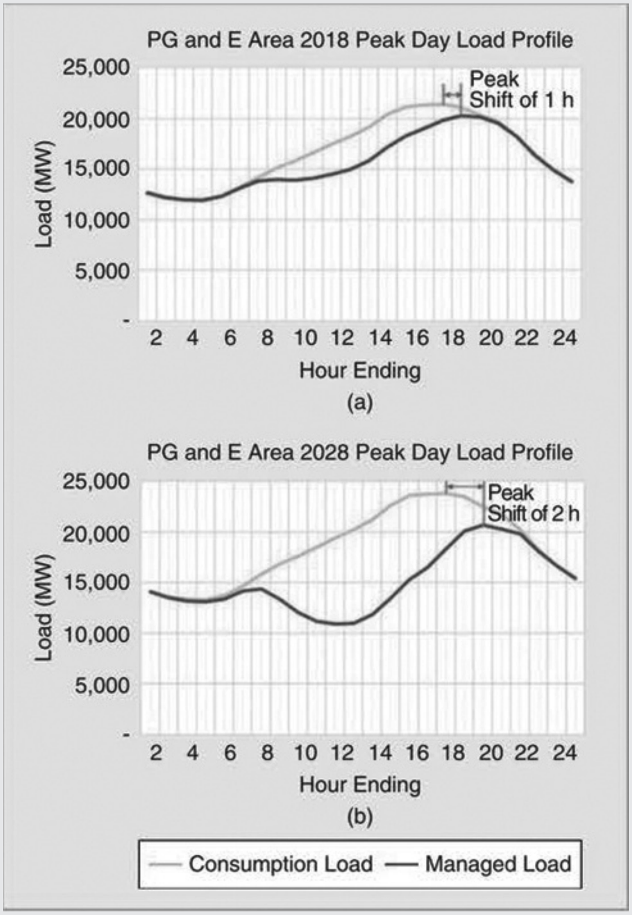


Figure 4 The PG&E net load impacts from DERs.

on the Pacific Gas & Electric (PG&E) net load profile, driving the need for different study times and net load levels from the CAISO's 2018–2019 transmission-planning process. The blue curves show the net load after subtracting the D-PVs' output, which is called the managed load. The figure clearly displays a shift in the peak net load time, which, in many parts of the state, is shifted outside the times when solar PV is available. D-PVs' penetration levels are also causing a drastic change in minimum net load levels, which need to be carefully studied. Sensitivity analysis is also needed to operate through and plan for ramping periods. All these issues are compounded by load modifiers, such as energy efficiency, demand response, time-of-use rates, and electric vehicle charging.

The uncertainty in net load forecasting, including D-PVs, is a concern for BPS reliability studies. The CAISO coordinates its load forecasts with and relies upon long-term forecasts produced by the California Energy Commission (CEC). The CEC's energy-demand forecast includes an hourly estimate of the consumption load and load modifiers to develop the managed outlook by which the transmission system is planned.

Since D-PVs are shifting net peak load periods, the selection of critical study conditions needs to change. Planning standards require an assessment of peak and off-peak conditions; however, with large numbers of DERs, critical system conditions may not occur during either of those periods. This requires even greater numbers of sensitivity studies of varying dispatch and load scenarios, including peak gross load, peak net load (at the transmission-distribution interface), and minimum net load conditions (for example, a spring weekend during off-peak load conditions). Tables 1 and 2 show how DERs were incorporated into the CAISO study scenarios during the 2018–2019 transmission planning process. In addition to these sensitivities, consideration for BPS-connected

	Day/Time			BTM-PV			AAEE			
Scenario	2020	2023	2028	2020	2023	2028	2020	2023	2028	Driver
Summer peak	10 Aug. HE 18	14 Aug. HE 19	14 Aug. HE 19	18%	3%	3%	90%	81%	76%	Hour of maximum managed load
Spring off peak	5 Apr. HE 12	6 Apr. HE 13	16 Apr. HE 13	79%	84%	85%	58%	56%	49%	Hour of minimum managed load
Winter off peak			13 Feb. HE 4			0%			28%	Hour of minimum consumption
Winter peak	15 Oct. HE 19	3 Oct. HE 18	3 Oct. HE 19	0%	1%	0%	77%	76%	72%	Hour of maximum managed load during winter

AAEE: additional achievable energy efficiency; HE: hour ending.

TABLE 1

The baseline scenarios and DER contributions.

Scenario	Starting Baseline Case	BTM-PV		AAEE	
		Baseline	Sensitivity	Baseline	Sensitivity
Summer peak with high CEC forecasted load	2023 summer peak	3%	3%	81%	0%
Off peak with heavy renewable output and minimum gas generation commitment	2023 off peak	84%	99%	56%	56%
Summer peak with heavy renewable output and minimum gas generation commitment	2020 summer peak	18%	99%	81%	81%

TABLE 2

The sensitivity scenarios and DER contributions.

generation dispatch and assumptions for neighboring planning areas is critical as they impact local or wide-area reliability issues. This leads to the need for wider coordination between planning administrators.

With the increasing penetration of DERs, CAISO has explicitly incorporated the forecast resources in power flow and stability studies for the past three planning cycles to account for their unique operational characteristics that are different from the end-use load behavior. This is especially important for stability studies, since the results between DERs netted with load versus modeled ones are significantly different. With a large penetration of DERs in California, study results would be inaccurate if DERs were only netted with load and would lead to erroneous conclusions. Retail-scale BTM DERs are modeled in the power flow and dynamic stability studies as part of a composite load model, and utility-scale DERs are modeled as aggregated generators on the transmission buses. Figure 5 illustrates these impacts on transient voltage response following a simulated BPS fault event. The results are different because modeling the DER characteristics explicitly (including DER tripping of legacy equipment) allows the simulation to differentiate between DERs' response and gross load response. This is critical as penetration levels of DERs increase, although DER prevalence has a study impact in all cases, even at low penetration levels.

CAISO currently uses parameter values for the DER models based on the Western Electricity Coordinating Council and North American Electric Reliability Corporation (NERC) guidelines and performs multiple sensitivity studies