Converter-Interfaced Energy Storage Systems

Gain an in-depth understanding of state-of-the-art converter-interfaced energy storage systems with this unique book, covering dynamic behaviour, modelling, stability analysis and control.

- Presents an in-depth treatment of the conceptual, technical and economic frameworks underpinning energy storage in modern power systems
- Includes a comprehensive review of technologies for cutting-edge converter-interfaced energy storage systems
- Addresses the impact of energy storage on the dynamic interaction of microgrids with transmission and distribution systems
- Provides a variety of reference models, and a generalized model for energy storage systems to enable benchmarking of control strategies and stability analysis

Accompanied by a wealth of numerical examples and supporting data online, this is the ideal text for graduate students, researchers and industry professionals working in power system dynamics, renewable energy integration and smart grid development.

Federico Milano is Professor of Power Systems Control and Protection, and Head of Electrical Engineering, at University College Dublin. He is a Fellow of the IEEE and the IET.

Álvaro Ortega Manjavacas is a Senior Power Systems Researcher in the School of Electrical and Electronic Engineering at University College Dublin.

"This is a timely and impressive book on an emerging and important topic. The comprehensive and in-depth overview of energy storage technologies, modelling, and dynamic simulation will make the book a valuable reference for practicing engineers and researchers working with the planning and operation of the future electric power system. The extensive list of references will be of great help for deepened studies."

Göran Andersson, *ETH Zürich*

"Energy storage systems (ESS) are considered by many as the Holy Grail of the upcoming decarbonised future. From rooftop PV microsystems to giant pumped storage units, virtually all ESS are expected to be interfaced through power converters, for the sake of added flexibility and efficiency. This volume, co-authored by one of the most recognized experts in modelling, analysis and control of power systems dynamic phenomena, constitutes a self-contained and unique blend of general concepts, motivating factors and technical details, satisfying in this way the interests of a wide audience and filling an important gap in the technical literature."

Antonio Gomez-Exposito, *University of Seville*

"Excellent and timely material written by experienced authors! You must read this book."

Jean Mahseredjian, *Polytechnique Montréal*

Converter-Interfaced Energy Storage Systems

Context, Modelling and Dynamic Analysis

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To my parents, Guido and Silvana.

F.M.

To my parents, Manuel Ángel and Mari Paz, and brother, José Miguel.

Á.O.M.

Energy is a very subtle concept.
It is very, very difficult to get right.†

Richard P. Feynman

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† Reproduced from [86], with the permission of the American Association of Physics Teachers.

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Preface

Background and Motivations

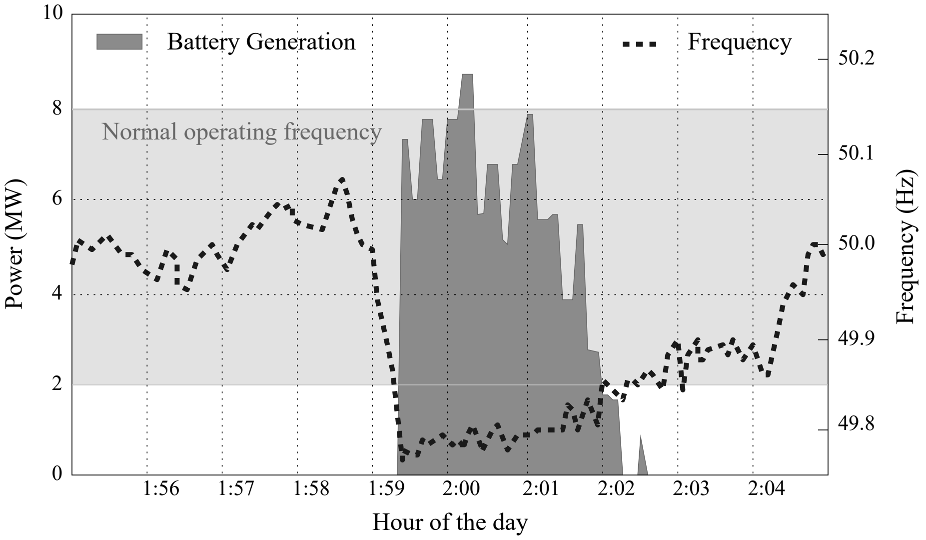
This book is the result of the work of the authors on modelling, simulation, control and stability analysis of converter-interfaced energy storage systems carried out in the period from 2010 to 2018. The first author (FM) started offering final projects on modelling of converter-interfaced energy storage technologies when he was working at the University of Castilla-La Mancha, Spain, and the second author (ÁOM) was brave enough to first undertake one of these final projects and then pursue his PhD on the same subject at University College Dublin, Ireland, which the first author joined in 2013.

Back in 2010, the idea of studying large-size converter-interfaced energy storage devices was considered, to use a euphemism, an oddity. Several colleagues were – and some still are – highly sceptical on the high cost of storage devices and on their scalability. The most common concern that we have learned to expect for every article we have submitted and presentation we have given in these years, has been related to the *inviability* of these devices for power system applications due to economic constraints. Also, the idea that a battery could be utilised to implement a continuous control, and not exclusively discrete on/off operations has often been considered a peculiar idea, again due to economic considerations.

In February 2017, the first author witnessed a heated discussion at a small workshop hold in Champéry, Switzerland, between a supporter and an opponent of battery energy storage devices for power system applications. The only argument of the opponent was economic viability. After the workshop, the storage-device enthusiast was driven home by his Tesla Model S.

Despite mixed feelings, the blooming of energy storage technologies is undeniable. The cover and most articles of the issue of September/October 2017 of the IEEE magazine *Power & Energy* are dedicated to ‘Opening the door to energy storage – Challenges for future systems’. Seminars and special sessions on energy storage applications at international conferences on power systems are omnipresent. A one-day tutorial with title ‘Energy Storage: An introduction to technologies, applications and best practices’ has been organised every year from 2015 to 2018 at the IEEE PES General Meetings. Also relevant were the one-day tutorials of the IEEE PES T&D 2018, Denver, Colorado, and of the Power System Computation Conference (PSCC) 2018, Dublin, Ireland.

In the real world, that is, in the world outside academia and symposia, the years from 2010 to 2017 have been an extraordinary period of intense brainstorming and exper-



The Hornsdale Power Reserve 100 MW battery responding to a drop in system frequency on 14 December 2017. (Courtesy of Australian Energy Market Operator).

imentation on energy storage solutions. Existing technologies, such as batteries, have been and are continuously being dramatically improved in terms of duration and reliability. One of the most well-known outcomes of this research is certainly the exponential growth of hybrid and plug-in electric vehicles. New, often very imaginative, prototypes that exploit a new chemical reaction or a new surprising solution come out on a monthly, if not weekly, basis.

Back in 2010, the cost of a lithium-ion battery was about \$1000/kWh. This cost dropped to about \$270/kWh in 2016 according to a survey carried out by Bloomberg New Energy Finance, i.e. a 73% drop in six years. Predictions are between \$190 and \$130 in 2020 and between \$75 and \$50 in 2030. This dramatic decrease is clearly due to the humongous interest arising from the business of electric vehicles, not power system applications. Yet, a 100 MW, 129 MWh lithium-ion battery has been built in less than 100 days and installed in Hornsdale, South Australia, by Tesla Inc., as a personal bet of the company co-founder and CEO, Elon Musk. This was – and still is at the time of completing this book – the world's largest grid-scale battery and charged for the first time at 8:36 am, on 1 December 2017, and reached 31 MW in 2 minutes.

While the habitual sceptics were wondering whether such a large battery was actually a solid business model, the Hornsdale battery has been utilised to provide frequency control to the Australian system, see figure, and its surprisingly fast time response has helped balance several major energy outages that have occurred since it was installed. We expect that the Hornsdale battery will help save much more money than that required for its construction. Other projects for similar or even larger grid-scale batteries are currently in progress or under evaluation.

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Organisation

The matter of the book is organised in nine chapters divided into three parts, as follows.

Part I – Context

Chapter 1 introduces the basic concepts of energy storage through a variety of examples that span several time scales, from the electromagnetic transients of transmission lines to the daily load levelling through pumped hydroelectric power plants. The technical background that motivates a monograph on converter-interfaced energy storage devices is also given in this chapter.

Chapter 2 defines the technical and economic parameters, challenges and issues that characterise energy storage devices. Particular emphasis is given to the definition of relevant quantities as well as grid applications and the levelised cost of electricity, which allow fairly comparing different storage technologies.

Chapter 3 provides high-level descriptions of the most important current technologies for energy storage applications. Emerging technologies that have reached the prototype stage are also considered. The second half of the chapter is dedicated to the description of real-world examples.

Part II – Modelling

Chapter 4 presents the structure and main elements that compose modern electrical energy systems. These include conventional devices, renewable and/or distributed energy resources and the smart grid concept. A dynamic model of microgrids that is adequate for the transient stability analysis of interconnected AC networks is also provided in this chapter.

Chapter 5 introduces the model and the basic controllers of the AC/DC voltage-sourced converter, namely the main device on which all energy storage devices considered in this book are based. The model described in this chapter is based on a dq-axis frame, average, fundamental frequency formulation and includes detailed dynamics of the DC side, primary controllers, and current and PI control limiters.

Chapter 6 presents the detailed models of each storage technology considered in the case studies discussed in Part III. These include battery, compressed air, flywheel and superconducting magnetic energy storage. Models of a few other emerging technologies are also presented along with simplified energy storage models. A description of the procedure to define a generalised yet accurate dynamic model of any converter-interfaced energy storage technology completes the chapter.

Part III – Dynamic Analysis

Chapter 7 provides a comprehensive comparison, through a variety of examples, of the detailed, simplified and generalised energy storage system models of the technologies described in Chapter 6. The features of each model as well as the advantages provided by the generalised model are discussed.

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Chapter 8 presents a variety of control strategies for energy storage devices. The primary frequency control and the performance of the ubiquitous PID controller as well as other non-conventional approaches, such as sliding mode and H-infinity, are thoroughly discussed. Then the chapter considers secondary frequency control of storage devices through model predictive control and a decentralised stochastic control of microgrids.

Chapter 9 completes the book with the stability analysis of power systems with inclusion of converter-interfaced energy storage devices. Frequency, small-signal, and voltage stability are considered. Brief outlines of converter-driven instability issues as well as of microgrid stability are also given in this chapter.

Software Tools

For the reader interested in software technicalities, all simulations included in the book are obtained using the Python-based software tool Dome [188]. The Dome version utilised is based on Fedora Linux 25, Python 3.6.2, CVXOPT 1.1.9, KLU 1.3.8, and MAGMA 2.2.0. The hardware consists of two 20-core 2.2 GHz Intel Xeon CPUs, which are utilised for matrix factorisation and Monte-Carlo time-domain simulations; and one NVidia Tesla K80 GPU, which is utilised for the small-signal stability analysis.

Lessons Learned

Writing a book is a long journey and an engaging learning process. We have learned that blunt economic considerations should not be utilised as an argument to destroy academic research. We wish to thank all our colleagues and anonymous reviewers around the world who, when commenting on our work, could not find any better argument than the high cost of storage devices. Their criticism reinforced our intuition that we were on the right track.

We have been very fortunate to work on converter-interfaced energy storage devices in these years. As for any emerging technology, this has been a period full of brainstorming, unresting ideas and unexpected developments. For this reason, in the book, we consider with the same agnosticism with which we started in 2010 not only batteries but also several less common energy storage technologies. We also propose an approach to model all technologies, including the ones that will not survive the battle with business models and even those that have not been invented yet.

At the time of writing the last paragraphs of this book, there is still no conclusive work on the dynamic analysis of converter-interfaced energy storage systems. There are more questions than answers, which is good. Vladimir Nabokov was wont to say that a good book should end with an open question. We trust that this book moves towards the right direction and provides some useful tools to answer these questions. We hope that the reader will have as much fun reading the book as we had while writing it.

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Dublin, Chiusa di Pesio, Quintanar de la Orden

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Fondúireacht Eolaíochta Éireann sfi Dá bhfuil romhainn

Disclaimer

Notation

Energy storage system models span many technologies and fields, ranging from electromagnetism and electrochemistry to mechanics and thermodynamics. Whenever there is no possible confusion, the simplest and most common notation for physical quantities is used, even if doing so sometimes leads to utilising the same letter for different quantities. In these cases, different styles or fonts are used. The context where such quantities appear also helps avoid confusion. Tables with a list of symbols of relevant variables and parameters and their definition are also included whenever relevant. The remainder of this section only reports the high-level notation adopted throughout the book. Whenever a different notation is used, quantities are defined in the text.

Scalars, Vectors and Matrices

v, V, $\mathcal{V}$	scalar variable, scalar parameter
$\boldsymbol{v}$, $\mathbf{v}$	vector, one-dimensional array
$\mathbf{V}$	matrix, two dimensional array

Reference frames

$v(t)$	time domain quantity (v is used if the context is unambiguous and in schemes for simplicity)
$\boldsymbol{v}_{\mathrm{abc}}(t)$	vector of three-phase time domain quantities
$v(s)$	frequency domain quantity (Laplace transform)
$\bar{v}_{\mathrm{dq}}$	Park vector in dq-axis reference frame, i.e. $\bar{v}_{\mathrm{dq}} = v_{\mathrm{d}} + jv_{\mathrm{q}}$
$\bar{v}$	phasor or complex quantity, i.e. $\bar{v} = v\angle\theta$
$\bar{v}^*$	conjugate of $\bar{v}$, i.e. $\bar{v}^* = v\angle - \theta$
$\underline{v}$	average quantity

Time derivatives

$\frac{\mathrm{d}}{\mathrm{d}t}$	time derivative in time domain
s	time derivative in frequency domain (Laplace transform)
$j\omega_o$	time derivative in phasor domain
$\frac{\mathrm{d}}{\mathrm{d}t} + j\omega_o$	time derivative in dq-axis reference frame (Park transform)
$\dot{v}$	rate of change with respect to time

Common Quantities

a	drift term of stochastic processes; transformer tap ratio
A	cross-sectional area
b	diffusion term of stochastic processes
B	susceptance
c_p	specific heat capacity
c_v	volumetric heat capacity
C	capacitance
ç	concentration of ions
d	duty cycle
D	damping
e	electromotive force (EMF); standard cell potential
E	energy
E	expectation
$\mathcal{E}$	electric field
f	electrical frequency
$\boldsymbol{f}$	vector of differential equations
f	mass or molar fraction
$\boldsymbol{g}$	vector of algebraic equations
G	conductance; Gibbs free energy
h	height
H	hentalpy; inertia constant
$\mathcal{H}$	magnetic field
i	current
j	imaginary unit
J	moment of inertia
k	coefficient in empirical formulas
K	controller gain
ℓ	length
L	inductance
$\mathcal{L}$	specific latent heat
m	mass; modulation amplitude of AC/DC converters
M	machine starting time ($M = 2H$)
$\mathcal{M}$	molar mass
n	number of moles
p	active power
P	pressure
$\mathbf{P}$	Park tensor
q	reactive power
q_e	electric charge
Q	heat

Q	volumetric flow
r	radius
R	resistance
$\mathcal{R}$	droop of primary frequency control
$\bar{s}$	complex power
s	Laplace transform variable
S	entropy
$\mathcal{S}$	sliding surface
t	time (r within integrals)
T	time constant
u	input signal
$\boldsymbol{u}$	vector of input signals
U	internal energy
v	voltage
V	volume
w	Wiener process
W	mechanical work
x	position; state variable; control signal
$\boldsymbol{x}$	vector of state variables
X	reactance
y	measured grid signal
$\boldsymbol{y}$	vector of algebraic variables
$\bar{Y}$	admittance
z	valency number
$\boldsymbol{z}$	extended state variable vector
$\bar{Z}$	impedance
α	autocorrelation
β	pitch angle of the blades of wind turbines; gate position of hydro turbines
γ	polytropic coefficient
δ	angular position
ε	permittivity
ζ	stochastic variable
η	efficiency
θ	phase angle of voltage phasors
Θ	temperature
λ	electricity price; tip speed ratio of wind turbines
μ	mean value; permeability
ξ	white noise
Ξ	total resource capacity available for AIMD control
ϖ	probability
ρ	density

ϱ	discount rate
σ	standard deviation
ς	switch status
τ	torque, time delay
υ	speed
ϕ	magnetic flux
φ	phase shift
ψ	total magnetic flux
ω	angular speed

Note. In per unit, the angular speed ω has the same value of the frequency f. For this reason, whenever the context is unambiguous, ω is also loosely referred to as *frequency*.

Common Superscripts and Subscripts

a	first phase of a 3-phase system
ac	AC quantity
b	base quantity
b	second phase of a 3-phase system
c	converter
c	third phase of a 3-phase system
d	direct axis of the dqo transform
D	demand quantity
dc	DC quantity
dq	dq-frame (Park) vector
e	electrical
G	generator quantity
L	transmission line quantity
m	mechanical
max	maximum value
min	minimum value
n	nominal or rated quantity
n	neutral point
o	reference, initial or base-case condition
o	zero axis quantity of the dqo transform
q	quadrature-axis quantity of the dqo transform
r	rotor quantity
ref	reference or set-point quantity
s	stator quantity
t	turbine quantity
T	transformer quantity
tot	total quantity
w	wind-related quantity

Constants

$\mathsf{F} = 96.487 \quad \left[\mathrm{kC\,mol^{-1}}\right]$	Faraday constant
$\mathsf{k}_B = 5.670 \cdot 10^{-8} \quad \left[\mathrm{W\,m^{-2}\,K^{-4}}\right]$	Boltzmann constant
$\mathsf{R} = 8.314 \quad \left[\mathrm{J\,mol^{-1}\,K^{-1}}\right]$	Universal gas constant
$\varepsilon_o = 8.854187817 \cdot 10^{-12} \quad \left[\mathrm{F\,m^{-1}}\right]$	Vacuum permittivity
$\mu_o = 4\pi \cdot 10^{7} \quad \left[\mathrm{N\,A^{-2}}\right]$	Vacuum permeability
$\pi = 3.14159265359 \quad [\mathrm{rad}]$	

Numbers

The order of vector and matrices is indicated with n and a suffix to indicate the variable to which such a number refers. For example, n_x indicates the order of the vector of state variables $\boldsymbol{x}(t)$.

Units

The units of absolute quantities follow the International System of Units (SI). Unless explicitly indicated, however, the equations that describe AC circuits are in per unit values, as usual in power system analysis. The bases are the three-phase apparent power, s_n, the phase-to-phase voltage v_n and the frequency f_n. All other bases are derived from these three quantities. For example, the bases of the impedance and the line current are, respectively:

$$Z_n = \frac{v_n^2}{s_n}\,, \qquad i_n = \frac{s_n}{\sqrt{3}\,v_n}\,.$$

The main device discussed in the book is the AC/DC converter (see Chapter 5). Hence equations of DC circuits appear very often. These are expressed in absolute values. When DC and AC quantities appear in the same expression, the units of each quantity are indicated explicitly.

Acronyms and Abbreviations

AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
ABB	ASEA Brown Boveri
AC	Alternating Current
AFC	Alkaline Fuel Cell
AGC	Automatic Generation Control
AHI	Aqueous Hybrid Ion
AIMD	Additive Increase Multiplicative Decrease
ALAB	Advanced Lead-Acid Battery
ARES	Advanced Rail Energy Storage
ATES	Aquifer Thermal Energy Storage
AVR	Automatic Voltage Regulator
BDF	Backward Differentiation Formulas
BEM	Backward Euler Method
BES	Battery Energy Storage
BTES	Borehole Thermal Energy Storage
C-CAES	Cavern-based Compressed Air Energy Storage
CAES	Compressed Air Energy Storage
CCGT	Combined-Cycle Gas Turbine
CCT	Critical Clearing Time
CDF	Cumulative Distribution Function
CESI	Centro Elettrotecnico Sperimentale Italiano
CHP	Combined Heat Power
CI-ESS	Converter-Interfaced Energy Storage System
CIG	Converter-Interfaced Generation
CoI	Centre of Inertia
CPV	Concentrated Photovoltaic
CSC	Current-Sourced Converter
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSWT	Constant-Speed Wind Turbine

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CT	Clearing Time
CTES	Cavern Thermal Energy Storage
DAE	Differential Algebraic Equation
DC	Direct Current
DER	Distributed Energy Resource
DFIG	Doubly-Fed Induction Generator
DFIM	Doubly-Fed Induction Machine
DoE	US Department of Energy
EAC	Equal Area Criterion
EC	Electrochemical Capacitor
ECES	Electrochemical Capacitor Energy Storage
EDF	Electricité de France
EDLC	Electric Double-Layer Capacitor
EIA	Energy Information Administration
EMF	Electromotive Force
EMS	Energy Management System
EMT	Electromagnetic Transient
ESS	Energy Storage System
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
FDF	Frequency Divider Formula
FeCrFB	Iron-Chromium Flow Battery
FERC	Federal Energy Regulatory Commission
FES	Flywheel Energy Storage
FLC	Fuzzy Logic Control
G-CAES	General Compressed Air Energy Storage
GEM	Generalised Energy Storage System Model
GPES	Gravel Potential Energy Storage
GTES	Gravel Thermal Energy Storage
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
HIC	H-Infinity Control
HT-UTES	High Temperature Underground Thermal Energy Storage
HVAC	Heating, Ventilation and Air Conditioning
HVDC	High-Voltage Direct Current

I-CAES	Isothermal Compressed Air Energy Storage
ICT	Information and Communications Technology
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IES	Inductive Energy Storage
IFAC	International Federation on Automatic Control
IGBT	Integrated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
ISO	Independent System Operator
ITM	Implicit Trapezoidal Method
KFSM	Kalman Filter-based Synchronisation Method
LAES	Liquid Air Energy Storage
LCoE	Levelised Cost of Electricity
LCoS	Levelised Cost of Storage
LEC	Levelised Energy Cost
LQC	Linear-Quadratic Control
MCFC	Molten Carbonate Fuel Cell
MG	Microgrid
MOST	Molecular Solar Thermal
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
MRI	Magnetic Resonance Image
MSTES	Molten-Salt Thermal Energy Storage
NASA	National Aeronautics and Space Administration
NEA	Nuclear Energy Agency
ODE	Ordinary Differential Equation
OECD	Organisation for Economic Co-operation and Development
OMIB	One-Machine Infinite-Bus
PAFC	Phosphoric Acid Fuel Cell
PCM	Phase Change Material
PDF	Probability Density Function
PEMFC	Polymer Exchange Membrane Fuel Cell
PES	Power & Energy Society
PI	Proportional Integral
PIC	Proportional Integral Control

PID	Proportional Integral Derivative
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PFC	Primary Frequency Control
PHES	Pumped Hydroelectric Energy Storage
PHTES	Pumped Heat Thermal Energy Storage
PLL	Phase-Locked Loop
PMSM	Permanent-Magnet Synchronous Machine
PSCC	Power System Computation Conference
PSDP	Power System Dynamic Performance
PSS	Power System Stabiliser
PV	Photovoltaic
PWM	Pulse-Width Modulation
RDFT	Recursive Discrete Fourier Transform
RES	Renewable Energy Source
RFB	Redox Flow Battery
RMS	Root Mean Square
RoCoF	Rate of Change of Frequency
SCADA	Supervisory Control And Data Acquisition
SDAE	Stochastic Differential Algebraic Equation
SDE	Stochastic Differential Equation
SFC	Secondary Frequency Control
SH	Smart House
SI-DAE	Semi-Implicit Differential Algebraic Equation
SIL	Storage Input Limiter
SLH	Specific Latent Heat
SMC	Sliding Mode Control
SMES	Superconducting Magnetic Energy Storage
SMPES	Solid-Masses Potential Energy Storage
SNG	Synthetic Natural Gas
SoC	State of Charge
SoE	State of Energy
SOFC	Solid Oxide Fuel Cell
SoH	State of Health
SR-PHES	Surface-Reservoir Pumped Hydroelectric Energy Storage
SRAM	Static Random-Access Memory
SS-PHES	Sub-Surface Pumped Hydroelectric Energy Storage
STATCOM	Static Synchronous Compensator
STF	Solar Thermal Fuel

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STSA	Stochastic Transient Stability Analysis
T-CAES	Tank-based Compressed Air Energy Storage
TCL	Thermostatically Controlled Load
TES	Thermal Energy Storage
TG	Turbine Governor
TSA	Transient Stability Analysis
ULTC	Under-Load Tap Changer
UTES	Underground Thermal Energy Storage
VCO	Voltage Controlled Oscillator
VRFB	Vanadium Redox Flow Battery
VRLAB	Valve Regulated Lead-Acid Battery
VS-PHES	Variable-Speed Pumped Hydroelectric Energy Storage
VSC	Voltage-Sourced Converter
WECC	Western Electricity Coordinating Council (former WSCC)
WSCC	Western Systems Coordinating Council
ZnBrFB	Zinc-Bromine Flow Battery