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Nicu Bizon · Naser Mahdavi Tabatabaei
Frede Blaabjerg · Erol Kurt
Editors

Energy Harvesting and Energy Efficiency

Technology, Methods, and Applications

Springer

Editors
Nicu Bizon
Faculty of Electronics, Communication, and Computers
University of Piteşti
Piteşti
Romania

Naser Mahdavi Tabatabaei
Electrical Engineering Department, Faculty of Engineering
Seraj Higher Education Institute
Tabriz
Iran

Frede Blaabjerg
Department of Energy Technology
Aalborg University
Aalborg East
Denmark

Erol Kurt
Department of Electrical and Electronics Engineering, Faculty of Technology
Gazi University
Ankara
Turkey

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Foreword

Energy efficiency has always been a major challenge for the scientist and the engineers. However, in recent years, the increased public concern for the preservation of natural resources and the protection of the environment has strongly stimulated the research and development activities in this area. More than 20,000 technical papers written in 2016 and stored in "Scopus" database have "energy efficiency" in their title, in their abstract or in their list of keywords. There were less than 4000 in 1996.

Energy harvesting is a much more recent topic. Less than 100 papers addressed it twenty years ago. More than 2500 articles were published in top-level journals from January to October 2016. The reason behind this spectacular growth is simple: Both academia and industry are interested in the design and engineering of energy-autonomous small electronic devices that can harvest the various forms of energy available in the environment (solar, eolian, and hydraulic) and convert them to electric power. The development of energy-harvesting applications is driven by the increased need of autonomous wireless electronic systems in various fields of human activities, ranging from medicine and aeronautics to civil engineering and animal tracking.

Textbooks and monographs are already available for anyone who wants to learn more on either "energy efficiency" or "energy harvesting." The merit of this book is that it brings together the two topics, which are more and more interrelated. The editors carefully selected the topics to be treated, and each chapter of this book is written by well-recognized experts in the field. This book introduces the reader to up-to-date research on nonlinearity of energy-harvesting systems, energy efficiency of hybrid power systems, and optimal design of autonomous electronic systems. It also contains instructive case studies and examples of experimental validation of the novel energy-saving or energy-harvesting techniques.

This book can be used in the classroom, to teach energy management courses to graduate students, and be suggested as further reading to undergraduate students in engineering sciences. It will also be a valuable information resource for the researchers and engineers concerned by energy efficiency issues or involved in the development and application of energy-harvesting techniques.

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Lucian Dascalescu
IEEE Fellow, Distinguished Professor
of Electrical Engineering
University of Poitiers, University Institute
of Technology, Angoulême, France

Preface

Energy harvesting and energy efficiency are two key topics for today's power community. In the development of modern society, one of the key factors is to save energy in order to become more independent of other resources. Two important approaches can be taken—one is to change behavior and thereby save energy and the second is to develop new technology which is able to save energy in different applications. Chapter 1 gives an overview of challenges and possibilities in terms of energy saving and also energy efficient use.

Initially, the first key topic—energy harvesting—becomes one of the most motivated fields of the multidisciplinary science due to the complicated features of the harvester materials, dependences on various mechanical, electrical, and magnetic parameters, rich responses on different external excitation frequencies and strength. Strictly speaking, vibrations stem from either man-made systems or natural processes can be used as an important electric resource for low-power-consuming electronic devices such as transducers and wireless sensors. That can contribute at the batteryless applications for much sustainable and renewable power generation, whereas some technical problems should be solved to achieve the expectations of the electronics society. Although conventional harvesters work on the basis of linear resonance, there exist certain parametrical limitations on their power generation. Indeed, excitation frequency, electrical load, manufacturing tolerance, and ambient temperature play important roles in order to determine the optimized energy generation. Besides, the nonlinear nature of the vibration phenomena contributes at the power, and these nonlinear effects cannot be neglected for an optimized harvester system. Thus, Part I of this book initially gives an outline to the reader on the electromagnetic and piezoelectric energy-harvesting systems and then focuses on the theoretical and experimental techniques by introducing different harvester systems.

In that context, Chap. 2 describes the harvesting sources with classical and novel types for the use of electromagnetic and piezoelectric hybrid structures. Various

experimental systems are described in detail in order to compare their output powers and their relation to the system parameters.

The batteryless applications of microscale harvesters have been explained in Chap. 3 for information technologies (IT). The importance of low-power harvesting systems for IT applications is particularly emphasized, and model systems have been discussed. One of the important practice areas of the harvesters is wireless sensor application. Therefore, a specific chapter (i.e., Chap. 4) is dedicated to the problems of electromagnetic and piezoelectric harvesters in wireless devices. This chapter gives both experimental and theoretical details on the matter. As the harvester systems have complicated equilibrium features for their time- and space-dependent nature, nonlinearity plays an important role to identify their dynamic behavior and power-generation strategy. Therefore, Chap. 5 is devoted to the nonlinear problems of the harvesters. Although the energy-harvesting issues mostly cover the systems related to the piezoelectric and electromagnetic ones in low power range, the most frequent energy-generation system—photovoltaics (PV) has been an important topic. Therefore, Chap. 6 focuses on the control phenomena of PV hybrid systems.

It can be emphasized that the chapters mentioned above provide a good background to the reader on the harvester systems and their applications. Both experimental and theoretical approaches to different harvesting problems help to understand the advanced problems and cutting-edge information, world widely, thereby the readers at different educational levels from undergraduate to the professionals can find interesting research topics in order to apply in their own studies.

Other main topic of this book is the energy efficiency. Due to the increasing population and industrial growth, energy efficiency has become a popular topic for every level of communities from ordinary to technical. There exist many attempts today that the energy efficiency itself can be counted as a new energy resource. Thus, interdisciplinary studies, which have been carried out in the fields of renewable energy, focus on different mechanisms that decrease the losses of the energy in methodological ways. In light of the present technology, the efficiency cannot be considered detached from the cost. Strictly speaking, the balance between the efficiency and system cost should be ascertained. With that respect, many energy systems such as solar, wind, and tidal can make use of good-quality materials or efficiency techniques if they are financially appropriate. Therefore, Chaps. 7–9 are devoted to the sun-tracking applications and maximal power point tracking (MPPT) techniques in PVs. In these chapters, both practices and theoretical backgrounds on the tracking mechanisms are presented including the case studies. Chapter 10 mentions the partial shading effect on the PV systems and clarifies the methodology on the solution of MPPT for those systems. The applications on solar cars are presented in Chap. 11. This chapter also sheds a light on the polymer composite materials in order to enhance the efficiency and gives some information on the charging stations.

The increasing demand for electricity supply along with higher requirements for power quality and system reliability, restrictions to use the available fossil fuels, and minimization of the environmental pollutants leads to the aggregation of clean

energy sources (renewable energy sources, fuel cell, etc.) in distributed generation systems and developing microgrids. Consequently, the energy efficiency of hybrid power system that integrates such clean energy sources must be improved through appropriate energy management strategies. Thus, the remaining parts of the book, namely II, III, and IV, analyze the energy efficiency based on fuel cell, PV, wind, and hybrid power systems.

The term "hybrid" means the use of other energy storage devices, or multiple input energy sources in hybrid power sources to sustain the load demand. Thus, the use of fuel cell system as energy source or energy storage devices in conjunction with an electrolyzer is analyzed in Chaps. 12 and 13. While Chap. 12 analyzes the possibility to use the extremum seeking control schemes for the reduction of hydrogen consumption in fuel cell hybrid power sources, Chap. 13 analyzes the efficiency of a fuel cell hybrid power source required for an automotive application. Chapter 14 proposes a stochastic model to analyze the microgrids with the goal of profit maximization and imbalance cost minimization. In this framework, a new method based on neural network theory is proposed for predicting wind speed and solar radiation. Other chapter (i.e., Chap. 15) analyzes the energy efficiency of a micro-combined cooling, heating, and power system driven by a solar dish stirling heat engine that is used for residential buildings. A novel methodology was introduced for short-term scheduling of small-scale trigeneration system, which can be used optimally and efficiently to provide cooling, heating, and power for residential applications, being environmentally friendliness, cost-cutting, and on-site applied.

The last part of this book is dedicated to some technical strategies, efficient methods, and applications in field of energy efficiency, so it will be of interest for all current researchers and specialists in that field as well as for technicians.

Chapter 16 presents wired and wireless communication systems in smart homes and buildings based on the recent developments proposed in applications. The basic principles of the smart homes and energy efficient buildings are introduced firstly in order to provide basic knowledge for readers and the chapter also gives an idea on the communication systems used for outdoor and indoor scenarios. Chapters 17 and 18 propose new flexible hybrid architecture for the power-conditioning unit for small satellites. Since the space agencies all over the world are interested today in very small satellites due to their advantages compared to heavier satellites, the advanced techniques are discussed including their converter and storage systems.

The batteries are unavoidable for any electricity system. Therefore, while making a discussion on the efficiency issues, one should also consider the storage techniques. Chapter 19 introduces a new method for determining the optimal model of batteries, puts a starting point in analyzing their discharge profiles, and employs a multicriteria analysis for processing the experimental data.

While considering the efficiency in solar, fuel cell and related hybrid systems, the energy efficiency in wind and water distribution systems should also be mentioned. In this manner, the optimal planning and operation of water distribution is presented in Chap. 20. This problem mainly involves the establishment of the operation schedule for all water hydrophore stations and uses a database of 85 urban

water hydrophore stations as a case study. Finally, the last chapter (i.e., Chap. 21) provides an overview about available knowledge, references, and investigations on the active and passive flow control devices, initially developed for aeronautical industry that are currently being investigated and introduced on wind turbines in order to improve their efficiency.

As a conclusion, a sustained research in the field of energy efficiency does not only give more chances to significant reduction of carbon dioxide, greenhouse gas emissions, and environmental pollution, but also increases the economic saving in fuel consumption and use of energy sources. Therefore, this book tries to highlight the difficulties of the basic methods on energy harvesting and energy efficiency and proposes advanced methods to solve these issues. All proposed methods were validated through simulation and experimental results. These "hot subjects" will be of interest for many decades and, at the same time, will be a challenge and hard task for the researchers all over the world, considering the new energy policies due to energy crisis.

We hope that this book will be very efficient for students and engineers who learn and wish to work in this field, because the chapters of this book cover all important and challenging subjects related to energy harvesting and energy efficiency. The book comprises the knowledgeable and up-to-date contents that present the state-of-the-art equipment and methods used for the energy harvesting and energy efficiency. Finally, the main arguments that may recommend this book to be read are the following: (1) It is the first comprehensive book on energy harvesting and energy efficiency of the power hybrid systems; (2) covers the operating principles, design methods, and real applications; (3) enables the low power for autonomous electronic system design; (4) introduces the high-power density technology and adiabatic concept to efficiently design the mission critical systems; (5) provides a much-needed system approach to hydrogen energy applications; (6) provides a comprehensive overview of the fundamentals of renewable power generation, conversion, and storage; and the last, but not the least, (7) can be used as a course text.

The editors and authors made all efforts to have a good book, and we hope interested readers to enjoy by reading this book and to be satisfied by its content.

Piteşti, Romania — Nicu Bizon
Tabriz, Iran — Naser Mahdavi Tabatabaei
Aalborg, Denmark — Frede Blaabjerg
Ankara, Turkey — Erol Kurt

Contents

Contributors

Necmi Altin Department of Electrical and Electronics Engineering, Faculty of Technology, Gazi University, Ankara, Turkey

Iñigo Aramendia Department of Nuclear Engineering and Fluid Mechanics, University of the Basque Country, Vitoria-Gasteiz, Araba, Spain

Nicu Bizon Department of Electronics, Computers and Electrical Engineering, University of Piteşti, Piteşti, Romania; University Politehnica of Bucharest, Bucharest, Romania

Frede Blaabjerg Department of Energy Technology, Center of Reliable Power Electronics (CORPE), Aalborg University, Aalborg, Denmark

Luminita-Mirela Constantinescu University of Piteşti, Piteşti, Romania

Pooya Davari Department of Energy Technology, Center of Reliable Power Electronics (CORPE), Aalborg University, Aalborg, Denmark

Mustafa Doğan Department of Electrical and Electronics Engineering, Baskent University, Ankara, Turkey

Ali Durusu Yildiz Technical University, Istanbul, Turkey

Bogdan-Adrian Enache Faculty of Electronics, Communications and Computers, University of Piteşti, Piteşti, Romania

Unai Fernandez-Gamiz Department of Nuclear Engineering and Fluid Mechanics, University of the Basque Country, Vitoria-Gasteiz, Araba, Spain

Adriana Florescu University POLITEHNICA of Bucharest, Bucharest, Romania

Gheorghe Grigoras Department of Power System, Faculty of Electrical Engineering, "Gheorghe Asachi" Technical University of Iasi, Iasi, Romania

Nazenin Gure Department of Mechanical Engineering, Faculty of Engineering, Marmara University, Istanbul, Turkey; Enhas R&D Energy Systems Ind. Co. Ltd, Istanbul, Turkey

Aytaç Gören Automatic Control and Robotics Laboratories, Department of Mechanical Engineering, Dokuz Eylul University, Izmir, Turkey

Sıtkı Çağdaş İnam Department of Electrical and Electronics Engineering, Baskent University, Ankara, Turkey

Farkhondeh Jabari Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

Ersan Kabalci Department of Electrical and Electronics Engineering, Faculty of Engineering and Architecture, Nevsehir HBV University, Nevsehir, Turkey

Yasin Kabalci Department of Electrical and Electronics Engineering, Faculty of Engineering, Omer Halisdemir University, Nigde, Turkey

Abdulkerim Kar Department of Mechanical Engineering, Faculty of Engineering, Marmara University, Istanbul, Turkey

Fevzi Kentli Department of Mechatronics Engineering, Technology Faculty, Marmara University, Istanbul, Turkey

Erol Kurt Department of Electrical and Electronics Engineering, Technology Faculty, Gazi University, Teknikokullar, Ankara, Turkey

Adrian-Ioan Lita University Politehnica of Bucharest, Bucharest, Romania

Ioan Lita University of Piteşti, Piteşti, Romania

Jose Manuel Lopez-Guede Department of Systems Engineering and Automatics, University of the Basque Country, Vitoria-Gasteiz, Araba, Spain

Behnam Mohammadi-Ivatloo Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

Ali Muhtaroğlu Department of Electrical and Electronics Engineering, Middle East Technical University, Northern Cyprus Campus, Güzelyurt, Mersin 10, Turkey

Ismail Nakir Yildiz Technical University, Istanbul, Turkey

Sergiu Oprea University POLITEHNICA of Bucharest, Bucharest, Romania

Mihai Oproescu University of Piteşti, Piteşti, Romania

Ö. Orkun Sürel Department of Electrical and Electronics Engineering, Baskent University, Ankara, Turkey

Saban Ozdemir Vocational School of Technical Sciences, Gazi University, Ankara, Turkey

Xiaohui Qu School of Electrical Engineering, Southeast University, Nanjing, China

Mircea Raceanu National Research and Development Institute for Cryogenics and Isotopic Technologies, Râmnicu Vâlcea, Romania; University Politehnica of Bucharest, Bucharest, Romania

Constantin Radoi University POLITEHNICA of Bucharest, Bucharest, Romania

Marian Raducu University of Piteşti, Piteşti, Romania

Jose Antonio Ramos-Hernanz Department of Electrical Engineering, University of the Basque Country, Vitoria-Gasteiz, Araba, Spain

Mohammad Rasouli Department of Electrical and Computer Engineering, School of Engineering, Penn State University, Erie, PA, USA

Javier Sancho Department of Nuclear Engineering and Fluid Mechanics, University of the Basque Country, Vitoria-Gasteiz, Araba, Spain

Andrei-Stefan Savu University POLITEHNICA of Bucharest, Bucharest, Romania

Ibrahim Sefa Department of Electrical and Electronics Engineering, Faculty of Technology, Gazi University, Ankara, Turkey

Elnaz Shahryari Department of Technical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

Hossein Shayeghi Department of Technical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

Alper Sisman Department of Electrical and Electronics Engineering, Faculty of Engineering, Marmara University, Istanbul, Turkey

Naser Mahdavi Tabatabaei Department of Electrical Engineering, Faculty of Engineering, Seraj Higher Education Institute, Tabriz, Iran

Erturul Tacgin Department of Mechanical Engineering, Faculty of Engineering, Marmara University, Istanbul, Turkey

Mugdesem Tanrioven Yildiz Technical University, Istanbul, Turkey

Yunus Uzun Department of Electrical and Electronics Engineering, Faculty of Engineering, Aksaray University, Aksaray, Turkey

Huai Wang Department of Energy Technology, Center of Reliable Power Electronics (CORPE), Aalborg University, Aalborg, Denmark

Musa Yilmaz Department of Electronics and Communications Engineering, Technology Faculty, Batman University, Batman, Turkey

Firuz Zare Power and Energy Group, The University of Queensland, Brisbane, QLD, Australia

Ekaitz Zulueta Department of Systems Engineering and Automatics, University of the Basque Country, Vitoria-Gasteiz, Araba, Spain

Abbreviations and Acronyms

AAHP	Air-to-Air Heat Pump
ABC	Artificial Bee Colony
AC	Alternative Current
ACA	Ant Colony Algorithm
AcVG	Actuator Vortex Generator
ADC	Analog-to-Digital Conversion
AES	Advanced Encryption Standard
aESC	Advanced Extremum Seeking Control
AF	Active Filtering
AFC	Active Flow Control
AFE	Active Frontend
AGS	Automatic Generating System
AI	Artificial Intelligence
AJVG	Air Jet Vortex Generator
AM	Amplitude Modulation
AMI	Advanced Metering Infrastructure
AMM	Automatic Meter Management
AMR	Automatic Meter Reading
ANN	Artificial Neural Network
AP	Access Point
ARIB	Association of Radio Industries and Businesses
ASD	Adjustable Speed Drive
ASHP	Air Source Heat Pump
a-Si	Amorphous Silicon
ASIC	Application-Specific Integrated Circuit
ASM	Assembly
BAN	Body Area Network
BB	Broadband
BCDMU	Battery Charge/Discharge Monitor Unit
BCU	Battery Charger Unit

BDR	Battery Discharge Regulator
BFV	Best Fixed Voltage
BGA	Ball Grid Array
BLDCM	Brushless Direct Current Motor
BMS	Battery Management System
BOL	(Battery's) Beginning of Life
BoP	Balance of Plant
BP	Belief Propagation
BPF	Band-Pass Filter
bpfESC	Band-Pass Filter ESC
BPSK	Binary Phase Shift Keying
BSN	Body Sensor Nod
BU	Battery Unit
CAD	Computer-Aided Design
CART	Classification and Regression Trees
CC	Constant Current
CCHP	Combined Cooling Heating and Power
CCK	Complementary Code Keying
CCM	Continuous Current Mode
CCP	Combined Cool and Power
CD	Charge Depletion
CDRG	Coulomb-Damped Resonant Generator
CFD	Computational Fluid Dynamics
CFL	Compact Fluorescent Lamp
CHP	Combined Heat and Power
CI	Charge Increasing
CMMR	Common Mode Rejection Ratio
COA	Centroid of Area
COE	Cost of Energy
COFDM	Coded OFDM
COTS	Commercial Off-the-Shelf
CP	Cyclic Prefix
CS	Charge Sustaining
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access/Collision Detection
CST	Current Sweep Technique
CT	Copper Thickness
CU	Chargers' Unit
CV	Constant Voltage
CVaR	Conditional Value at Risk
D8PSK	Differential 8-Phase Shift Keying
DA	Day Ahead
DAQ	Data Acquisition
DBPSK	Differential Binary Phase Shift Keying

DC	Direct Current
DCM	Discontinuous Conduction Mode
DCSK	Differential Chaos Shift Keying
DET	Direct Energy Transfer
DG	Distributed Generation
DM	Damper Motor
DMS	Data Management System
DNLP	Discontinuous Nonlinear Program
DO	Disjoint Operation
DOD	Depth of Discharge
DOF	Degree of Freedom
DPE	Direct Piezoelectric Effect
DQPSK	Differential Quadrature Phase Shift Keying
DRIBA	Double-Regulated Intermediate Bus Architecture
DS	Delay Stall
DSL	Digital Subscriber Line
DTU	Denmark Technical University
DVS	Dynamic Voltage Scaling
e.i.r.p.	Equivalent Isotropic Radiated Power
EA	Evolutionary Algorithms
EH	Energy Harvester
EHing	Energy Harvesting
EM	Electromagnetic
EMF	Electromotive Force
EMHs	Electromagnetic Energy Harvesters
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EMS	Energy Management Strategy
EOL	(Battery's) End of Life
EP	Evolutionary Programming
EQ	Equivalence
ES	Energy Sources
ESA	European Space Agency
ESC	Extremum Seeking Control
ESR	Equivalent Series Resistance
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
EWEA	Energy Wind Energy Association
FC	Fuel Cell
FCC	Federal Communications Commission
FCHPS	Fuel Cell Hybrid Power Source
FEA (FEM)	Finite Element Analysis (Finite Element Method)
FEC	Forward Error Correction
FEM	Finite Element Method

FFT	Fast Fourier Transform
FLC	Fuzzy Logic Controller
FSK	Frequency Shift Keying
FT	Fuzzy Techniques
FW	Freewheeling Diode
GA	Genetic Algorithm
GAMS	General Algebraic Modeling System
GaN	Gallium Nitride
GEO	Geosynchronous Earth Orbit
GFSK	Gaussian Frequency Shift Keying
GMPP	Global Maximum Power Point
GMPPT	Global Maximum Power Point Tracking
GP	Global Peak
GSTP	General Support Technology Program
GUI	Graphical User Interface
H_1	First Harmonic
HAN	Home Area Network
HAWT	Horizontal Axis Wind Turbine
HC	Hill Climbing
HEHs	Hybrid Energy Harvesters
HEO	Highly Elliptical Orbit
HF	High Frequency
HID	High Intensity Discharge
hoESC	High-Order Extremum Seeking Control
HPF	High-Pass Filter
HPS	Hybrid Power Source
HRTHs	Hybrid Rotary-Translational Harvesters
HSAT	Horizontal Single Axis Tracking
HT	Hydro-Turbines
IC	Integrated Circuit
ICE	Internal Combustion Engine
ICT	Information and Communication Technologies
IEA	International Energy Agency
IGBT	Insulated-Gate Bipolar Transistor
IncCond	Incremental Conductance
IOD	In-Orbit Demonstration
IRRWBF	Implementation-Efficient Reliability Ratio-Based Weighted Bit Flipping
ITU	International Telecommunication Union
IU	Isolation Unit
I-V	Current–Voltage
IWBF	Improved Weighted Bit Flipping
LAN	Local Area Network
LDPC	Low-Density Parity Check
LDR	Light-Dependent Resistor

LE	Leading Edge
LED	Light-Emitting Diode
LEO	Low-Earth Orbit
LET	Linear Energy Transfer
LF	Low Frequency
LFP	$LiFePO_4$ Battery
LLR	Log-Likelihood Ratio
LP	Local Peak
LPF	Low-Pass Filter
LRCM	Linear Reoriented Coordinates Method
M2M	Machine-to-Machine
MAC	Media Access Control
MAPE	Mean Absolute Percentage Error
MC	Mid-Chord
MCA	Multicriteria Analysis
MCP	Marginal Clearing Price
MCU	Microcontroller Unit
MDO	Multidisciplinary Design Optimization
MEMS	Micro-Electro-Mechanical Systems
MEO	Mid-Earth Orbit
MEP	Maximum Efficiency Point
mESC	Modified Extremum Seeking Control
MG	Microgrid
MILP	Mixed-Integer Linear Programming
MLI	Multilevel Inverter
MLP	Multilayer Perceptron
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
MSE	Mean Square Error
MT	Micro-Turbine
MTBF	Mean Time between Failures
NB	Narrowband
NGSO	Non-Geostationary Orbit
NN	Neural Network
NOCT	Normal Operating Cell Temperature
NREL	National Renewable Energy Laboratory
NTC	Negative Temperature Coefficient
O&M	Operation and Maintenance
OC	Only Current Photovoltaic
OCC	One-Cycle Control MPPT
OCV	Open-Circuit Voltage
ODE	Ordinary Differential Equations
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On–Off Keying
OPGW	Optical Power Ground Wire

O-QPSK	Offset Quadrature Phase Shift Keying
ORC	Organic Rankine Cycle
ORING	OR-ing Output Logic Function
OV	Open Voltage
P&Q	Perturb and Observe
PAGV	Power Augmentation Guide Vane
PAM	Pulse Amplitude Modulation
PAN	Personal Area Network
PASAT	Polar-Aligned Single Axis Tracking
PC	Personal Computer
PCB	Printed Circuit Board
PDE	Partial Differential Equations
PE	Piezoelectric
PEC	Packet Error Check
PEHs	Piezoelectric Energy Harvesters
PEM	Proton Exchange Membrane
PEMFCS	Proton Exchange Membrane Fuel Cell Stack
PET	Polyethylene Terephthalate
PF	Passive Filtering
PFC	Power Factor Correction
PG	Pressure Growth
PI	Proportional Integral
PID	Proportional Integral Derivative
PLC	Power Line Communication
POL	Point of Load
POL/D	Point-of-Load/Distribution
POU	Point of Use
PPM	Pulse Position Modulation
PSC	Partially Shading Condition
PSO	Particle Swarm Optimization
PV	Photovoltaic
P-V	Power-Voltage
PVGJ	Pulsed Vortex Generator Jet
PVHPS	Photovoltaic Hybrid Power Source
PWM	Pulse Width Modulation
PZT	Lead Zirconate Titanate
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RANS	Reynolds-Averaged Navier Stokes
RC	Resistance–Capacitor
RCC	Ripple Correlation Control
RES	Renewable Energy Sources
RF	Radio Frequency
RLP	Representative Loading Profiles
RMS	Root Mean Square

RS	Reed Solomon
RWT	Reference Wind Turbine
S3R	Sequential Switching Shunt Regulator
SAPV	Stand-Alone Photovoltaic
SAT	Single Axis Tracking
SBEMS	Smart Building Energy Management Systems
SCPB	Short-Current Pulse-Based
SCRIMP™	Seemann Composites Resin Infusion Molding Process
SDSHE	Solar Dish Stirling Heat Engine
SEB	Single Event Burnout
SEBP	Single Event Burnout Phenomenon
SECE	Synchronous Electric Charge Extraction
SEE	Single Event Phenomenon
SEGR	Single Event Gate Rupture
SEL	Single Event Latch-up
SEPIC	Single-Ended Primary Inductor Converter
SEU	Single Event Upset
S-FSK	Spread Frequency Shift Keying
SGEMP	System-Generated EMP
SGI	Silhouette Global Index
Si	Silicon
SiC	Silicon Carbide
SIDO	Single İnductor Dual Output
SM	Smart Meter
SME	Shape Memory Effect
SMPS	Switched Mode Power Supply
SoC	State of Charge
SOFC	Solid Oxide Fuel Cell
SoH	State of Health
SS	Spread Spectrum
SSPB	Single-Supply Pre-Biasing
SST	Shear Stress Transport
STAR	Space Technology and Advanced Research
STC	Standard Test Conditions
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TE	Trailing Edge
TEG	Thermoelectric Generator
TENG	Triboelectric Nanogenerator
THD	Total Harmonic Distortion
TID	Total Ionizing Doze
TSAT	Tilted Single Axis Tracking

TT&C	Telemetry, Tracking, and Telecommand
TVAC-PSO	Time Varying Acceleration Coefficients Particle Swarm Optimization
UC	Ultracapacitor
UDDS	Urban Dynamometer Driving Schedule
VARIM	Vacuum-Assisted Resin Infusion Molding
VAWT	Vertical Axis Wind Turbine
VBRTM	Vacuum Bag Resin Transfer Molding
VDRG	Velocity-Damped Resonant Generator
VG	Vortex Generator
VRM	Voltage-Regulated Module
VSAT	Vertical Single Axis Tracking
W	Daily Electrical Energy Consumption
WAN	Wide Area Network
WAST	Warm Air Storage Tank
WBF	Weighted Bit Flipping
WBG	Wide Band-Gap
WF	Daily Water Flow
WiSH	Wind-Solar Hybrid
WLAN	Wide Local Area Network
WM-Bus	Wireless M-Bus
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
WT	Wind Turbine
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching