Off-Grid Electrical Systems in Developing Countries

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To Kristine

Preface

Over one billion people do not have access to electricity. The majority live in developing countries in Sub-Saharan Africa and South Asia. The consequences of this form of energy poverty can be severe. Most activities end at sunset, unless dangerous and expensive kerosene lamps or candles are used. Children breathe air polluted by smoke from open fires. Women give birth in darkness or without the aid of life-saving electronic medical devices. Rural communities become even more isolated without access to news and information by radio or television.

Now, perhaps more than ever, electricity access has caught the attention of the global community. Access to affordable and sustainable energy is one of the United Nation's Sustainable Development Goals. Large philanthropic and development organizations are prioritizing electricity access. Even multi-billion-dollar technology companies have started electricity access initiatives.

An estimated US$50 billion per year is needed through 2030 to achieve universal electricity access. It is estimated that over 100,000 mini-grids will be needed, and that one in three households presently without electricity access will have an off-grid system of some form. This will not happen without a workforce of engineers well prepared to innovate and design systems in the unique context of off-grid communities in developing countries.

The purpose of this book is to provide engineers with the essential foundational knowledge of designing and operating off-grid electricity systems in developing countries. This is a first-of-its-kind book that brings together the electrical engineering concepts relevant to off-grid systems. The scope is broad. Throughout the book, examples, design approaches, and practical considerations especially relevant to off-grid systems in developing countries are provided.

The book focuses on electrical aspects of off-grid systems. It assumes the reader has basic proficiency in DC and AC circuit analysis, including phasor and stead-state power analysis. Previous exposure to balanced three-phase circuit analysis is helpful, but not required. Wherever possible, the single-phase (per-phase) model is used. It is appropriate for third or fourth year undergraduate students, or first year graduate students. Although aspects of renewable energy engineering and power electronics are covered, it does not replace a course or book dedicated to these topics. Practitioners may find the book as a useful reference.

The book is arranged in four parts. The first part, Chaps. 1 to 4, is focused on electricity access in general. Chapters 1 and 2 describe the state of energy consumption in the world in general, and in off-grid communities in developing countries in particular. Chapter 3 describes electricity access through grid extension, whereas Chap. 4 introduces off-grid systems.

The second part of this book, Chaps. 5 through 7, is focused on the energy conversion technologies used in off-grid systems. Readers with a background in renewable energy and electromechanical energy conversion may find some of this material familiar. However, the information is presented considering small-scale off-grid applications, which most readers will find fresh.

The third part of this book, Chaps. 8 and 9, covers energy storage and electronic converters and controllers. Chemical batteries are incredibly important in many off-grid systems, yet most engineers do not have a firm understanding of the underlying electrochemistry. Chapter 9 discusses converters. Readers with a background in power electronics will find some concepts familiar.

The fourth and final part of the book ties the concepts presented in the previous chapters. In Chap. 10 we see how the components discussed in the second and third part of the book operate together in an off-grid system. Chapter 11 begins a two-chapter description of how off-grid systems are designed, beginning with load and resource assessment. Off-grid system design is the focus of Chap. 12. Here a realistic example of a solar-based mini-grid is used to illustrate the design of the energy production and distribution systems. Chapter 13 is focused on solar home systems and solar lanterns. The book concludes with a short chapter on practical considerations.

In writing this book, I drew heavily upon my experience in off-grid electrical systems. My work with the nonprofit organization KiloWatts for Humanity, IEEE Smart Village, and time living in Zambia as a Fulbright Scholar is especially formative. Most of the text is oriented toward electricity access in the Sub-Saharan African experience.

It is with some hesitation that the title of this book includes the term "developing country." To some, this is a degrading term. Of course, it is not intended to be interpreted in this way. Rather, the term is used to connote the general circumstances that the off-grid systems discussed in this book exist: in at-risk, underserved, and/or impoverished communities. These conditions also exist in countries not classically considered developing.

I am especially grateful to the many reviewers, organizations, and individuals whose insight and feedback helped shape this book. In particular, Dr. Paul Neudorfer and Dr. Eric Watson, S.J. of Seattle University; Steve Szablya, P.E., and Daniel Nausner of KiloWatts for Humanity; Peter Dauenhauer from the University of Strathclyde; Dr. Pritpal Singh of Villanova University; Brett Bauer of Canyon Industries; Frank Bergh, P.E. of Sigora Haiti; Ifeanyi Orajaka of GVE Projects; and Isaiah Lyons-Galante and Sam Slaughter of Power Gen.

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Seattle, WA, USA Henry Louie
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Contents

Acronyms

AAAC	All aluminum alloy conductor
ABC	Aerial bundled conductor
ABS	Acrylonitrile butadiene styrene
ACSR	Aluminum conductor steel reinforced
AGM	Absorbed glass mat
AGR	Annual growth rate
Ah	Amperehour
AM	Air Mass
ARPU	Average revenue per user
AVR	Automatic voltage regulator
AWEA	American Wind Energy Association
BTU	British Thermal Unit
CAR	Central African Republic
CF	Coincidence Factor
CFL	Compact florescent light
CHP	Combined heat and power
CI	Compression ignition
DF	Demand factor
DoD	Depth-of-discharge
DRC	Democratic Republic of Congo
ELC	Electronic load controller
GOGLA	Global Off-Grid Lighting Association
GPRS	General Packet Radio Service
GPS	Global Positioning System
HDI	Human Development Index
IC	Incremental conductance
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ITC	Internet, telecommunications, computers
KCL	Kirchhoff's Current Law

KVL	Kirchhoff's Voltage Law
koe	kilogram of oil equivalent
LCOE	Levelized cost of energy
LED	Light Emitting Diode
LF	Load factor
LI	Lithium ion
LPG	Liquefied petroleum gas
LVD	Low voltage disconnect
MHP	Micro hydro power
MOSFET	Metal–oxide–semiconductor field-effect transistor
MPP	Maximum power point
MPPT	Maximum power point tracker
MTF	Multi-Tier Framework
NOCT	Normal Operating Cell Temperature
OPzV	Ortsfest PanZerplatte Verschlossen
PCD	Pitch Circle Diameter
PDF	Probability density function
PF	Power factor
PMSG	Permanent magnet synchronous generator
PO	Perturb & observe
PV	Photovoltaic
PVC	Polyvinyl chloride
PWM	Pulse width modulation
REAs	Rural Electrification Authorities
REMP	Rural electrification master plan
RMS	Root mean square
RPM	Revolutions per minute
SA	South Asia
SHS	Solar home system
SI	Spark ignition
SL	Solar lantern
SLA	Sealed lead–acid
sLCOE	Simplified LCOE
SLI	Starting, lighting and ignition
SPWM	Sinusoidal pulse width modulation
SOC	Standard operating conditions
SoC	State-of-charge
SSA	Sub-Saharan Africa
STC	Standard test conditions
SWER	Single Wire Earth Return
toe	Tonne of oil equivalent
THD	Total harmonic distortion
TSR	Tip speed ratio
UPE	User premise equipment

UPS	Uninterruptible Power Supply
VRLA	Valve regulated lead–acid
WECS	Wind energy conversion system