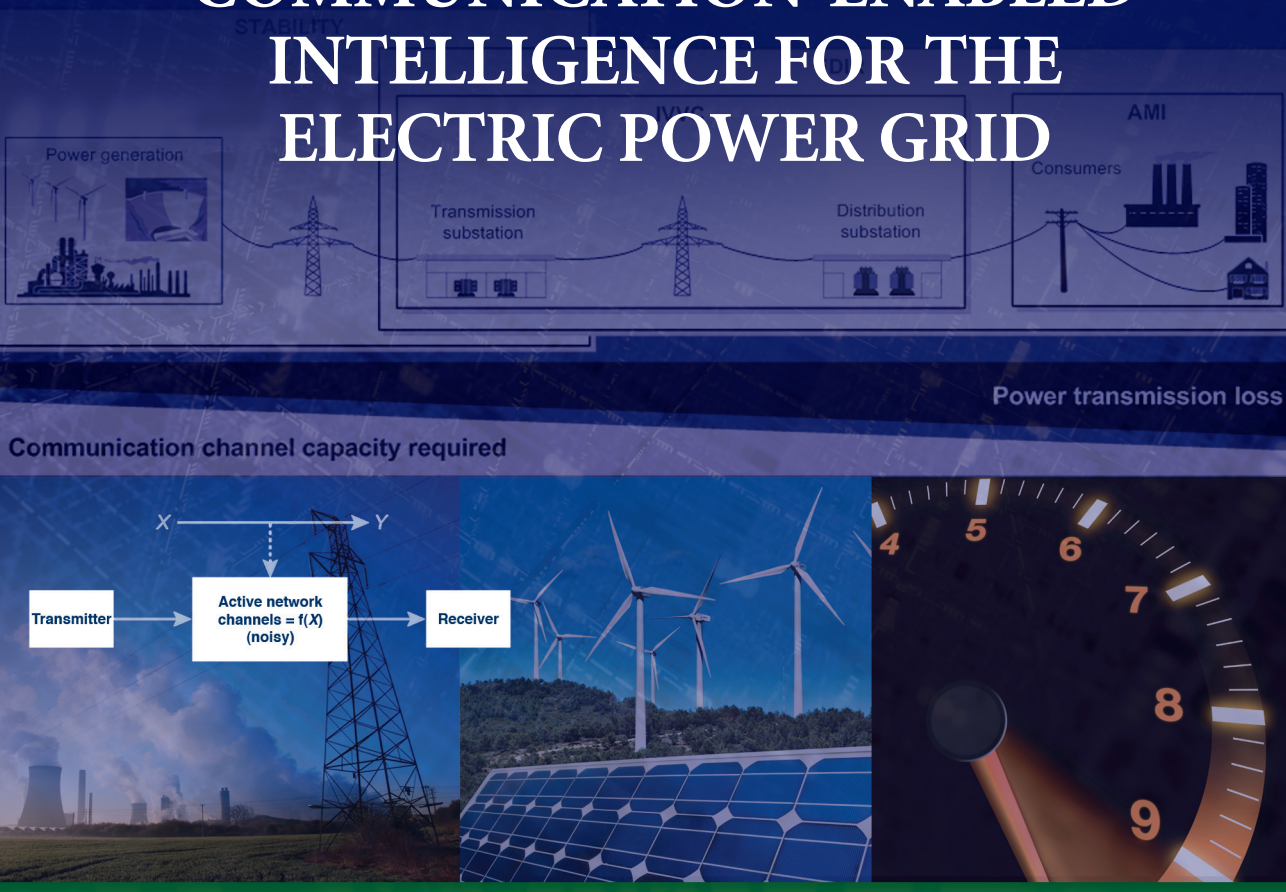
STEPHEN F. BUSH

SMART GRID

COMMUNICATION-ENABLED INTELLIGENCE FOR THE ELECTRIC POWER GRID



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COMMUNICATION-ENABLED INTELLIGENCE FOR THE ELECTRIC POWER GRID

Stephen F. Bush
General Electric Global Research, USA

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About the Author

Stephen F. Bush graduated from Carnegie Mellon University and worked at General Electric Information Services. From there, he obtained his PhD while working as a researcher at the Information and Telecommunications Technologies Center at the University of Kansas, participating in the design of a self-configuring, rapidly deployable, beamforming wireless radio network.

Stephen currently enjoys his role as senior scientist at the General Electric Global Research Center, where he has published numerous conference papers, journal articles, and book chapters, and taught international conference tutorials on novel communication- and network-related topics. His previous book publication, *Active Networks and Active Network Management: A Proactive Management Framework*, explained the development and operation of the intriguing and controversial active networking paradigm. Dr Bush was presented with a gold cup trophy awarded by Defense Advanced Research Projects Agency (DARPA) for his work in active-network-related research. Dr Bush has been the principal investigator for many DARPA and Lockheed Martin sponsored research projects, including: Active Networking (DARPA/ITO), Information Assurance and Survivability Engineering Tools (DARPA/ISO), Fault-Tolerant Networking (DARPA/ATO), and Connectionless Networks (DARPA/ATO), involving energy-aware sensor networks. Stephen also likes creative interaction with students while teaching Quantum Computation and Communication at the Rensselaer Polytechnic Institute and Computer Communication Networks at the University at Albany. Stephen has written "Nanoscale Communication Networks," which has helped to define this new field. He is Director of the IEEE Communications Society Standardization Program Development Board and also serves on the IEEE Smart Grid Communications Emerging Technical Subcommittee and is Chair of the IEEE P1906.1 Recommended Practice for Nanoscale and Molecular Communication Framework standards working group. Stephen also served as an IEEE Distinguished Lecturer on Smart Grid Communications.

Preface

Objective

> The center of your culture is left without electric power for a few hours only, and all of a sudden crowds of American citizens start looting and creating havoc. The smooth surface film must be very thin. Your social system must be quite unstable and unhealthy.
>
> —Alexander Solzhenitsyn at Harvard Class Day Afternoon Exercises
> Thursday, June 8, 1978

It is natural for the reader who is not fully versed in both power systems and communications to be curious about many aspects of the evolving technologies. For example, how did power systems and communication develop to their present states where something like the term "smart grid" could be coined? Certainly power systems and communications are both offshoots of electrical engineering and both involve the manipulation of power. Why have the two fields diverged so radically? Thinking about these questions leads to more fundamental questions. What is the relationship between electric power and information? And more specifically, what is the fundamental relationship between power systems and communication theory? Thinking about these questions helps us address more practical questions. What are the potential impacts of communication on efficiency in electric power transmission and distribution efficiency? What types of communication are most appropriate for different portions of the power grid? It is also intriguing to consider the more distant future. What will the power grid look like in the decades to come? How could wireless power transmission revolutionize the power grid? What are the fundamental limiting factors? Is there a fundamental limit to the amount of distributed generation that is possible and, if so, how can this limit be overcome? Will communication in the power grid really enable more consumer participation, machine intelligence, and self-organization as many are predicting? What are the opportunities for your particular research to contribute to the future of the power grid? This book will provide you with the background needed to form your own conclusions to these and many other questions on this fascinating journey through the intersection of power systems and communications. It is important for information and graph theorists and network science researchers to better understand power systems to advance information theory and network analysis in order to implement fast, efficient, and realistic approaches within the power systems domain. If not, these theorists could remain in a world of simplified toy problems, not understanding how the power grid really works or simply become constrained within the strait jacket of existing theory.

The primary objective of this book is to bridge the divide between the fields of power systems engineering and computer communication. In my experience within these early stages of this

round of "modernization" of the electric power grid, many power systems engineers tend to be a little overconfident in the capability of communication systems to work reliably, with sufficient capacity, and with low latency under any condition. This is not surprising given that communication networks are nearly ubiquitous and embedded within increasingly smaller devices. It is natural for noncommunication engineers to assume that communication networking is a solved problem, ready for application anywhere and everywhere. On the other hand, the power grid is also so ubiquitous and reliable that most nonpower systems engineers take electric power for granted. In fact, most of us tend to assume that an electric power socket will always be within easy reach and that our electronic devices will work perfectly once plugged into that socket. Rarely does anyone think about the complexity of the electric power grid when inserting a plug into a socket or operating their electronic devices. In a sense, both the power grid and communications have suffered from their own respective successes – the electric power grid tends to be taken for granted and communication networks are assumed to work perfectly under almost any condition and for any application. The reader will soon find that both the electric power grid and communications are each highly complex systems in their own right; the manner in which they are integrated will have far-reaching consequences.

Another objective of this book is to remove the previously mentioned dangerous assumptions: to show the complexity and operational requirements of the evolving power grid, the so-called "smart grid," to the communication networking engineer, and similarly to show the complexity and operational requirements for communications to the power systems engineer. At the time this is being written, there are few practitioners who have depth of knowledge in both power systems and computer communications and networking. Thus, another objective of this book, and probably the most important, is to provide a path towards a fundamental understanding in both power systems and communication networking. Just as power systems require a broad set of knowledge ranging from high-power device physics to protection mechanisms to power flow and stability analysis, so too communication networking requires an understanding of topics ranging from signal processing, information theory, and graph theory to cybersecurity. It is my hope that these fundamental topics of power systems and communications combine in novel ways to form far more than the sum of their parts. In other words, it would be a shame for power systems engineers to remain restricted to thinking only about their traditional discipline while directing communication engineers where to implement communications; that is, losing the chance to incorporate new ideas into their repertoire. Similarly, it would be a shame for communication engineers to blindly submit to the direction of power systems engineers and implement communications without looking at new ways to better integrate power systems and communications. My hope is that this book may serve as the impetus leading to the discovery of fundamental new relationships between the properties of electric power, energy, and information.

An overriding objective of this book is to focus on fundamentals – underlying concepts that are most resistant to change. Smart grid standards and technology are currently undergoing rapid evolution; this evolution will continue into the foreseeable future. Thus, standards and technologies as they exist today will soon change or disappear no matter how strongly their advocates may feel. Understanding more fundamental concepts that reside closer to the physics of operation will pay higher dividends for the reader. Thus, for example, understanding information entropy in the power grid per kilowatt of power delivered or the radio frequency communication power expended within the power grid per kilowatt of power delivered will be more valuable than understanding the detailed packet structure of a half-dozen supervisory

control and data acquisition protocols. In particular, Section 6.3 develops the fundamental relationship among energy, communication, and computation. These are beautiful relationships that even an expert in communications or power systems should not overlook. Given rapid changes in technology, it is important to understand that technology undergoes predictable evolutionary processes, not unlike a biological organism. For example, the pressures of the market and the nature of the intellectual property processes drive technology to follow the predictable path that we see the smart grid following. It is possible, using this general knowledge of technology evolution, to predict how the power grid will evolve and thus anticipate future challenges.

Finally, many books on the topic of the smart grid, and renewable energy in particular, utilize the notion of global warming and impending environmental catastrophe to promote the importance and urgency of their topic. The reader will note that I purposely avoid discussion of this controversial topic. I believe that we can all agree upon the need for efficient power delivery, lower cost, and less reliance on imported energy. If these can be accomplished in a clean and environmentally friendly manner, then that is an added bonus.

Genesis

My prior books have always focused upon fundamental new ideas; for example, active networks or nanoscale communication networks. So readers may wonder why I have chosen to write about a topic as seemingly practical and mundane as the recent advances in power systems. As the reader will notice, I have not lost interest for thinking "outside the box." While conveying the required practical information, I have attempted to find new ways of looking at the problem wherever possible in order to add new perspectives that hopefully add deeper insight.

There is no doubt in my mind that the definition of smart grid will continue to change over time. At the time this book is being written, smart grid is synonymous with communications coupled with the power grid to accomplish novel power applications. However, smart grid will, and should, expand over time to encompass machine learning applied within the power grid and the development and incorporation of smarter power components. However, it is always important to keep in mind that without underlying communications most of the other advancements will not be possible.

There are a few fundamental trade-offs that apply to communication and networking that recur often; namely, trade-off among performance metrics such as latency, bandwidth, availability, energy consumption, transmission range, and so on. To a first order, designing the smart grid is about determining the correct trade-offs in the correct part of the power grid. For example, the so-called advanced meter reading infrastructure has very different communication requirements, and thus a different design philosophy than power protection. Understanding the reason for the different requirements is critical.

This book had its genesis in 2010 when I became involved in smart-grid-related projects and could not find a comprehensive source for communications within the electric power grid. This book also became intertwined with my IEEE Distinguished Lecture Tours in 2011. It became clear from audiences on the lecture tours that there was, and continues to be, widespread and intense interest in the "smart grid." It also became clear, as previously mentioned, that there is a fundamental lack of understanding between the fields of electric power systems and communications.

It is also evident from my experience on smart grid projects that communications is often assumed to exist when in reality it may not. Complex algorithms are developed that rely upon geographically dispersed information under the assumption that communications can be easily engineered later into the process. It is important for power systems engineers to be aware of the challenges involved in communication networking. As a simple example, establishing point-to-point wireless communication through ground clutter is a nontrivial task. Relying on a cellphone carrier introduces problems of coverage, availability, and often uncertainty regarding the bandwidth available at any specific time, in addition to excessive cost. Power line carrier suffers many problems, not the least of which is the loss of communication through a downed power line; that is, communication may be lost when it is needed most. These form only a small subset of the challenges faced by communications in the power grid; hopefully, the point that there is no simple, trivial solution will become clear.

I also noticed that, just as local regions develop their own dialects in human language, power systems and communication engineers continue to develop their own independent and unique terminology, sometimes attributing very different meaning to the same terms, causing potential confusion. For example, "security" to a power systems engineer means something that is entirely different to a communication and networking engineer. Take an "active network" or "active networking" as another example; to a power engineer it refers to a microgrid, while to a communication engineer it refers to an advanced form of programmable network. Another source of terminological confusion is "power routers": is it literally a device that routes electric power or is it just a "communication network router" that serves to control the routing of power? These and other differences in terminology are explained in detail in the text. It can be said that power systems and communications are separated by a common language. The origin of this book grew out of an attempt to understand the similarities and differences between the two disciplines.

But why is a holistic approach towards smart grid – such as that proposed in this book – expected or desired? A common example can be found in the evolution of the Internet and telecommunications, which drove exploration for the relationship between communications and information and ultimately led to information theory. The Internet and telecommunications in turn created a platform for applications that could never have been conceived at the time. A more holistic approach allows us to be more innovative – to see how components interact in a deeper manner in order to find efficiencies and develop entirely new applications. It was the drive to make the system more efficient and reduce the cost of transporting a product that drove the theory, just as the power grid is doing today in the so-called smart grid. For information theory, in Shannon's case, it was an industrial research laboratory rather than a university that created the key innovation. Again, as typically happens, it is the case today that fundamental innovation and insight are driven by, and come from, industry.

Approach and Content

The power grid is in a state of rapid evolution. Any attempt to convey a comprehensive state of the policies, standards, and even specific technologies will likely be out of date even before going to print. Thus, this book focuses upon fundamentals as much as possible; information theory and power electronics will change more slowly than policy, regulation, and standards. The reader can be confident that the material presented will always be relevant; only its implementation may change. Reliability, safety, low cost, and high efficiency

have been, and will likely remain, key drivers of the technology regardless of how business models change.

In fact, the technology for what we call the "smart grid" did not suddenly appear, but has been in development for some time. Attempting to draw a precise boundary between the "legacy power grid" and the "smart grid" would not be a simple task and would perhaps not even be sensible to attempt. Communication has been an integral part of the power grid since the last century, so the idea of simply adding communication is neither novel nor does it make the grid smart. Part of the approach of this book is to explore, and perhaps sometimes debunk, why the word "smart" is in smart grid. In that regard, it has been important in writing this book to separate fact from proposed idea: what really exists and is likely to exist in the power grid from what academics often incorrectly "think" exists in the power grid.

This book covers the evolving electric power grid and its integration with communications assuming as little prerequisite knowledge as possible. We begin with a brief and intuitive introduction to the fundamentals of power systems and progressively build upon that foundation while pointing out relationships with communications and networking wherever appropriate along the way.

The book is organized into three parts with five chapters in each part. Figure 1 shows the organization of the book. Part One of the book will ground the reader in the basic operation of the electric power grid. This part covers fundamental knowledge that will be assumed in Parts Two and Three of the book. Part Two introduces communications and networking, which are critical enablers for a smart grid. The manner in which communication and networking are integrated into the power grid is an ongoing process; thus, we also consider how communication and networking are anticipated to evolve as technology develops. This part lays the foundation for Part Three, which utilizes communication within the power grid. The smart grid will ultimately become "smart" when intelligence is implemented upon the communication framework explained in Part Two. Thus, Part Three must draw heavily upon both past embedded intelligence within the power grid and current research to anticipate how and where computational intelligence will be implemented within the smart grid.

Each part is divided into chapters and each chapter has a set of questions useful for exercising the reader's understanding of the material in that chapter. The book is written so that when the chapters are read in consecutive order the material will flow well, each chapter building upon the previous chapters. However, there are other ways to read the book for readers with different backgrounds and perspectives. A power systems engineer would presumably have a strong background in the traditional power grid and would not need to read Part One of the book, so could begin reading starting with Part Two. On the other hand, a communications engineer could potentially skip Chapter 6, with the exception of Section 6.4 on power system information theory. A reader who is interested only in a summary of the technology could simply read the first chapter of each part, namely Chapters 1, 6, and 11.

One of the interesting aspects of the evolving power grid is that as it has evolved, it has become harder to neatly divide the power grid into the traditional components of generation, transmission, distribution, and consumption. These parts are becoming more interrelated. If one were interested only in generation, then Chapters 1, 8, and 15 (nanoscale power generation) would be most relevant. If one were interested only in transmission, then Chapters 3, 6, 12, and 13 might be most appropriate. If one were interested in distribution, then Chapters 4, 9, 12, and 13 would perhaps be most relevant. However, aspects of distributed generation, demand-response, and fault detection, isolation, and restoration, state estimation and stability,

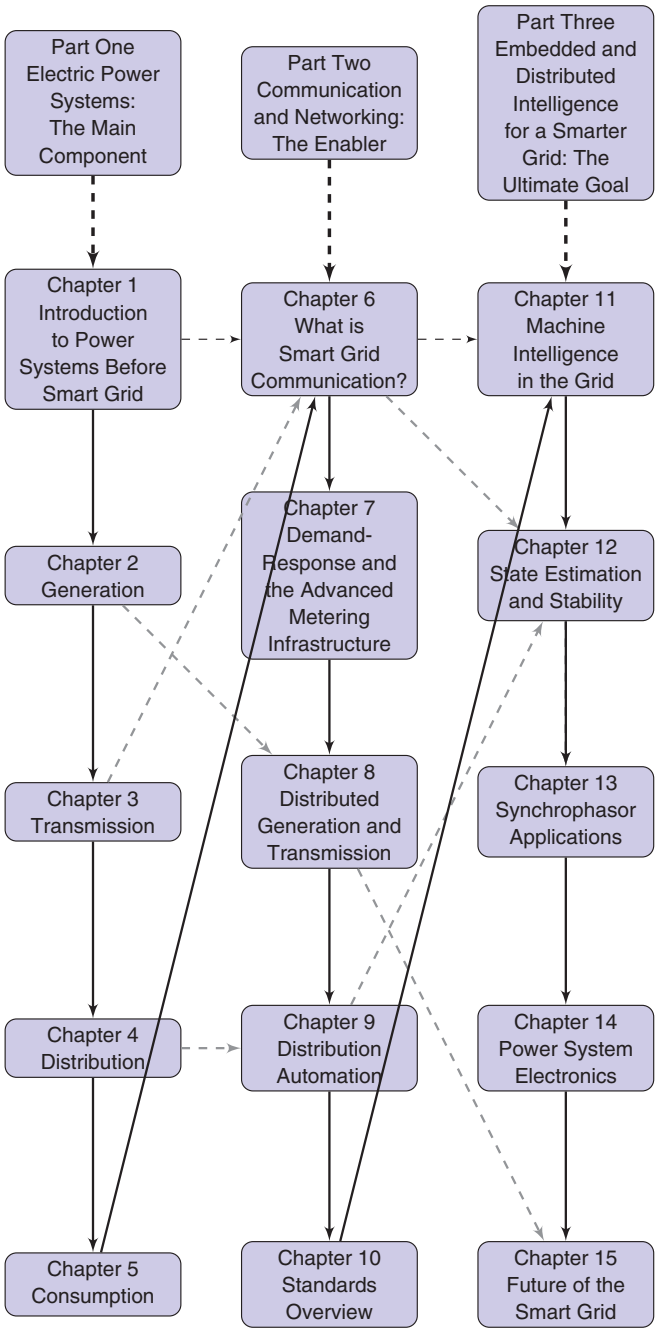

Figure 1 Selected reading arrangements are illustrated for readers interested in specific subtopics. Those interested in power generation could start from Chapter 2 and follow the dashed lines; those interested in power transmission could begin with Chapter 3 and follow the dashed lines; those interested in power distribution could start with Chapter 4 and follow the dashed lines.

synchrophasors, and so on. will all be taking place simultaneously within the power distribution network.

As will be seen throughout this work, the smart grid communication vision presented here foreshadows a high degree of integration between information theory and power systems. Specifically, fundamental relationships between information theory and Maxwell's equations could yield new insight into understanding exactly where to place communication, since entropy would be known at a low level within the power grid. Today, this placement is done in a rather ad hoc manner. We may also someday know the precise theoretical "bits per kW" needed to distribute electric power safely. Finally, we can imagine that new forms of efficiency resulting from advances in small-scale power generation could lead to widespread use of nanoscale power generation and distribution and the required nanoscale communication to support such systems. For example, a consumer's electric vehicle may be recharged by extraneous electromagnetic fields from radio transmissions. Research and references on both extracting energy from extraneous electromagnetic transmissions and nanoscale communications are provided in later chapters of this book. In the distant future, we might even imagine the quantum teleportation of energy. All of these topics are covered in the last chapter of the book.

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Stephen F. Bush

Acronyms

6LoWPAN	IPv6 over low-power wireless personal area networks
ACE	area control error
ACFFI	average communication failure frequency index
ACIDI	average communication interruption duration index
ACK	acknowledgment
ACO	ant colony optimization
ACSE	association control service element
ACSR	aluminum conductor steel-reinforced cable
ADA	advanced distribution automation
ADI	advanced distribution infrastructure
ADP	adaptive dynamic programming
AGC	automatic grid control
AHP	analytical hierarchical programming
AIEE	American Institute of Electrical Engineers
AMI	advanced metering infrastructure
AMR	automated meter reading
ANSI	American National Standards Institute
AODV	ad hoc on-demand distance-vector
APDU	application protocol data unit
API	application program interface
ARQ	automatic repeat-request
ASCII	American Standard Code for Information Interchange
ASK	amplitude-shift keying
ASN.1	abstract syntax notation 1
ATM	asynchronous transfer mode
BAN	body-area network
BAS	building automation system
BCS	Bardeen–Cooper–Schrieffer
BE	best-effort
BFSK	binary frequency-shift keying
BMC	best master clock
BPL	broadband over power line
BPSK	binary phase-shift keying
BS	base station

CA	contingency analysis
CAES	compressed air energy storage
CAIDI	customer average interruption duration index
CAIFI	customer average interruption frequency index
CAN	controller-area network
CBR	constant-bit rate
CC	control center
CCITT	Comité Consultatif International Téléphonique et Télégraphique (International Telegraph and Telephone Consultative Committee)
CID	connection identifier
CIGRE	Conseil International des Grands Reseaux Electriques (International Council on Large Electric Systems)
CIM	common information model
ComSoc	IEEE Communications Society
COSEM	companion specification for energy metering
CRC	cyclic redundancy checksum
CSM	common signaling mode
CSMA	carrier-sense multiple-access
CSMA-CA	carrier-sense multiple-access with collision avoidance
CSMA-CD	carrier-sense multiple-access with collision detection
CT	current transformer
CTAIDI	customer total average interruption duration index
CVR	conservation voltage reduction
CVT	constant voltage transformer
DA	distribution automation
DAG	directed acyclic graph
DAU	data aggregation unit
DCF	distribution coordination function
DCT	discrete cosine transform
DESS	distribution energy storage system
DG	distributed generation
DHP	dual heuristic programming dielectric
DIO	DODAG information object
DLMS	device language message specification
DMI	distribution management infrastructure
DMS	distribution management system
DNP	distributed network protocol
DNP3	distributed network protocol 3
DODAG	destination-oriented directed acyclic graph
DR	demand-response
DSL	digital subscriber line
DSM	demand-side management
DSP	digital signal processor
DSSS	direct-sequence spread-spectrum
DVR	dynamic voltage restorer
EDFA	erbium-doped fiber-optic amplifier

EHV	extra-high voltage
EIA	United States Energy Information Agency
EMC	electromagnetic compatibility
EMF	electromotive force
EMS	energy management system
ENS-C	energy not served due to communication failure
EPRI	Electric Power Research Institute
EPS	electric power system
ertPS	extended-real-time-polling service
ESI	energy services interface
ETSI	European Telecommunications Standards Institute
EPSEM	extended protocol specification for electronic metering
FACTS	flexible alternating current transmission system
FAN	field-area network
FCL	fault current limiter
FCS	frame check sequence
FDIR	fault detection, isolation, and restoration
FDM	frequency-division multiplexing
FERC	Federal Energy Regulatory Commission
FET	field-effect transistor
FFD	full function device
FFT	fast Fourier transform
FHSS	frequency-hopping spread-spectrum
FN	false-negative isolated fault segment vector
FSK	frequency-shift keying
GenCo	generating company
GFCI	ground-fault circuit interrupter
GIC	geomagnetically induced current
GIS	geographic information system
GOOSE	generic object-oriented substation events
GPS	global positioning system
HAN	home-area network
HART	highway addressable remote transducer
HDP	heuristic dynamic programming
HEMP	high-altitude electromagnetic pulse
HMAC	keyed-hash message authentication code
HTS	high-temperature superconductor
HTS-ISM	high-temperature superconducting induction-synchronous machine
HVDC	high-voltage direct-current
IAE	integral absolute error
ICCP	inter-control center communications protocol
ICT	information and communications technology
IE	information element
IEC	International Electrotechnical Commission
IED	intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers

IEM	intelligent energy management
IETF	Internet Engineering Task Force
IFFT	inverse fast Fourier transform
IFM	intelligent fault management
IGBT	insulated-gate bipolar transistor
IHD	in-home display
IMF	interplanetary magnetic field
IoT	Internet of things
IP	Internet protocol
IPv6	Internet protocol version 6
IRE	Institute of Radio Engineers
ISE	integral squared error
ISO	independent system operator *or* International Standards Organization
IT	information technology
ITAE	integral time-weighted absolute error
ITIC	Information Technology Industry Council
ITU	International Telecommunication Union
IVVC	integrated volt-VAr control
L2TP	layer 2 tunneling protocol
L2TPv3	layer 2 tunneling protocol version 3
LAC	L2TP access concentrator
LAN	local-area network
LBR	LLN border router
LC	inductor–capacitor
LDP	label distribution protocol
LED	light-emitting diode
LEO	low Earth orbit
LER	label edge router
LLC	logical-link control
LLN	low-power and lossy network
LM/LE	load modeling/load estimation
LMP	location marginal pricing
LMS	load management system
LNS	L2TP network server
LPDU	link protocol data unit
LRC	longitudinal redundancy check
LR-WPAN	low rate-wireless personal-area network
LSE	load serving entity
LSR	label-switch router
LTC	load tap changing
LV	low voltage
M2M	machine-to-machine
MAC	media-access control
MAIFI	momentary average interruption event frequency index
MAN	metropolitan-area network
MDL	minimum description length