Anurag K. Srivastava • Venkatesh Venkataramanan
Carl Hauser

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Anurag K. Srivastava
West Virginia University, Morgantown, WV, USA

Venkatesh Venkataramanan
National Renewable Energy Laboratory, Golden, CO, USA

Carl Hauser
Washington State University, Pullman, WA, USA

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About the Authors

Anurag K. Srivastava, PhD, is the Raymond J. Lane Professor and Chairperson of the Lane Department of Computer Science and Electrical Engineering in the Benjamin M. Statler College of Engineering and Mineral Resources at West Virginia University. He is the director of the Smart Grid Resiliency and Analytics Lab (SGREAL) and an IEEE Fellow.

Venkatesh Venkataramanan, PhD, is a Researcher at the National Renewable Energy Laboratory, working on cyber-physical systems. He was previously with Washington State University and Massachusetts Institute of Technology.

Carl Hauser, PhD, is emeritus faculty in Computer Science at Washington State University. He received his PhD from Cornell University. Following 20 years in industry at IBM Research and Xerox Research, he joined WSU where he conducted research on communications and cybersecurity for electric grid operations.

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Acronyms

ASTA	Arrivals See Time Averages
BHCA	Busy Hour Call Attempts
BR	Bandwidth Reservation
b.u.	bandwidth unit(s)
CAC	Call/Connection Admission Control
CBP	Call Blocking Probability(-ies)
CCS	Centum Call Seconds
CDTM	Connection-Dependent Threshold Model
CS	Complete Sharing
DiffServ	Differentiated Services
EMLM	Erlang Multirate Loss Model
erl	The Erlang unit of traffic-load
FIFO	First in–First out
GB	global balance
GoS	Grade of Service
ICT	Information and Communication Technology
IntServ	Integrated Services
ITU-T	International Telecommunication Unit – Standardization sector
IP	Internet Protocol
LIFO	Last in–First out
LHS	left hand side
LB	local balance
MMPP	Markov Modulated Poisson Process
MPLS	Multiple Protocol Labeling Switching
MRM	multi-retry model
MTM	multi-threshold model
PASTA	Poisson Arrivals See Time Averages
pdf	probability density function
PDF	probability distribution function

PFS	product form solution
QoS	quality of service
RED	random early detection
r.v.	random variable(s)
RLA	reduced load approximation
RHS	right-hand side
SIRO	service in random order
SRM	single-retry model
STM	single-threshold model
TH	Threshold(s)
TCP	Transport Control Protocol
UDP	User Datagram Protocol

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Introduction to the Smart Grid

The power grid has been evolving from a physical system to a "cyber-physical" system to sense, communicate, compute, and control with enhanced digitalization. The cyber-physical smart grid includes components from the physical power system, digital devices, and the associated communication infrastructure. To realize the vision of the smart grid, massive amounts of data need to be transferred from the field devices to the control devices or to the control centers. As more optimal algorithms are deployed for best possible control at a faster time scale, the communication infrastructure becomes critical to provide the required inputs. At the same time, increased number of "smart" devices in the grid also increase the attack surface for potential cyber attacks. It is necessary to study the power system's exposure to risks and vulnerabilities in the associated cyber system.

1.1 Overview of the Electric Power Grid

The electric power grid can be defined as the entire apparatus of wires and machines that connects the sources of electricity with the customers. A power grid is generally divided into four major components as shown in Figure 1.1:

1. Generation
2. Transmission
3. Distribution
4. Loads

Electricity was first generated, sold, and distributed locally in 1870s via direct current (DC) circuits over very small distances. As the demand for electricity became more widespread, the cost of construction and distribution of local generation and DC circuits to carry the power over long distances became prohibitively expensive. Hence, alternating current (AC) generation, transmission, and distribution became the standard that is used to this day. However, the

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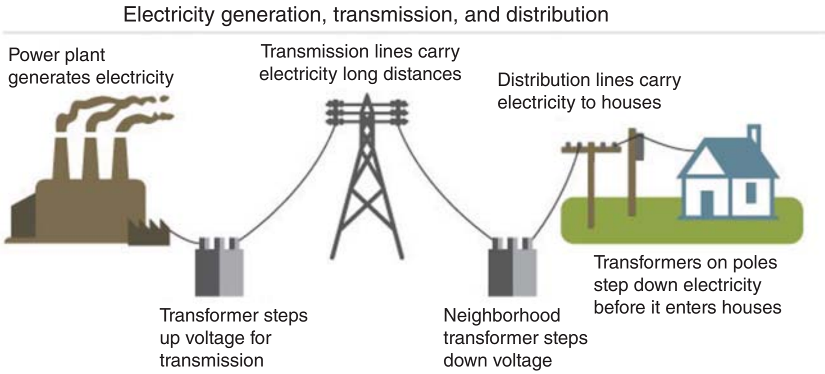

Figure 1.1 Major components of the power grid. Source: Energy Information Administration (EIA), public domain.

infrastructure of the power grid is getting older – the average age of a transformer is greater than 50 years old and has already exceeded its expected lifetime. The electric grid faces several problems, including a problem with the oncoming retirement of at least 5% of the workforce and one of the lowest R&D expenditure as compared to other critical infrastructures.

The situation is getting better, however, with increasing interest in national security and acknowledgment of the critical role that the power grid plays in the overall quality of life. In a full circle, localized generation using distributed energy resources (DERs) is making a comeback, with a combination of both AC and DC systems. Today's generation systems are a combination of different types of sources – including fossil fuels, natural gas, renewable resources, and nuclear energy. These generation systems are often located in remote areas for ease of doing business and for environmental reasons.

The power that is generated at the generating stations is brought to the consumers by a complex network of transmission lines. The North American power grid comprises of four major interconnections as shown in Figure 1.2:

1. Western interconnection
2. Eastern interconnection
3. Quebec interconnection
4. Electricity Reliability Council of Texas (ERCOT) interconnection

These interconnections are zones in which the electric utilities are electrically tied together, indicating that the areas are synchronized to the same frequency and power can flow freely in that area. The interconnections operate nearly independently of each other except for some high-voltage direct current (HVDC)

Figure 1.2 Interconnections in the North American Power Grid. Source: North American Energy Reliability Corporation (NERC), public domain.

interconnections between them. DC converter substations enable the synchronized transfer of power across interconnections regardless of the operating frequency as DC power is non-phase dependent.

The flow of electricity is instantaneous, indicating that the power that is being consumed is also being simultaneously generated. Commercially viable mechanisms for storing electricity for longer duration do not exist currently; hence, the power plants and the grid are constantly operating. The structure of the flow of electricity is illustrated in Figure 1.3, which shows the critical nature of the transmission system in bringing electricity from the generating plants to the customer's use.

Power demand constantly fluctuates throughout the day depending on consumer behavior. There are various factors that create this changing behavior, including population density, work schedules, weather, and other activities. In addition, special activities that involve a large number of people also have to be considered, such as big sporting events or an impending weather event over a large area. Figure 1.4 shows a typical daily "load" curve as it is referred to, which shows how the electric load varies across a day depending on the activities