

SECOND EDITION

# ELECTRIC POWER SYSTEMS

A CONCEPTUAL INTRODUCTION

ALEXANDRA von MEIER

 **IEEE Press**



**WILEY**



## **Electric Power Systems**

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*Second Edition*

*Alexandra von Meier*

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*To my late grandfather  
Karl Wilhelm Clauberg  
who introduced me to  
The Joy of Explaining Things*



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## Preface

This book is a labor of love. It is intended to bridge the gap between standard engineering texts and more popularly accessible descriptions of electric power technology. I discovered this gap as a graduate student struggling to understand power systems, which had always fascinated me, but which I now needed to understand properly in the context of my passion, implementing solar energy. Although I had studied physics as an undergraduate, I found the subject of power systems difficult and intimidating.

The available literature seemed to fall into two categories: easy-to-read, qualitative descriptions of the electric grid for the layperson on the one hand, and highly technical books and papers on the other, written for professionals and electrical engineering majors. The second category had the information I needed, but guarded by a layer of impenetrable phasor diagrams and other symbolism that clearly required some sort of initiation.

I was very fortunate to study with renowned experts at the University of California, Berkeley, including Leon Chua and Felix Wu, who were also generous and gifted teachers and brought me up to speed in deciphering the academic and engineering literature. The formative learning experience was a research project beginning in 1989 at several large nuclear and fossil-fueled steam generation plants, where our team interviewed the staff as part of a study on High-Reliability Organizations. My own subsequent research on power distribution took me into the field with five U.S. utilities and one in Germany. Aside from the many intriguing things we learned about the operating culture in these settings, I discovered how clearly the power plant staff could often explain technical concepts about their working systems. Their language was characteristically plain and direct and was always guided by practical considerations, such as, What does this dial tell you? What happens when you push that button?

In hindsight, the defining moment for inspiring this book occurred in the Pittsburg control room when I revealed my ignorance about reactive power (ironically, having just boasted about my physics degree, to the operators' benign amusement). They generously supplied me with a copy of the plant operating manual, which turned out to contain the single most lucid and comprehensible explanation of electric generators, including reactive power, I had seen. That manual proved to me that one can write about electric power systems in a way that is accessible to audiences who have not undergone the initiation rites of an academic engineering program, but who nevertheless want to get the real story. I imagined there might be other people much like myself—outside the engineering profession or the power industry but vitally concerned with it—who could benefit from such a practical approach.

After finishing my dissertation in 1995, I decided to give it a try. My goal was to write the book that I would have wanted to read as a student. The guiding principle was to assume a minimum of prior knowledge on the part of the readers while trying to relate as much as possible to their direct

experience and intuition. In essence, the book should explain how the electric grid works and what its relevant technical constraints are. It should convey a sense of the complexity of the system as a whole and point to the tools used by power engineers to navigate that complexity. Though it could not be expected to offer a full professional training in the use of these tools, it should prepare readers for the more specialized literature or advanced coursework. Enough historical context should be provided to view technological innovation both from the standpoint of modern opportunities and the challenges presented by the legacy infrastructure.

From the start, I envisioned two main audiences. The first consists of students and researchers who are learning about electricity and power engineering in an academic setting, and who feel that their understanding would be enhanced by a qualitative, conceptual emphasis to complement the quantitative methods stressed in technical courses. This audience might include students of diverse backgrounds or differing levels of preparation, perhaps transferring into an engineering program from other disciplines. Such students often need to solidify their understanding of basic information that is presumed to be second nature to advanced undergraduates in technical fields. As a supplement to standard engineering texts, the first edition aimed to provide a clear and accessible review of units, definitions, and fundamental physical principles; to explain in words the ideas shown by equations; to contextualize information, highlighting connections among different topics and pointing out their relevance; and to offer a glimpse into the practical world of the electric power industry.

The second major audience consists of professionals working in and around the power industry whose educational background may not be in electrical engineering, but who wish to become more familiar with some of the technical details and the theoretical underpinnings of the system they deal with. This group might include analysts, administrators, and managers coming from fields of business, economics, law, or public policy, as well as individuals with technical or multidisciplinary training in areas other than power engineering.

The project was more ambitious than I had imagined, and the first edition took a decade to write—but it also met with more success than I had dared to hope. After 13 years as a professor of Energy Management & Design at Sonoma State University, I returned to Berkeley in 2012 to teach a power systems course in the Department of Electrical Engineering and Computer Science and to direct electric grid research at the California Institute for Energy and Environment. My group's research primarily focused on the application of novel sensing, analytics, and control strategies to facilitate the grid integration of renewable resources. This work gave me the opportunity to connect with and learn from many experts, especially through the North American Synchrophasor Initiative (NASPI). It also reinforced the sense that a growing audience of scholars and practitioners from diverse fields could use help understanding how the electric grid works.

The two-semester course *Introduction to Electric Power Systems* I developed and taught for 10 years gives an overview of the legacy electric grid and highlights opportunities and challenges associated with incorporating new technologies. The course has served engineering majors as well as students at both the undergraduate and graduate level from other departments with an interest in the electric grid and with enough preparation to handle the quantitative assignments. I used the first edition of this book for my class, but had to supplement it with other resources to cover some of the more technical aspects. Over time, my accumulated lecture notes evolved into this substantially expanded second edition, which aims to serve as a reasonably complete stand-alone text for introductory engineering courses like mine.

To this end, some chapters were amended to cover more technical points and problem-solving tools, some material was reorganized, and seven new chapters were added. Along with more formal treatment and quantitative examples for many topics, new material in this second edition



includes Thévenin and Norton equivalents, symmetrical components, ZIP load models, transmission line analysis, transformer and generator modeling, load frequency control, power transfer limits, power electronics, measurement and data, and a summary chapter on generation and storage resources. Finally, it includes some end-of-chapter problems, with solutions made available separately through the publisher's website.

While meeting the needs of a rigorous engineering text, this second edition should not sacrifice accessibility for general audiences. It aspires to satisfy readers who think in mathematical terms, and those who don't. As a rule, conceptual explanations precede mathematical statements, and the more technical portions can be skipped without leaving the reader disoriented. Sections are extensively cross-referenced and intended to be modular. The idea is that the reader can open up the book to any page that piques their curiosity or answers a nagging question and be assisted in locating background information and relevant context elsewhere in the book. There are many plausible ways to organize the material—or likely some subset of it—for a course. Chapters need not be read or covered in sequence. Instructors should be able to select and tailor material to their purposes.

One major change in recent years is the availability of technical content on the Internet, including Wikipedia and YouTube tutorials. Especially for animated visualizations (say, rotating machines!), some of these resources can be immensely valuable. But aside from reliable quality control, what the Internet does not provide is coherent guidance and context. For autodidactic readers, this book aims to serve as a foundation and structure that will support them in the critical consumption and interpretation of other educational materials about electricity-related topics.

This is a great time for many more students, whether inside or outside traditional academic settings, to develop a passion for understanding electric power systems. The electric grid is central to our society, our economy, and our efforts to address global climate change. While being host to a shifting base of energy resources, including inverter-based generation, the infrastructure itself is in the process of being modernized with digital technology. Nobody yet can answer the question, “What does the grid of the future look like?” We urgently need diverse talents and skills applied to this vital problem area. My hope is that this book can make a helpful contribution.

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