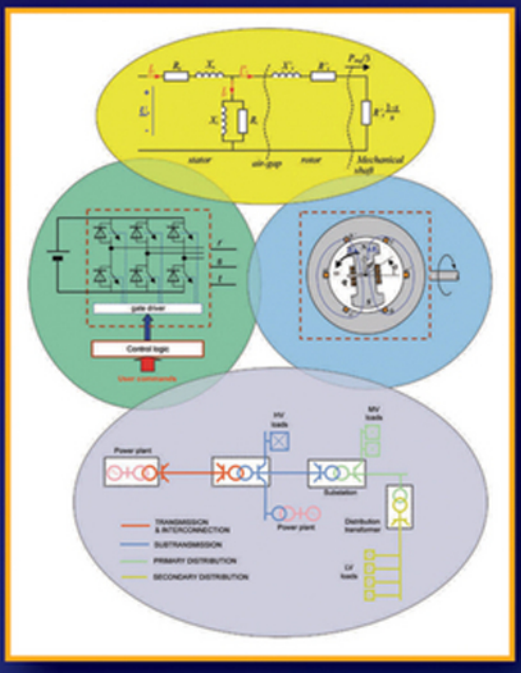
Fundamentals of Electric Power Engineering



MASSIMO CERAOLO
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IEEE Press
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FUNDAMENTALS OF ELECTRIC POWER ENGINEERING

From Electromagnetics to Power Systems

MASSIMO CERAOLO
DAVIDE POLI

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Library of Congress Cataloging-in-Publication Data:

Ceraolo, Massimo.
Fundamentals of electric power engineering : engineering: from electromagnetics to power systems / Massimo Ceraolo, Davide Poli.
pages cm
Summary: “Covers topics such as: circuits, electrical machines and drives, power electronics, power system basics. new generation technologies”– Provided by publisher.
Includes bibliographical references and index.
ISBN 978-1-118-67969-2 (hardback)
1. Electric power systems. I. Poli, Davide. II. Title.
TK1001.C444 2014
621.31–dc23

2013044541

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Everything should be made as simple as possible, but not simpler.

Albert Einstein

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PREFACE

Electrical engineering is a field of engineering that in general deals with the study and application of electricity, electronics, and electromagnetism. Depending on how it is intended in different areas of the world, it may cover a wide range of subfields, including electronics, digital computers, power engineering, telecommunications, control systems, and signal processing.

This broad range of fields of interest can be split into two main areas:

- what we could call *signal-oriented* electrical engineering, for which electric quantities (voltage, current, etc.) are used to carry signals—for example, inside TV sets or computers or through electromagnetic waves;
- what we could call *power-oriented* electrical engineering, for which electric quantities are used to manage and transfer power—for example, in power lines, electric machines, rectifiers, or inverters.

Indeed, from a practical point of view, these two kinds of electrical engineering are very different from each other. The approach to analysing applications is different; the physical objects that fulfil different functions tend also to be very different. For instance, while the dimensions of signal-oriented electric devices have shrunk by several orders of magnitude in the last decades (think of computers or mobile phones, for instance), the dimensions of apparatuses tend to be much more stable whenever large powers are involved (e.g., the size of a 100 kW electric motor or a 100 MW power station has not changed significantly).

Electric power engineering is a branch of industrial engineering, while signal electrical engineering is generally not considered as such.

University students of nonelectrical engineering, such as students of civil, mechanical, aerospace, chemical, or even control engineering, will be interested in power-oriented electrical engineering. Mechanical or aerospace engineers, for instance, should be able to understand in detail how an electric motor or an electric drive works. Civil engineers might need to understand how electrical installations are built and how the external power system feeding them operates. Basic information about the safety aspects of electricity might interest all of them.

This book aims to give university teachers support to teach nonelectrical engineering students all they need to know about basic electric phenomena, circuits, and electric machines and drives, as well as the basics of electric safety and an introduction to how large power systems are built and operated.

It might also be useful for professional engineers who want to have a source of updated, though concise, information of nearly everything that happens in power-oriented electrical engineering.

We have made every effort to explain each subject in the simplest way. However, in the case of more complex concepts, we have tried, rather than feigning simplicity, to illustrate them as clearly as possible. Taking our cue from Albert Einstein, we have adopted the approach of *making everything as simple as possible, but not simpler*.

This book tends to say things in a concise way. This is because we believe that this way it offers a stimulus to students: were we to describe each path of reasoning in detail, we would not stimulate the student's independent flow of reasoning.

In Chapters 3 and 4, special attention has been devoted to ensuring that a clear distinction is made between physical systems and their mathematical models. This is important, not only for the study of the topics in this book, but also as a lesson to students on how engineering proceeds: first we model reality, then we analyse the models. If the results of our analysis are not satisfactory, this might depend on the model we originally chose, and perhaps a more accurate version must be selected and used.

A few final comments:

- We have used graphic symbols, mathematical formulations, and even wording in compliance with the standards of the International Electrotechnical Commission. Details of this are in Chapter 1.
- We have tried to ensure that the exercises offer not only the chance to consolidate theoretical knowledge but also an opportunity for further learning. The reader is first led by hand through worked examples embedded in the text. At the end of Chapters 4–7 and 10–12 there are several exercises of increasing complexity and a solution is outlined for the least straightforward of these.

- At the end of some chapters we have added short biographies of the scientists who have given their names to the laws described in the chapter. Although very concise, these biographies offer some idea of the period and background of each scientist's discoveries. Whenever available, the correct pronunciation of the scientists' names is given, based on the International Phonetic Association Alphabet.

READERSHIP AND PREREQUISITES

This book is aimed at all students of engineering, with the exception of electrical engineering students (who require additional details of each topic). The book should also be very useful for nonelectrical qualified engineers, who may not have retained good support material from their student years or who may need to brush up on their knowledge of the fundamentals of electrical engineering without resorting to specialist books.

The most important prerequisite in order to take full advantage of the book is some knowledge of electromagnetics. The best results will be obtained easily by students who have already attended a university-level electromagnetics course. However, we have made every effort to make the book accessible to students who have only basic knowledge of electromagnetic phenomena from their secondary school studies. Chapter 2 will help these students to refresh their memory and to become acquainted with the symbols and approach used in the book.

LEVELS OF READING

This book caters to different levels of study. The most important example concerns electronic power conversion and Chapter 8. Electronic power conversion is widely used in electric drives and power systems. However, to fully understand it requires time. Although Chapter 8 contains a fairly lengthy description of how power electronics components are composed and operate, this chapter is not essential to an understanding of Chapters 10–12 (which deal with electric drives in addition to electric machines). Chapter 15 also deals with electronic converters in power systems, but, again, students are not required to have first studied Chapter 8. Needless to say, if there is time available in a university course to include Chapter 8, it follows that Chapters 10–12 and 15 can then be studied at a higher level of understanding.

The book also has some "more in depth" boxes. These contain extra information that is not essential for a clear understanding of the rest of the chapter to which they belong. "More in depth" boxes are included to trigger the curiosity of the reader, who can decide whether or not to read or study them.

ACKNOWLEDGMENTS

We would like to thank all our friends who have contributed to this project. In particular, we thank Luca Sani for his careful revision of the chapters on electric machines and drives.

MASSIMO CERAOLO
DAVIDE POLI

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PART I

PRELIMINARY MATERIAL

Introduction

The Fundamental Laws of Electromagnetism

Fundamentals of Electric Power Engineering: From Electromagnetics to Power Systems, First Edition.
Massimo Ceraolo and Davide Poli.
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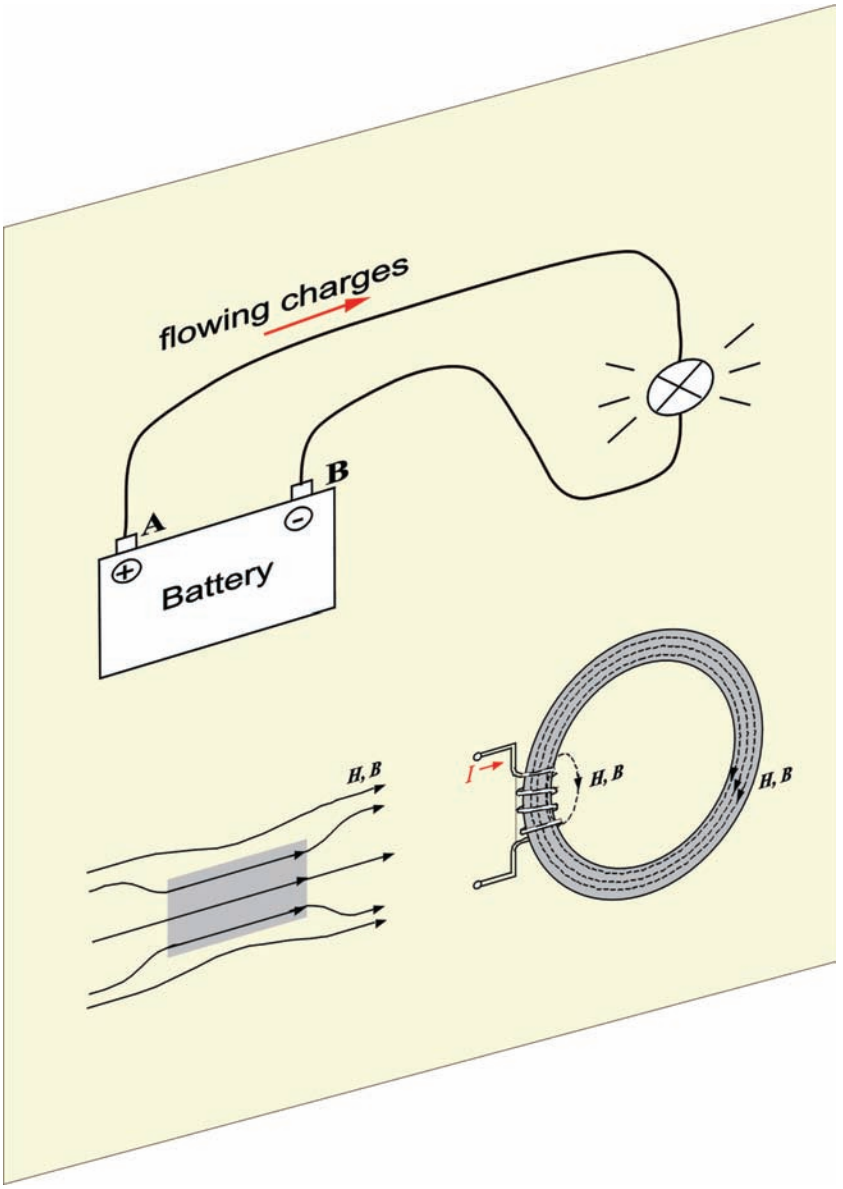
flowing charges
A
B
Battery
H, B
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H, B

1

INTRODUCTION

1.1 THE SCOPE OF ELECTRICAL ENGINEERING

It is universally agreed that Electrical Engineering is a branch of engineering that deals with the phenomena of electricity. Apart from this vague statement, however, there is no worldwide agreement on the actual scope of an electrical engineer. In particular, there are two main approaches:

- In some cases, electrical engineering is considered as encompassing those disciplines in which electrical quantities (voltages, currents) are used to transfer *signals* (e.g., in computers, radio and TV sets, etc.) and those in which electrical quantities are used to manage and transfer *energy* and *power* (electrical machines and lines, electrical household installations, etc.). This approach is, for instance, normally followed in North America.
- In other cases, electrical engineering is considered to be involved only when electrical quantities are used to *transfer* and *convert* energy and power. This approach is usually followed in Europe. This kind of electrical engineering is often called *electric power engineering*.

This book follows this second approach, hence its title. Generally speaking, the whole scope of Electric Power Engineering comprises everything needed to manage electric energy, from its generation to its final utilization.

Fundamentals of Electric Power Engineering: From Electromagnetics to Power Systems, First Edition.
Massimo Ceraolo and Davide Poli.
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The word "generation" might be a bit misleading since energy cannot, indeed, be generated: the term means production of electricity by conversion from other forms of energy. For instance, the electric alternators of large oil or gas power plants "generate" electricity by conversion from mechanical energy, in turn obtained by using other machines, like steam or gas turbines. Photovoltaic panels are another example of electricity generators: they produce electric energy through the conversion of solar radiation.

The final utilization of electricity very often involves another conversion; for example, the final energy form can be heat (in heaters or ovens) or mechanical energy (in industrial electric motors, in electric cars, etc.). There are cases, however, in which electric energy is used as such; the most significant example is for supplying computers or other electronic apparatuses.

Between generation and final utilization, electric energy can be transformed several times (for instance in power transformers, which raise the voltage while lowering the current and vice versa), and transferred for distances of up to hundreds or thousands of kilometres, by means of power lines.

Indeed, it will be seen in this book, especially in Part IV, that the more power to be transmitted, the higher the required voltage level. Therefore, the power system has low voltage (LV) parts (for instance, power in homes and offices is always LV), medium voltage (MV) parts (the alternators of large power plants generate power at MV level), and high voltage (HV) and extra high voltage (EHV) levels.

All these apparatuses, which convert or transfer energy, are therefore parts of a great system, one of the largest that mankind has ever built, that encompasses the generation, transformation, transmission, distribution, and utilization of electric energy and is called a *power system*. All this can be visualized in the diagram in Figure 1.1, which shows the main functions of a power system along with the different energy forms involved.

A typical situation includes electricity generation in power plants, transformation toward high voltage in transformers, transmission toward load centres, transformation into medium or low voltage, distribution to single loads, and conversion to final usage. In the figure, the term "Bulk Generation" refers to large-scale centralized facilities, which inject their production into the transmission grid. "Distributed Generation" (DG) is instead composed of a large number of small-scale power plants, installed

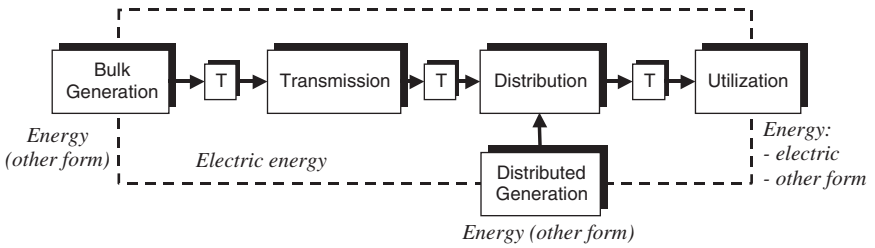

FIGURE 1.1. General structure of a (full) electric power system (T blocks indicate transformation made by power transformers).

close to the final users and directly connected to a distribution network. In the same figure, "T" represents the transformation performed by power transformers; other forms of electric-to-electric transformation are usually made inside the biggest blocks; for instance, utilization could involve a combined rectifier/inverter pair that allows maximum flexibility to the electric motor speed variation. The DG can be provided with power transformers, depending on the voltage of the generator and of the receiving network.

> The outline of the electric power system shown in Figure 1.1 is much simplified, in line with the aims of this chapter. A more detailed and accurate description of the electric power system will be given in Part IV of this book.

When a *power system* is mentioned, what is usually intended is one of the very large networks that link power plants (large or small) to loads, by means of an electric grid that may be as large as a continent, such as the whole of Europe or North America. A power system, in this sense, extends from a very large power plant (e.g., having thousands of MW of generated power) right up to either the lamp that might now be lit on your table or the sockets giving electricity to loads from the nearest wall! Smaller power systems could be made of sections of a larger system. Examples are shown in Figure 1.2.

Figure 1.2a contains several components (breaker, cable, motor), which operate together and are connected to a feeding network. The subsystem represented in

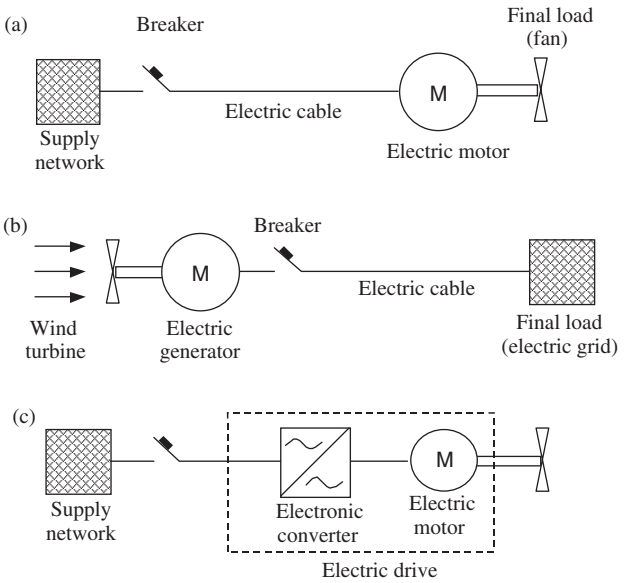

FIGURE 1.2. An electric power system fed by a supply network: a partial electric power system.

Figure 1.2a could be one of the final users of the electric energy in the utilization block shown in Figure 1.1.

Figure 1.2b contains many of the same components as Figure 1.2a, but its purpose is totally different. Instead of the fan, we have a wind turbine, which has some similarities to a large fan, but with the power flow reversed: it receives power from an air flow to produce mechanical energy, while a fan uses mechanical energy to obtain an air flow. The subsystem represented in Figure 1.2c could be one of the small power plants contained in the block of distributed generation shown in Figure 1.1.

Finally, Figure 1.2c contains a variation of the system in Figure 1.2a. The presence of the electronic converter allows much greater flexibility in the use of the electric motor and, in particular, allows variable speed operation of the fan. The electronic converter modifies electrical quantities, thus transforming *electricity into electricity*, differently from motors and generators that convert, respectively, mechanical energy into electricity and vice versa. Electronic converters tend to be increasingly present in power systems, even though they are not in evidence in the simplified diagram in Figure 1.1.

A very large number of power systems like the ones shown in Figure 1.2 operate only when connected to the mains—for example, a feeding network.

A power system such as that shown in Figure 1.1 is called a *full power system*, since its operation does not require feeding points from other electricity sources and the produced electricity is supplied to loads.

Power systems that are fed instead by an external electricity source or that produce (by conversion from other sources) electricity and convey it to a larger grid are called *partial power systems*.

There are also full power systems that are much smaller than the large power systems (such as those of Europe or North America) discussed earlier, but still, on a smaller scale, perform the basic functions of generation, distribution, and utilization of energy. An example is the small system created to feed a building yard, along with the cables and loads. Another example is the electric system on board electric cars: battery, inverter, motor, and accessory parts.

It should be stressed that a power system is basically composed of power lines and apparatuses that convert energy (*energy converters*). Power lines are relatively simple in their inner structure and do not need a great deal of explanation, especially in an introductory book.

The energy converters that are of interest to electric power engineering can be divided into two categories:

- Apparatuses for converting electricity into other forms of energy and vice versa. With reference to Figure 1.1, these are usually at the source of the system ("Bulk Generation" block), where electric energy is produced through conversion from other forms of energy and at its end ("Utilization" block), where electricity, when not used as such, is converted into other forms. Of great importance are the apparatuses that convert electricity into mechanical energy and vice versa—that is, those used for *electromechanical-energy conversion* (electromechanical converters).

- Conversion from electrical energy into electrical energy with different characteristics—that is, *electric-to-electric energy conversion*. This kind of conversion is carried out by power transformers (like those shown in Figure 1.1), but also in other situations. For instance, electricity can be converted from alternating current (AC) into direct current (DC) (using rectifiers) or from DC into AC (using inverters), and so on. This kind of conversion, not explicitly shown in the simplified diagram of Figure 1.1, is becoming increasingly frequent in power systems; each of the larger blocks in Figure 1.1 can contain electric-to-electric conversion apparatuses. For instance, an electric motor is often fed by an inverter, to form a system called *electric drive*.

1.2 THIS BOOK'S SCOPE AND ORGANIZATION

Nonelectrical engineers do not need to know the details of electric power systems; however, they need to master its basic functions in order to be able to exploit their application and to effectively collaborate with electrical engineers in more complex cases.

Since this book is intended for use in courses of one or two semesters, the authors have had to make important decisions on how deeply each topic should be dealt with. Our final decision was to focus on showing (a) how a physical system can be modelled using circuits and (b) how circuits can be analysed. Once readers have gained the ability to "solve" circuits—that is, to numerically compute currents, voltages, and power—they will have gained sufficient knowledge of the phenomena in any electric device; at that point, the way has been paved for learning more about electric machines, drives, and power systems.

To pursue its objectives, the book has been divided into the following four parts:

Part I: Preliminary Material. This part contains two very different chapters, both of which are introductory to the book's core material. Chapter 1 includes miscellaneous topics such as a discussion of the very meaning of electrical (or electric power) engineering, as well as an overview of the scope and organization of the book. Chapter 2, on the other hand, creates a bridge between the core material of this book and the student's previous knowledge. It is organized into two levels, and students can select the one most appropriate to their previous knowledge of electromagnetism.

Part II: Electric circuit Concept and Analysis. The main purpose of this part, as mentioned previously, is to show readers how to handle electric circuits. For this, we have adopted an innovative approach: readers will learn that circuits are mathematical/graphic tools to model physical systems operating with electric quantities. We will show that, because they are models, the results we obtain from mathematically solving circuits are accurate only to the extent to which they correctly model physical systems. We will also explain that they are zero-dimensional models, while actual systems are distributed-parameter, that is, three-dimensional. This explanation is useful not only for building a sound base

of electrical engineering knowledge, but also as a significant example of how engineering is practiced in all of its fields.

Part III: Electric Machines and Power Converters. We saw in the previous paragraph that electric power systems contain several apparatuses to convert energy. These are the main subjects of Part II of this book.

This part combines three disciplines that are traditionally distinct: *electric machines* (machines for electromechanical conversions, plus the power transformer), *power electronics* (dealing with electric-to-electric conversion, different from that of power transformers), and *electric drives*.

The aim is to interpret the modern world, where these disciplines are strictly related to each other, and to present information in the form best suited to readers of this book, whether or not they are electric engineering students.

Part IV: Power Systems Basics. The description of power systems in Section 1.1 is very concise. Depending on how this book is used, more detailed information about the whole electric power system may be required. This is given in Part IV of the book, which contains (a) a description of the structure and operation of the system and (b) basic information about the risks of electricity for livestock and about how to prevent accidents.

Since this book is intended for courses of one or two semesters, some parts have been written in such a way that they can be omitted for shorter programmes.

Each chapter of the book starts with a "For the Instructor" box explaining the approach to be followed, along with (whenever possible) advice as to what can be safely omitted in shorter courses.

Examples of one-semester courses that can be taught using this book are:

- A course subsequent to a circuit course. In this case, Part II can be omitted and the material for the course can be drawn from Parts III and IV.
- A one-semester course on the fundamentals of electric power engineering, as the only electrical engineering course in a programme. In this case, Chapters 8, 14, and 15 can be totally omitted. If further reductions are necessary, Chapter 13 can also be omitted.

1.3 INTERNATIONAL STANDARDS AND THEIR USAGE IN THIS BOOK

1.3.1 International Standardization Bodies

Since it is written in the third millennium, this must be a *global* book. It is therefore intended for any reader from anywhere in the world. This means that the graphics and conventions for drawings and writing equations must be independent, as far as possible, of individual country preferences.