ELECTRICAL ENERGY CONVERSION AND TRANSPORT
A complete list of titles in the IEEE Press Series on Power Engineering appears at the end of this book.
ELECTRICAL ENERGY
CONVERSION AND
TRANSPORT

An Interactive
Computer-Based
Approach

SECOND EDITION

George G. Karady
Keith E. Holbert

IEEE PRESS SERIES ON POWER ENGINEERING

Mohamed E. El-Hawary, Series Editor

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This book provides material essential for an undergraduate course covering the fundamental concepts of electric energy conversion and transport—a key branch of electrical engineering. Every electrical engineer should know why a motor rotates and how electric energy is generated and transported. Moreover, the electric power grid is a critical part of any national infrastructure. The maintenance and development of this vital industry requires well-trained engineers who are able to use modern computation techniques to analyze electric systems and understand the theory of electrical energy conversion.

Engineering education has improved significantly during the last decade due to advancements in technology and the widespread use of personal computers. Engineering educators have also recognized the need to transform students from passive listeners in the classroom to active learners. The paradigm shift is from a teacher-centered delivery approach to that of a learner-centered environment.

Computer-equipped classrooms and the computer aptitude of students open up new possibilities to improve engineering education by changing the delivery method. We advocate an interactive presentation of the subject matter, in which the students are intimately engaged in the lectures. This book is designed to support active learning, especially in a computer-based classroom environment. The computer-assisted teaching method increases student mastery of the course material as a result of their participation in its development. The primary goal of this approach is to increase student learning through their dynamic involvement; secondarily, students’ interest in power engineering is enhanced through their own attraction to computer technologies. This interactive approach provides students with a better understanding of the theory and the development of solid problem-solving skills.

As many universities and instructors firmly favor the use of one software package versus another, we leave the instructor to freely choose the software employed. This book applies Mathcad®, MATLAB®, and PSpice® throughout, and as such appendices introduce the basic use of these three programs. Less emphasis is paid on dedicated power engineering simulation tools due to the extended time and effort needed to learn such specialized software. In contrast, general-purpose programs permit students to focus more on the connection between the theory and computational analysis.

The extensive computer use permits analyzing complex problems that are not easily solvable by hand computations with calculators. In fact, the experienced instructor will find that their students are able to work complicated problems that were previously too difficult at this level. This is a significant modernization of the classical topic
of electric energy conversion. Students familiar with the application of modern computational techniques to electrical power applications are better prepared to meet the needs of industry.

This textbook facilitates interactive teaching of the subject material. Through the students’ active participation, learning is enhanced. The advantages of this method include:

1. Better understanding of the subject because the students participate in its development;
2. Development and advancement of problem-solving skills;
3. Simultaneously learning the practical engineering application of the material using computerized methods accepted by industry;
4. Extending the students’ attention span and maintaining their interest during the lecture—this method eliminates boredom that inhibits students toward the end of most lectures;
5. The students analyze the results and draw the conclusions, thus enhancing learning; and
6. The students gain experience with general-purpose mathematical and scientific computing programs frequently utilized by industry.

The authors recommend the textbook to faculty who want to modernize their electric power curriculum. The book is also intended for engineers interested in increasing their knowledge of electrical power and computer-based problem-solving skills. Such knowledge may open up or expand career opportunities in the electric power industry.

This second edition has inserted an additional chapter by moving and substantially expanding the treatment of electric power generation. Furthermore, the technical coverage of all the chapters has been expanded with the addition of material in areas such as the intelligent (smart) grid, symmetrical components, long transmission lines, induction generators, flexible alternating current (ac) transmission systems, buck and boost converters, and the protection of transformers, generators, motors, and transmission lines.

HOW TO USE THIS BOOK EFFECTIVELY

This textbook differs noticeably from others in that classical derivations are combined with numerical examples. In doing so, the reader is not only provided with the general analytical expressions as the theoretical development proceeds, but additionally, the concurrent numerical results assist the student in developing a sense for the correct magnitude of various parameters and variables. The authors have found Mathcad particularly well suited to this approach. Regardless of which software the reader chooses to use, we recommend that the reader first familiarize himself or herself with the information in Appendix A (“Introduction to Mathcad”), since Mathcad expressions are utilized throughout the text. This will allow the reader to reap the full benefits of this delivery method. Although this book employs Mathcad, MATLAB, and PSpice, other
computational software can also be utilized effectively—this includes HSpice, Maple, Mathematica, and even spreadsheet packages such as Excel.

The authors suggest a course syllabus ordering that parallels the textbook. The textbook may be used for either a single semester or a two-semester course. For instance, Chapter 2 (“Electric Generating Stations”) can be skipped without significant loss of continuity for those instructors and readers who wish to do so. Similarly, Chapter 3 (“Single-Phase Circuits”) represents a review of basic circuit analysis, albeit in the context of computer-based analysis, which is generally a prerequisite to a course such as this. Suggested timelines for one and two three-semester-hour courses are outlined in the tables below.

<table>
<thead>
<tr>
<th>One-Semester Course</th>
<th>Two-Semester Course</th>
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<tr>
<td><strong>Week</strong></td>
<td><strong>Topic</strong></td>
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<tr>
<td>1</td>
<td>Chapter 1: Electric Power Systems</td>
</tr>
<tr>
<td>2</td>
<td>Chapter 3: Single-Phase Circuits (emphasizing Section 3.4 and Section 3.5)</td>
</tr>
<tr>
<td>3–4</td>
<td>Chapter 4: Three-Phase Circuits (omit Section 4.6, Section 4.7, and Section 4.8)</td>
</tr>
<tr>
<td>5–6</td>
<td>Chapter 5: Transmission Lines (omit Section 5.5.3, Section 5.5.4, Section 5.7.3, Section 5.8.2, and Section 5.9)</td>
</tr>
<tr>
<td>7–8</td>
<td>Chapter 6: Electromechanical Energy Conversion (omit Section 6.1.5, Section 6.4, and Section 6.5)</td>
</tr>
<tr>
<td>9–10</td>
<td>Chapter 7: Transformers (omit Section 7.2.3, Section 7.3.7, Section 7.3.8, and Section 7.3.10)</td>
</tr>
<tr>
<td>11–12</td>
<td>Chapter 8: Synchronous Machines (omit Section 8.3.4 and Section 8.5)</td>
</tr>
<tr>
<td>13–14</td>
<td>Chapter 9: Induction Machines (omit Section 9.3.6, Section 9.5, and Section 9.6)</td>
</tr>
<tr>
<td>15</td>
<td>Chapter 10: DC Machines (omit Section 10.3)</td>
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<td>27–30</td>
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</table>

Here, we present a brief overview of the suggested instructional technique for a representative class period. The basis of the approach is that after introducing the hardware and theory, the basic formulae and their practical application are developed jointly with the students using computers. Having divided the particular topic into sections, the instructor outlines each step of the analysis, and students then proceed to develop the
equation(s) using his or her computer. While students are working together, the instructor is free to move about the classroom, answer student questions, and assess their understanding. After allowing students sufficient time to complete the process and reach conclusions, the instructor confirms the results and the students make corrections as needed. This procedure leads to student theory development and analysis of performance—learner-centered education.

Through computer utilization, a seamless integration of theory and application is achieved, thereby increasing student interest in the subject. The textbook derivation of the system equations and the operational analyses are presented using numerical examples. The numerical examples reinforce the theory and provide deeper understanding of the physical phenomena. In addition, computer utilization provides immediate feedback to the student.

Again, paralleling the classroom activities, each chapter first describes the hardware associated with that topic; for example, the construction and components are presented using drawings and photographs. This is followed by the theory and physics of the chapter material together with the development of an equivalent circuit. The major emphasis of the chapters is operational analysis. The questions at the end of each chapter are open ended to promote deeper investigation by the reader.

The interactive method is also applicable in a self-learning environment. In this case, the text outlines each step. The reader is encouraged to initially ignore the solution given in the text, but instead derive the equations and calculate the value using his or her computer. The reader then compares his or her results with the correct answers. This process is continued until the completion of the instructional unit.

ACKNOWLEDGMENTS

The second edition of this textbook has benefited from the constructive criticism of others. The authors would like to express their sincere gratitude to the late Professor Richard Farmer, who was a member of the National Academy of Engineering, for his thorough review of both the first and second editions of the book manuscript. We also humbly thank the Institute of Electrical and Electronics Engineers (IEEE) Education Society for its recognition of the merits of computer-based active learning through the IEEE Transactions on Education Best Paper award to us.

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Keith E. Holbert
Tempe, AZ
April 2013

The purpose of the electric power system is to generate, transmit, and distribute electrical energy. Usually, a three-phase alternating current (ac) system is used for generation and transmission of the electric power. The frequency of the voltage and current is 60 Hz in the United States and some Asian countries, and is 50 Hz in Europe, Australia, and parts of Asia. Sometimes, exceptions are the rule, as in the case of Japan for which the western portion of the country is served by 60 Hz, whereas the eastern side operates at 50 Hz.

In the 1880s, during the development of electricity distribution, the pioneers’ choice as to whether to use direct current (dc) or ac was contested. In particular, Thomas Edison favored dc, whereas both George Westinghouse and Nikola Tesla supported ac. AC transmission won this so-called War of the Currents due to the ability to convert ac voltages from higher to lower voltages using transformers and vice versa. This increased ac voltage permitted electric energy transport over longer distances with less power line losses than with dc.

The ac electrical system development started in the end of the 19th century, when the system frequency varied between 16.66 and 133 Hz. A large German company introduced 50 Hz frequency around 1891, after flickering was observed in systems
operating at 40 Hz. In 1890, the leading U.S. electric company, Westinghouse Electric, introduced the 60 Hz frequency to avoid arc light flickering at lower frequencies.

The major components of the power system are:

- power plants, which produce electric energy,
- transmission and distribution lines, which transport the electric energy,
- substations with switchgear, which transform voltages, provide protection, and form node points, and
- loads, which consume the energy.

Figure 1.1 shows the major components of the electric power system.

This chapter describes the construction of the electric transmission and distribution system; discusses the substation equipment, including circuit breakers (CBs), disconnect switches, and protection; and describes the low voltage distribution system, including residential electric connections.

1.1. ELECTRIC NETWORKS

Power plants convert the chemical energy in coal, oil, or natural gas, or the potential energy of water, or nuclear energy into electric energy. In fossil nuclear power plants, the thermal energy is converted to high-pressure, high-temperature steam that drives a turbine which is mechanically connected to an electric generator. In a hydroelectric plant, the water falling to a lower elevation drives the turbine-generator set. The
generator produces electric energy in the form of voltage and current. The generator voltage is around 15–25 kV, which is insufficient for long-distance transmission of the energy. To permit long-distance energy transportation, the voltage is increased and, simultaneously, the current is reduced by a transformer at the generation station. In Figure 1.1, the voltage is raised to 500 kV, and an extra-high-voltage (EHV) line carries the energy to a faraway substation, which is usually located in the outskirts of a large town or in the center of several large loads. For example, in Arizona, a 500 kV transmission line connects the Palo Verde Nuclear Generating Station to the Kyrene and Westwing substations, which supply a large part of Phoenix (see Fig. 1.2).

The electric power network is divided into separate transmission and distribution systems based on the voltage level. The system voltage is described by the
root-mean-square (rms) value of the line-to-line voltage, which is the voltage between phase conductors. Table 1.1 lists the standard transmission line and the subtransmission voltages. The line voltage of the transmission systems in the United States is between 115 and 765 kV. The ultra-high-voltage lines are generally not in commercial use; although in 2011 China started the operation of a 392 miles (630 km) long 1000 kV ultra-high-voltage ac line with a maximum capacity of 3000 MVA. The 345–765 kV transmission lines are the EHV lines, with a maximum length of 400–500 miles. The 115–230 kV lines are the high-voltage lines with a maximum length of 100–200 miles. The high-voltage lines are terminated at substations, which form the node points on the network. The substations supply the loads through transformers and switchgear. The transformer changes the voltage and current. The switchgear protects the system. The most important part of the switchgear is the circuit breaker, which automatically switches off (opens) the line in the event of a fault. Distribution line lengths are around 5–30 miles (8–48 km) with voltages at or below 46 kV.

1.1.1. Transmission Systems

The transmission system transfers three-phase power from the electric generating stations to the load centers. As an example, Figure 1.2 sketches a typical electrical network that supplies the metropolitan areas in Arizona and interconnects to the power systems of neighboring states. In this system 500, 345, 230, and 115 kV lines connect the loads and power plants. Note that the system in Figure 1.2 is a loop network, where at least two lines supply each load and the generating stations are connected to the network with three, or even four, lines. This arrangement assures that the failure of one line does

<table>
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<th>Name or Category</th>
<th>Nominal Voltage (kV)</th>
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<td></td>
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<td>500</td>
</tr>
<tr>
<td></td>
<td>765</td>
</tr>
<tr>
<td>Ultra-high voltage</td>
<td>1000 (China)</td>
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</table>

\[a\] ANSI C84.1-1995, Voltage ratings for electric power systems and equipment (60 Hz).
\[b\] ANSI C92.2-1987, Alternating-current electrical systems and equipment operating at voltages above 230 kV nominal—preferred voltage ratings.
not produce an outage. The electric system in the United States must withstand at least a single contingency, which means that loads and generators at a specific node are connected by at least two independent power system paths (e.g., power lines).

In addition, the map shows that 500, 345, and 230 kV lines interconnect the Arizona (AZ) system with California, Nevada, Utah, and New Mexico. These interconnections provide instantaneous assistance in cases of lost generation and line outages in the AZ system. Interconnection also permits the export or import of energy depending on the need of the area.

In open areas, overhead transmission lines are used. Typical examples are the interconnection between towns or a line running along a road within a city. In large, congested cities, underground cables are frequently used for electric energy transmission. An underground system has significantly higher costs but is environmentally and aesthetically preferable. Typically, the cost per mile of the overhead transmission lines is 6–10 times less than the underground cables.

At an EHV substation, transformers reduce the voltage to 230 or 345 kV. In Figure 1.1, a 230 kV high-voltage transmission line transports the energy to a high-voltage substation, typically located on the outskirts of the town. The voltage is further reduced at the high-voltage substation. Typically, 69 kV subtransmission lines connect the high-voltage substation to local distribution stations, which are located in the town. The subtransmission lines are built along larger streets.

In addition to the ac transmission system, high-voltage dc (HVDC) lines are used for long-distance, large energy transmission. Figure 1.3 depicts the main components of an HVDC system. The HVDC link contains two converters interconnected by a dc transmission line. The converters are electronic devices able to operate as a rectifier or as an inverter. Figure 1.3 shows that both converters are divided into two units connected in series. The middle point of the series-connected units is grounded. If the power is transferred from Converter 1 to Converter 2, then Converter 1 functions as a rectifier and Converter 2 acts as an inverter. The rectifier mode converts ac voltage to dc, and the inverter mode changes the dc voltage to ac. The dc transmission line typically has only two conductors, a positive (+) conductor and a negative (−) conductor.

HVDC is used to transport large amounts of energy over a long distance; typically, a dc line is not economical for less than around 300 miles (~500 km). A representative

![Main components of a high-voltage dc (HVDC) transmission system.](image_url)
example for HVDC transmission is the Pacific DC Intertie, which is an 846 miles (1362 km) long HVDC transmission line between the Celilo Converter Station at The Dalles, Oregon and the Sylmar Converter Station north of Los Angeles, California. The line has two conductors with a maximum operating voltage of \( \pm 500 \) kV between the conductors and the ground; the maximum capacity of the Intertie is 3100 MW.

The large capacitance of the ac cables limits the power transfer through the cable, because the cable must carry both the load and the capacitive current. Using dc eliminates the capacitive current, which justified building HVDC underwater cable systems all over the world. One of the frequently discussed systems is the HVDC cable interconnection between the United Kingdom (UK) and France. This system is capable of transporting 2000 MW through a 45-km long HVDC underwater cable. Another advantage of the HVDC system is the elimination of the inductive voltage drop.

### 1.1.2. Distribution Systems

The distribution system uses both three-phase and single-phase networks. The larger industrial loads require a three-phase supply. A subtransmission line or a dedicated distribution line directly supplies large industrial plants and factories. A single-phase system delivers power to ordinary residences.

The voltage is reduced at the distribution substation, which supplies several distribution lines that deliver the energy along streets. The distribution system voltage is less than or equal to 46 kV. The most popular distribution voltage in the United States is the 15 kV class, but the actual voltage varies. Typical examples for the 15 kV class are 12.47 and 13.8 kV. As an example, in Figure 1.1, a 12 kV distribution line is connected to a 12 kV cable, which supplies commercial or industrial customers. The graphic also illustrates that 12 kV cables supply the downtown area in a large city.

A 12 kV cable can also supply the residential areas through step-down transformers, as shown in Figure 1.1. Each distribution line supplies several step-down transformers distributed along the line. The distribution transformer, frequently mounted on a pole or placed in the yard of a house, reduces the voltage to 240/120 V. Short-length low-voltage lines power the homes, shopping centers, and other local loads. One distribution transformer can serve six to eight residential customers.

### 1.2. TRADITIONAL TRANSMISSION SYSTEMS

The North American electric power system is presently divided into four isolated systems referred to as interconnections. The interconnections, as indicated in Figure 1.4, are:

1. the Eastern Interconnection,
2. the Electric Reliability Council of Texas (ERCOT) Interconnection,
3. the Western Interconnection, and
4. the Québec Interconnection.
The four systems are connected through regulated back-to-back HVDC links, HVDC transmission lines, and regulated ac tie lines. A back-to-back HVDC link is an HVDC system without a transmission line, that is, it contains two directly interconnected converters. High-power electronic devices can regulate the power flow through the ac line. In the last two decades, the industry developed the flexible ac transmission system (FACTS), which is able to electronically control the operation of a high-voltage ac line. Chapter 11 discusses both HVDC and FACTS systems.

The regulated connections permit energy transfer in normal operation and in case of an emergency. They block system oscillations and cascading outages. As examples, ERCOT in Texas uses back-to-back HVDC links, and the Western Electricity Coordinating Council (WECC) connects to the Eastern Interconnection through powerful HVDC transmission ties.
1.2.1. Substation Components

The connection diagrams for actual power networks are confidential material because of security concerns. Figure 1.5 presents the Institute of Electrical and Electronics Engineers (IEEE) published 118 bus power flow test case network, which is the one-line diagram of a typical three-phase system illustrating the nature of an actual power network. The diagram shows a loop network that should withstand at least a single contingency, but in most cases will withstand multiple contingencies. This implies that at least two transmission lines supply each bus.

Figure 1.6 details a portion of the system, where each transmission line is connected to a substation bus, which is a node point of the system. There are simple load buses, like the Pokagon bus, which is supplied by only two lines (i.e., meets single-contingency requirement). Other buses have both load and generation like Twin Branch with seven connecting lines—it may withstand six outages. A third type of bus has load, generation, and parallel connected capacitor, or synchronous condenser, for example, New Carlisle. The capacitor is a switched unit, which is used at high load to produce reactive power and reduce voltage drop. Similarly, switched inductive load is connected in parallel to selected buses to reduce overvoltages in case of light loading. A synchronous condenser is a rotating device, like a generator, which produces or absorbs reactive power (vars). It can be permanently connected to the system and regulates voltage by producing or absorbing vars. A synchronous condenser can be used instead of a capacitor. At the Olive substation in Figure 1.6, a regulating autotransformer
interconnects the substation with the lower portion of the network. This transformer regulates the voltage within a ±10% range. The transformer neutral point may be grounded through a reactance to reduce the ground fault-produced short circuit current.

Other components not shown include:

- switched or electronically controlled series capacitors that are inserted in selected transmission lines to compensate for the line inductance and reduce voltage drop, and
- CBs, which are protecting the system and switch off the line in case of short circuit.

1.2.2. Substations and Equipment

Substations form the node points of the electric system. Figure 1.7 pictures a typical distribution substation. The major role of substations is to distribute the electric energy and provide protection against faults on the lines and other equipment. Figure 1.1 reveals three types of substations that are used:

1. EHV substations (500/230 kV);
2. high voltage substations (230/69 kV); and
3. distribution substations (69/12 kV).
Although the circuit diagrams of these substations are different, the general circuit concept and major components are the same. Figure 1.8 presents a conceptual diagram for an EHV substation. That circuit is frequently called the “breaker-and-a-half bus scheme.” The rationale behind the name is that two lines have three CBs.

The primary substation equipment is as follows:

The CB is a large switch that interrupts load and fault currents. The fault current automatically triggers the CB, but the CB can also be operated manually. A CB has a fixed contact and a moving contact placed in a housing that is filled with gas or oil. Sulfur hexafluoride (SF$_6$) gas is the most common. Figure 1.9 illustrates a simplified contact arrangement for a typical breaker. In the closed position, the moving contact is inside the tubular fixed contact. Strong spring loading assures low contact resistance in the closed position. The switch is operated by pulling the moving contact out of the tubular fixed contact. The opening of the switch generates arcing between the contacts. The simultaneous injection of high-pressure SF$_6$ blows out the arc. Figure 1.10 demonstrates the operating principle for an actual CB. The CB has two tubes serving as fixed contacts (marked 1, 2, and 9) placed in a porcelain housing and a moving part with sliding contacts (3, 8, and 5), which connect the two fixed parts when the breaker is closed (Scene 1). The breaker is filled with SF$_6$ gas, which has high dielectric strength. The opening of the breaker drives the moving part downward (Scene 2). First, contact 3 separates and the moving contact compresses the SF$_6$ gas in chamber 7. This is followed by the separation of the main contact 5. The opening of contact 5 produces arcing between 4 and 5, and simultaneously initiates the fast, jet-like flow of the compressed SF$_6$, as portrayed by the small arrows in Scene 3. The SF$_6$ jet blows out the arc and interrupts the current (Scene 4).

The industry uses two types of CBs: live-tank and dead-tank breakers. In a live-tank breaker, insulators support the breaker, and the breaker is placed in a horizontal porcelain housing and insulated from the ground. Figure 1.11 presents a live-tank breaker. The switch is in the crossarm. The vertical porcelain column insulates the