# POWER ELECTRONICS STEP-BY-STEP

## DESIGN, MODELING, SIMULATION, AND CONTROL

Weidong Xiao

McGraw Hill

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**Power Electronics Step-by-Step: Design, Modeling, Simulation, and Control**

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**To my son, William, and my daughter, Emily**

## About the Author

**Weidong Xiao** is Associate Professor in the School of Electrical and Information Engineering and the Centre for Future Energy Networks at the University of Sydney. His research involves modeling, design, simulation, and control of power electronics with focus on photovoltaic power systems. Dr. Xiao has authored one book and hundreds of technical papers and is on an editorial board at IEEE.

# Contents

# Preface

Power electronics has drawn significant attention in recent years because of the trend toward modern electrical systems, the variety of load profiles, and the high demand for integrating renewable energy. Although there are quite a few books on the subject available for use in academia and industry, there is a lack of proper guidebooks for beginners and self-learners to learn modern power electronics efficiently. Traditional power electronics instructors focus on AC/DC and AC/AC conversion because AC has been dominant among applications since the 1880s. For example, many books put great emphasis on the analysis and design of various AC/DC rectifiers using either diode or thyristor bridges, usually with the consideration of all kinds of load profiles. However, some topologies have been phased out due to stricter power quality requirements and limited functionality. The latest power electronics relies on active switching technologies using modern power semiconductors. One distinguishing characteristic of this book is the focus on the latest technologies and solutions.

The topologies for non-isolated DC/DC conversion are introduced at the beginning to demonstrate the switching concept, which is fundamental in power electronics. The concept is essential for learners because an increasing proportion of generation and load units is based on DC instead of AC. In particular, one chapter is dedicated to bidirectional DC power flow devices, which are widely used for rechargeable batteries, ultracapacitors, and solid-state transformers. Throughout the book, the instructions for each important subject in power electronics are given within a clear framework. The step-by-step approach is aimed at helping readers build up their knowledge progressively. For example, the knowledge of DC/AC (Chap. 5) and AC/DC (Chap. 6) conversion naturally leads to the discussion of galvanic isolated DC/DC converters (Chap. 7) since many topologies are based on the integration of both conversion stages, which finally join together as DC/AC/DC configurations with isolation transformers. The insights of the step-by-step approach come from the author's self-learning and teaching experience in power electronics and renewable power systems.

Dynamic modeling methods are properly categorized into multiple classes, including switching, averaging, and small-signal models, following the scales of linearity from highly nonlinear to piecewise linear. The switching dynamics leads to the development of detailed simulation models that are only based on basic blocks in MATLAB/Simulink, which is a commercial software widely available in universities. In particular, averaging dynamic modeling mostly leads to switching-agnostic models that can be utilized for fast simulation and nonlinear control measures. It has been proven effective in simulating long-term operations of a system with a large number of power converters and distributed generation units. Moreover, the final phase of dynamic modeling features linearized mathematical functions, based on dynamic analysis and linear control theory. For a closed-loop controller design, the technique of affine parameterization is introduced, which translates controller parameters to stability and performance. The step-by-step approach allows readers to understand the basics of system simulation and to bridge the gap between linear control theory and power electronics.

This book can serve as a reference book as well as the textbook in a senior-level university course related to the subject of power electronics. It also covers practical design subjects that can be very useful for readers in industry who seek to master the subject matter through self-study or professional training. Familiarity with the fields of electronics, signal theory, and linear control engineering is recommended so as to fully benefit from this book.

## Key Features

This book is comprehensive in covering the fundamental subjects in modern power electronics and control engineering. The book is organized as follows:

- The common platforms and tools for developing power electronics are introduced at the beginning.
- A comprehensive classification of power electronics applications is presented in terms of signal waveforms, power flow directions, and voltage levels.
- One important feature of this book is the emphasis on computer-aided analysis, design, and evaluation. Without losing generality, all simulation models are built and mathematical analyses are carried out using the fundamental blocks in Simulink.
- Gate drivers for power switches, which are essential for modern power electronics, are covered.
- The book also covers the topologies used for bidirectional DC/DC conversion, which has been widely adopted in industry because of the increasing usage of energy storage, such as rechargeable batteries.
- Modeling for simulation follows a modular and step-by-step approach such that a converter system is divided into individual blocks, including the power train, low-pass filtering, load, modulation, and control. The development follows the operational principle and creates a clear framework that makes it easy to understand, construct, and debug.
- Simulation models are built for most converter topologies and related modulation methods for readers to follow.
- A dedicated chapter is provided to demonstrate the averaging technology for modeling and simulation purposes. The averaging methodology is general and covers not only continuous conduction mode but also discontinuous conduction mode.
- The development of mathematical models for dynamic analysis and controller synthesis is separate from the discussion on converter simulation. Linearization and small-signal methodology are utilized to mathematically construct linear

models to accommodate the well-established linear control theory for the analyses of damping, speed, stability, and robustness.

- Most chapters provide a significant number of practical examples in the form of case studies in order to demonstrate and verify the design. Readers can duplicate the results through various computer-aided design and analysis platforms, which also provide a systematic way to develop and evaluate new systems.
- Abundant photos, diagrams, graphs, equations, and tables appear throughout the book for a clear explanation of the subject matter. A significant number of flowcharts have been drawn to show the procedures of system design as well as component selection in a step-by-step manner.
- A brief introduction to tools and types of equipment is recommended for those who wish to practice power electronics, including electrical computer-aided design, simulation platforms, and hardware.
- A comprehensive summary is presented at the end of each chapter.

## Organization by Chapter

The book is divided into 12 chapters, organized in such a way as to provide easy following and understanding. The text provides step-by-step introductions of the individual components and controls for power electronics systems. A brief description of each chapter follows:

Chapter 1 provides a brief background about power electronics. Some important terms are clarified in this chapter to avoid ambiguity.

Chapter 2 introduces important components of power electronics. The power electronics industry came into existence upon the diode's invention. Switching technology led to the development of various transistors and thyristors. The characteristics of power inductors, capacitors, and resistors are discussed in this chapter.

Chapter 3 introduces the best-known topologies for non-isolated DC/DC conversion, namely buck, boost, buck-boost, and Ćuk. Simulation verification accompanies each design state.

Chapter 4 focuses on power computation to evaluate power equivalence, loss analysis, and power quality, which naturally leads to the necessity of gate driver circuits.

Chapter 5 discusses DC to single-phase AC conversion, especially the bridge circuit and modulation methods to achieve the design objective.

Chapter 6 introduces power conversion from single-phase AC to DC and addresses the related power quality concerns.

Chapter 7 focuses on isolated DC/DC conversion, which is an advanced arrangement built on the topologies in previous chapters.

Chapter 8 deals with three-phase AC power conversion. It covers DC/AC, AC/DC, and AC/AC conversion. The modulation for DC to three-phase AC conversion is also introduced.

Chapter 9 focuses on the topologies for bidirectional power conversion, featuring non-isolated DC/DC, isolated DC/DC, and DC/AC converters. A special topology is introduced and analyzed, which is the dual active bridge.

Chapter 10 introduces an averaging technique for dynamic modeling and fast simulation of different converters in the cases of continuous conduction modes and discontinuous conduction modes.

Chapter 11 discusses mathematical modeling of power converters for dynamic analysis. Linearization is widely used to derive the small-signal models. The non-minimal-phase issue is also discussed.

Chapter 12 provides control system analysis and design. Affine parameterization is introduced as a systematic way to synthesize controllers for power conversion regarding the balance of stability, robustness, and performance.

## Acknowledgments

I would like to thank Mr. Jacky Han for a great work of proofreading, technically and grammatically. Special thanks go to Ms. Lara Zoble, Senior Editor in the Professional Group at McGraw Hill, for providing professional support for this project through all phases. Since I was busy writing this book for the past two years, I missed sharing quality time with my family members. Hence, last but not the least, I heartily thank all of them for their great patience and understanding, because without their continuous support and sacrifices this book would not have been possible.

## Technical Support

All modeling and simulation for case studies in this book were developed by the basic functions of Simulink® and MATLAB®, which will help readers understand the fundamental principles behind various simulation tools. Version R2018b or higher of the MATLAB® and Simulink® software can be used to repeat the results of the example cases or to develop new studies accordingly.

*Weidong Xiao*

# Power Electronics
# Step-by-Step

# CHAPTER 1
# Background

Direct current (DC) flows in only one direction of electric charge, whereas its counterpart, alternating current (AC), periodically reverses current flowing direction. These two forms of currents widely present in power electronics and power systems. The "battle of the currents" refers to the significant debate and competition of electric power transmission systems in the United States, either AC or DC, in the late 1880s. It turned out that the AC-based power distribution and transmission prevailed because of its more cost-effectiveness and efficiency than DC. Power grids started with AC-based networks. Thanks to the early development of line-frequency (LF) power transformers, AC voltage can be either "stepped up" or "stepped down" to achieve different voltage levels. For a given level of power, higher voltage indicates less current flow and lower conduction loss in the transmission. Up to now, the LF power transformer is still the backbone in the power grids around the world to support high-voltage (HV) power transmission, medium-voltage (MV) distribution, and low-voltage (LV) supply to end-users. The lack of power electronics is considered one of the critical reasons leading to the failure of DC in the "battle of the currents" and the dominance of AC in the present power networks.

Technological development brings optimism that DC will eventually win, since the recent trend indicates more and more DC-based power generation, transmission, distribution, and applications. DC can eliminate the long-term difficulties of AC related to its frequency stability, power factor, synchronization, and interconnection. For example, the renewable resource of photovoltaic and fuel-cell generators produces DC. The utilization of energy storage of rechargeable batteries is mainly through DC. These components are important to represent the future energy network in terms of "smart" and "green" energy systems. Meanwhile, the steep growth of DC-powered loads is due not only to the computer-related products but also to the spread of devices for lighting and home appliances. Even though the majority of electric motors are conventional AC devices, high performance can only be realized by using the driver system, which is based on power electronics and mostly supplied by DC. High-voltage DC (HVDC) is becoming the norm for long-distance power transmission, thanks to the advantage of low loss and simple interconnection. The broad utilization and fast advance of power electronics make DC weigh more than before for all different voltage levels, such as high voltage (HV), medium voltage (MV), low voltage (LV), and extra-low voltage (ELV).

Power electronics uses the solid-state technology to convert, process, and regulate electric power flow in terms of voltage and current from one form to another. The static power conversion technology serves as the power interface for a variety of applications. The industry started with the invention of the p-n junction to produce diodes. It boomed with the availability of thyristors thanks to the turn-on controllability. The power semiconductor devices can achieve safe and efficient power conversion and regulate the different levels of voltage, current, and power. Recently, the rapid growth of power electronics is considered as the backbone of modernized power systems, high-efficiency power supplies, and future energy networks because of the following factors:

- Advances in power semiconductor devices for controllable, high-efficiency, reliable, and versatile implementations.
- Trend toward modern electrical systems regarding distributed power generation, modular energy storage, and renewable power generation.
- Rise of portable consumer electronics and high-efficiency appliances.
- Advances and maturity of control engineering regarding both hardware and software to achieve high-performance and reliable operation.
- Demand for high-efficiency power supply systems to reduce pollution and retire low-efficiency devices.

## 1.1 Classification of Power Conversion

The level of power conversion can be different from the milliwatt to megawatt capacity. Various criteria can be applied to classify the system of power electronics. A device that converts power signals from one form to another is commonly called "converter," which has become the most common term in power electronics. Therefore, one classification can be based on the conversion form in terms of DC and AC:

- AC-to-DC conversion (AC/DC)
- DC-to-AC conversion (DC/AC)
- DC-to-DC conversion (DC/DC)
- AC-to-AC conversion (AC/AC)

The AC-to-DC converter is commonly called a "rectifier," referring to the rectification operation. Meanwhile, the DC-to-AC converter is sometimes called the "inverter." Figure 1.1 illustrates the blocks to present the classification of AC/DC, DC/AC, DC/DC, and AC/AC. These will be applied in system diagrams throughout the book.

Another classification is based on the direction of active power flow in steady state. For example, rechargeable batteries require bidirectional power flow to charge and discharge when one converter is utilized for the power interface. The same operation is commonly required for the power conversion to interface ultracapacitors. Thus, the power conversion can be classified as either unidirectional or bidirectional, as illustrated in Fig. 1.2. The input and output ports can be clearly identified in the unidirectional power conversion. The input port is always connected to the source; meanwhile, the load is linked to the output port. When energy storage is applied, e.g., rechargeable batteries, the definition of input and output ports is no longer clear for

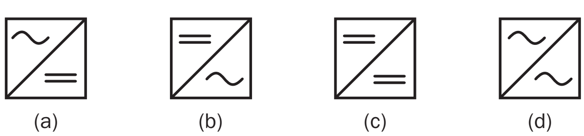



**Figure 1.1** Blocks of power conversion: (*a*) AC/DC; (*b*) DC/AC; (*c*) DC/DC; (*d*) AC/AC.

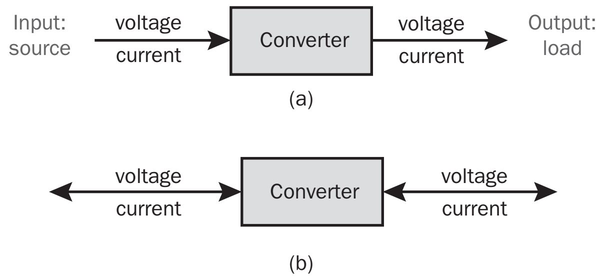



**FIGURE 1.2** Diagrams showing power conversion: (*a*) unidirectional; (*b*) bidirectional.

the bidirectional converters. The DC terminal of rechargeable batteries can be either the source or load, depending on the conversion operation. The bidirectional power conversion shows fast growth due to the wide utilization of rechargeable batteries. The bidirectional power conversion can have any of the following forms: AC/DC, DC/AC, DC/DC, and AC/AC.

Classification can be defined and based on the voltage level. Power converters are widely utilized to supply portable devices, such as tablets, mobile phones, and laptops, which are classified as the group of extra-low-voltage (ELV) applications. Based on the average value of human body resistance, the voltage level is usually considered as low risk to life. Other voltage levels are higher and pose a threat to life; therefore, devices having such a higher voltage should be strictly isolated from human contacts. The following definitions are considered as a reference for the discussion and analysis that follow.

- Extra-low voltage (ELV): <50 V
- Low voltage (LV): 50–1000 V
- Medium voltage (MV): 1–35 kV
- High voltage (HV): 35–230 kV
- Extra-high voltage (EHV): >230 kV

Classification of voltage levels can be sourced from the International Electrotechnical Commission (IEC). It should be noted that the voltage rates listed above are just for a general reference. The strict definition varies for DC and AC, and is different from one country to another. Figure 1.3 demonstrates the diagrams of power systems indicating various voltage levels at the different conversion stages. Theoretically, the higher the voltage level, the lower the conduction loss for long-distance transmission and distribution.

The conventional power system is represented by the highly centralized grid structure, as shown in Fig. 1.3*a*. The power from the centralized power generation facility is eventually delivered to end-users through the networks of transmission and distribution. Voltage conversion mainly relies on power transformers. The modernized network adopts more renewable energy resources, distributed power generations, demand response, and energy storage. The impact of microgrids and smart grids is likely to change the future grid infrastructure, especially at the distribution levels, as illustrated in Fig. 1.3*b*. An important element of such power systems is the prosumer that is able to supply power to grids from the local power generation system. Power electronics eventually plays an important role in supporting the transition into modern

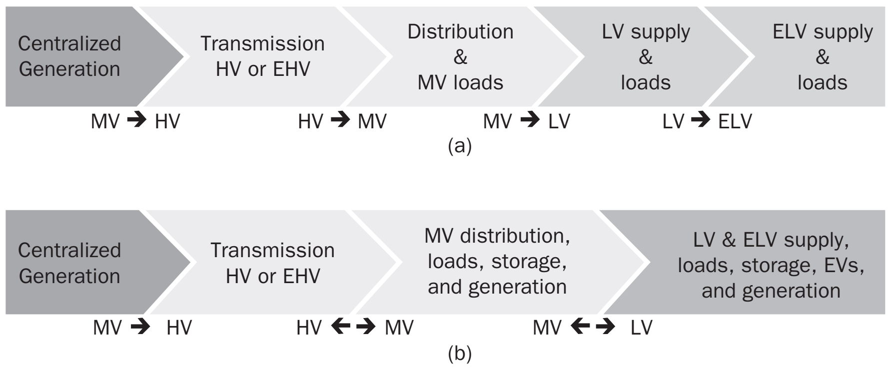



**FIGURE 1.3** Conversion for power systems: (*a*) conventional; (*b*) modernized.

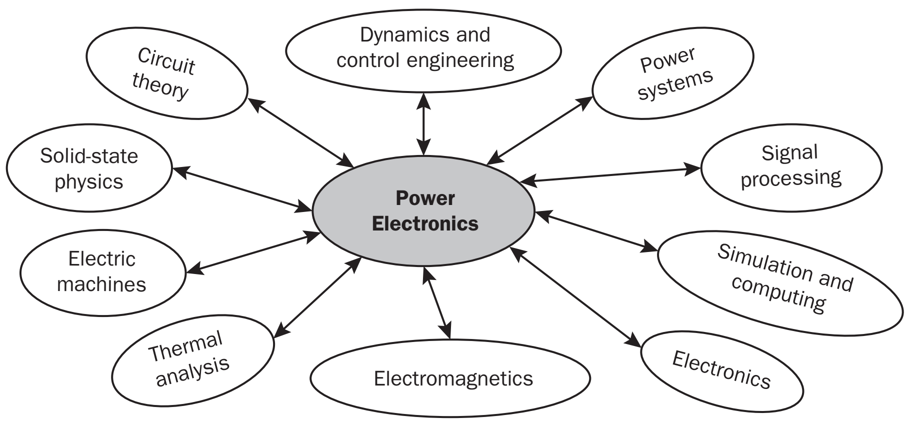



**FIGURE 1.4** Interdisciplinary nature of power electronics.

electrification. The bidirectional power conversion will be demanded at different levels to make the future system efficient, adaptable, reliable, and more.

## 1.2 Interdisciplinary Nature of Power Electronics

Power electronics is commonly considered as the bridge between the power engineering and electronic application. The subject actually covers many technologies more than power and electronics. The interdisciplinary nature of power electronics is illustrated in Fig. 1.4.

Accurate power conversion cannot be realized without the support of control engineering. Modern power electronics tends to use digital control technology and relies on fast computing hardware and digital signal processors to improve control capability and performance. The solid-state components of electromagnetics and electronics form the foundation of power electronics. The power switching operation relies on the advances in power semiconductor devices to reduce both conduction and high-frequency loss.

System analysis and design are always based on circuit and electromagnetic theories. Fast computer simulation has become a norm for the concept proof and guides for system improvement. Additionally, more and more power conversions are digitally controlled by various computational devices such as microprocessors, digital signal processors, microcontrollers, and field-programmable gate array (FPGA). Electric machines bridge mechanical engineering and electrical engineering, but rely on power electronics to efficiently and accurately drive the motion and convert generating power for utilization. Thermal analysis is commonly linked to mechanical analysis and design but becomes an important sector to support the highly efficient and reliable power conversion.

## 1.3 Typical Applications

The telecommunications industry mainly relies on DC and uninterrupted power supplies (UPS), which require the conversion of AC/DC and DC/DC. The DC power traditionally supports the operation of signal processing, transmission, amplifier, etc. Modern power electronics tends to directly serve as the power amplifiers for communication purposes, which provide simplicity and improve the overall system efficiency.

Modern transportation tends to be electrified to reduce pollution and better dynamics. The concept of electric vehicles (EVs) is referred to as not only ground automobiles but also any form of transportation in air and water. The propulsion is based on electric motors, drivers, energy storage units, etc. Power electronics is essential for the system coordination, power management, speed regulation, battery charging, and discharging. EVs are also expected to participate in the grid support for future energy network in partnership with power electronics. Aerospace relies on power supplies to operate space shuttles, stations, satellites, etc. Modern aircrafts demand more power electronics to coordinate the power balance among loads, generators, and energy storage units for high efficiency and high power density.

Modern homes are full of various electrical appliances, e.g., microwave ovens, air-conditioners, induction cookers, high-efficiency lightings, and residential photovoltaic (PV) power generators. Power electronics plays an important role in supporting the smart operation, high efficiency, reliability, and flexibility. Portable electronic devices are increasingly being used in our daily lives. DC and conversion are required for power supply to computers, cell phones, and tablets.

Future energy networks demand more power conditioning to interface various renewable energy resources such as PV and wind. The HVDC applications have shown significant advantages over HVAC for long-distance transmission. The operation relies on the AC/DC and DC/AC conversion at the HV level. Solid-state transformers at the MV level have become the trend for grid support and make the system more controllable, based on the application of bidirectional power conversion. Further, the utilization of energy storage, e.g., rechargeable batteries, requires power converters for energy management and power regulation.

Recently, DC systems show high potential to replace traditional AC power infrastructure at different voltage levels because of advances in power electronics. The ELVDC and HVDC have become the norms in daily life and long-distance power transmission. More efforts will focus on the applications of LVDC and MVDC in attaining high efficiency, high reliability, flexible interconnection, and low cost.

## 1.4 Tools for Development

Hardware equipment and software platforms are required to practice power electronics, which commonly include:

- Software packages for electronic and electrical computer-aided design (ECAD).
- Software platforms for circuit simulation and control system analysis.
- Oscilloscopes with high-bandwidth probes for measuring and recording voltage and current signals.
- Desktop or portable multimeters to detect voltage, current, resistance, and temperature.
- DC and AC programmable power supplies to sufficiently support dynamic speed and power rating.
- Function generators to produce required signals for quick tests.
- Programmable AC and DC loads to emulate variable load profile, meet power rating requirement, and perform disturbed load variation.
- Soldering machines and repair stations for prototyping and practical solution.
- Impedance analyzers or LCR meter to evaluate a circuit network or individual components, e.g., inductor and capacitor, etc.
- Data logger for long-term data acquisition or evaluation of long-term system performance, such as battery charge/discharge cycle and power quality, etc.
- Thermal imager or thermal meter for untouched temperature sensing and thermal assessment.

It is worthwhile to emphasize the importance of thermal analysis in power electronics even though the subject is traditionally related to other disciplines. Regarding power conversion, the temperature is considered an indirect measure of the system efficiency and electrical performance. More and more studies treat the device temperature as the direct indicator of aging and lifespan prediction. Therefore, the thermal imager and meter are important tools for practicing power electronics. The thermal sensing embedded in circuits also becomes the trend to operate a highly reliable and efficient power conversion system.

### 1.4.1 Electrical Computer-Aided Design

One key feature of ECAD software is to develop circuit schematics and printed circuit boards (PCBs). Typical, commercially available ECAD software platforms are as follows:

- EAGLE
- Circuit maker and Altium Designer
- Allegro PCB Designer
- OrCAD PCB Designer

Even though the ECAD software platforms are different from each other, the PCB design generally follows the same step-by-step procedure, as illustrated in Fig. 1.5. Schematic symbol libraries should be first created or loaded from other existing

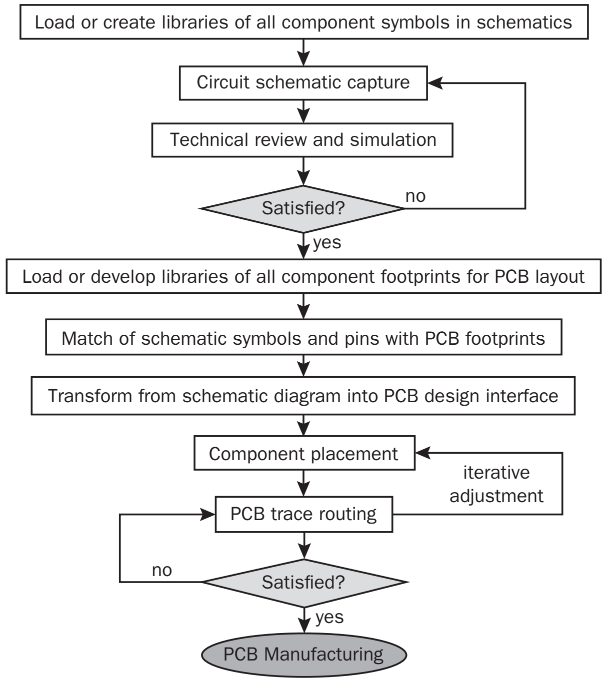



**FIGURE 1.5** Schematics showing computer-aided design procedure to manufacture PCB.

resources, including all components that need to be placed in the circuit diagram. The circuit schematic should first be developed for simulation and technical review. The simulation can be performed by the same ECAD software or a completely different platform, such as MATLAB/Simulink.

When the schematic design is approved, the next important step is to select physical components. The selection involves a comprehensive procedure that largely influences the system performance, cost, and reliability. Some PCBs can be directly picked from off-the-shelf products. Many need to be specifically designed and custom-made, e.g., magnetic components of inductors and transformers. The component footprint links the conceptual and representative symbols in the schematic to the practical device mounted on the PCB. It is essential for the library of the component footprints to correspond to/with the symbols and pins in the schematic diagram while representing the real footprints of practical components. The schematic diagram should be updated to include the information of footprints or other physical information resulting from the footprint libraries.

The next step is to transform all the components and connection of the schematic diagram to the PCB design platform, which will appear as the practical footprints in the PCB design interface. The interconnection should strictly follow the design in the schematic diagram. The final step is the PCB layout and routing. The most important step is to place all components in the best location and rotate them for the simplest interconnection. Performing optimal placement and making iterative adjustments are time-consuming, but they are the only ways to minimize the critical and total routing length with full consideration of the thermal constraints as well as system performance. Short traces in PCBs not only improve board density and cost-effectiveness but also show many benefits. The short trace on board leads to low loss, low parasitic inductance, and low electromagnetic inference (EMI), which results in high efficiency, clean signal path, low oscillation, and system robustness. Grounding design is another key factor that should be carefully considered. It provides many benefits of creating one complete layer just for the common ground interconnection. Thermal consideration and ventilation design in PCB are also critical since power converters prefer a "cool" environment for a long-term operation, which links to the reliability and long lifespan.

In general, the PCB design is a time-consuming but critical step in power electronics, which requires a comprehensive review in each step to minimize mistakes and imperfections. Modern power electronics relies on high-frequency power switching and depends on optimally designed PCB to achieve high performance.

### 1.4.2 Simulation

Simulation is an effective tool to prove the concept of theoretical design and circuit analysis. Computer simulation for circuits started with the development of the Simulation Program with Integrated Circuit Emphasis (SPICE) in the 1970s. A group of scholars at the University of California, Berkeley, initialized this significant development in the computer simulation history. Based on the principle of SPICE, the Personal Simulation Program with Integrated Circuit Emphasis (PSPICE) was founded and released by the company MicroSim. The addition of "P" refers to the software operating platform, the personal computer (PC), which became affordable and widely used in the 1980s. Coding was generally required to operate the early version of PSPICE. The latest versions provide graphic-based human–machine interfaces that are easy to learn and use. Following the success of PSPICE, several software packages are commercially available to simulate power electronics. Some of them are listed below:

- PSpice Simulator by Cadence Design Systems Inc. (https://www.cadence.com)
- PSIM by Powersim Inc. (https://powersimtech.com/)
- LTspice by Analog Devices, Inc. (https://www.analog.com)
- PLECS by Plexim GmbH (https://www.plexim.com)
- Simscape Electrical™ package with MATLAB/Simulink by MathWorks (https://www.mathworks.com)

A schematic capture interface is commonly provided by the software packages to develop the circuit-based model. The graphic interface can illustrate the simulation result in terms of time-domain waveforms and frequency-domain analysis. Most components in the library can be integrated with non-ideal factors, such as equivalent series resistors (ESRs), the voltage drop of power semiconductors, and even parasitic parameters. It aims to show the capability for accurate simulation, close to the real-world conditions.

Convergence failure is one critical issue for the circuit-based simulation. It has been a common problem for new users to use the early version of PSPICE. The issue generally results from the lack of fundamental knowledge of simulation and power electronic dynamics. The improper setting is another common cause of nonconvergence. Due to the constraints of numerical simulation, some parameters must be included in the model to guarantee convergence. For example, the circuit design can allow a voltage source suddenly applied to a capacitor with a different voltage charge. It causes the convergence issue if the capacitor parameters include zero value of ESR. In theory, the current should jump to an infinite level in response to the step voltage change and lead to nonconvergence in numerical simulation.

There are arguments about the precise simulation including all non-ideal factors. The challenge leads to how the parameters of non-ideal factors can be accurately extracted from a practical system to represent the real-world scenario. Otherwise, this can create a dilemma for learners of power electronics if the problem is not clearly and properly addressed. It is even difficult for experienced engineers to develop accurate models including all non-ideal factors, such as parasitic components in power electronic devices. Even though a component datasheet provides some information about the non-ideal factors, it is simply considered a quick reference since the test is based on a very specific condition. A simple example shows that the ESR value of power semiconductor devices is only valid for one specific operating condition since it changes significantly with the core temperature. The reality faces nonlinear and time-variant factors in a physical system. Circuit parameters mostly becomes unpredictable in real-time operations since they change with the operating conditions, environmentally and electrically. The body temperature or core temperature of a physical device is difficult to be accurately predicted in reality. Therefore, making simulation exactly follow the experimental result requires significant effort and experience, but the accuracy is only guaranteed case by case, not in general.

The author always recommends the start of simulation to be based on all ideal components for quick concept proof without too much complication. The misdefinition of non-ideal factors can only result in more trouble of simulation rather than any precise representation. It has been found that many users simply rely on the random or default values of non-ideal factors to start a circuit-based simulation. It turned out to show more misleading information rather than accuracy and precision. The misleading information is mostly hard to be explained or debugged due to the lack of a deep understanding of simulation fundamentals. Power electronics trusts more on the experimental result rather than on the so-called "accurate simulation," confronting the complication of non-ideality in the real world.

Throughout this book, simulation is only based on ideal components to avoid any mixed and confusing information about non-ideal factors. The discussion focuses on system dynamics to construct the fundamental knowledge of simulation principles. All simulation models shown in this book are based on the fundamental blocks of MATLAB/Simulink, without any complication or dedicated software tools. The approach allows beginners to better understand the simulation fundamentals, utilizing the given functions instead of being inhibited by the constraints on a certain software platform. It also shows the best agreement with the theoretical analysis in terms of steady states and transient responses.

## 1.5 Ideal Power Conversion

Modern power electronics tends to develop converters with the balance of conversion efficiency, lifespan, reliability, cost-effectiveness, power quality, power density, and functionality. The following expectations from power converters lead to continuous improvement and research:

- Stable and robust operation, regardless of disturbance or non-ideal environment.
- Conversion efficiency to be close to 100%.

- High power quality appearing at all converter terminals referred to the nominal form of DC or AC.
- Accurate and fast regulation of voltage, current, and power.
- A fast and robust response to reject all sorts of disturbance.
- High power density to forge a small size and efficient operation.
- Low cost without compromising the lifespan.

Efficiency is one of the most important measures of power conversion. The low-efficiency power converters also increase the device size due to significant volume of heat sinks required. Modern power electronic devices are compact, thanks to high-frequency switching and higher efficiency. The efficiency curve is a common illustration for conversion performance according to the variation of the input and/or output characteristics in terms of power, voltage, and current. However, engineers always face the dilemma of maintaining the balance among the performance indices described earlier. As per the current technology, there is a clear trade-off among the factors of affordability, power density, and life expectancy. For example, a long-life capacitor is typically bulkier and more expensive than its short-life counterparts. Thus, a clear and detailed specification should be developed at the beginning of the design stage to find the best balance for the performance indices detailed earlier.

## 1.6 AC and DC

Modern power electronics deals with various forms of voltage and current, which are typically classified as DC, single-phase AC, and three-phase AC. Ideal DC can be plotted as a straight line as the waveform showing nothing but the zero-frequency component. Power electronics produce all different kinds of DC waveforms that can be significantly different from the ideal one. DC follows only one direction, of which the signal waveform does not show zero-crossing. However, the definition does not limit current amplitude as it can vary significantly and periodically from time to time. Thus, the averaged value, peak-to-peak ripple amplitude, and root-mean-square (RMS) value are the important measures for the rating and quality of such DC waveforms, which are covered in Chap. 4.

### 1.6.1 Single-Phase AC

An ideal single-phase AC voltage refers to the sinusoidal waveform showing the constant values in terms of frequency ($\omega$) and amplitude ($V_m$), which is expressed by $v_{ac} = V_m \sin(\omega t)$. When the voltage is applied to a pure resistive load, $R$, the current is expressed by $i_o = \dfrac{V_m}{R}\sin(\omega t)$. The instantaneous power is represented by (1.1), where $P_m = \dfrac{V_m^2}{R}$. The averaged value of $p_o$ can be derived and expressed by (1.2).

$$p_o(\omega t) = v_{ac}(\omega t) \times i_o(\omega t) = P_m \times \frac{1-\cos(2\omega t)}{2} \tag{1.1}$$

.

$$AVG\left[p_o(\omega t)\right] = \int_0^{\pi} \left[P_m \times \frac{1-\cos(2\omega t)}{2}\right] d(\omega t) = \frac{P_m}{2} \tag{1.2}$$

Figure 1.6 shows the waveforms of voltage, current, and power. The power waveform does not show zero-crossing since it follows one direction from the source to the

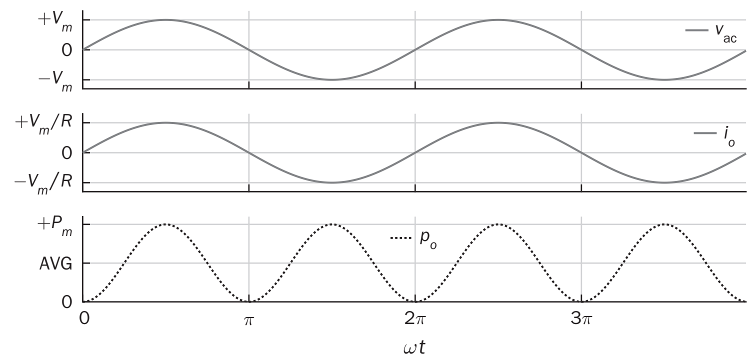



**FIGURE 1.6** Waveforms of ideal single-phase AC source and load including voltage, current, and power.

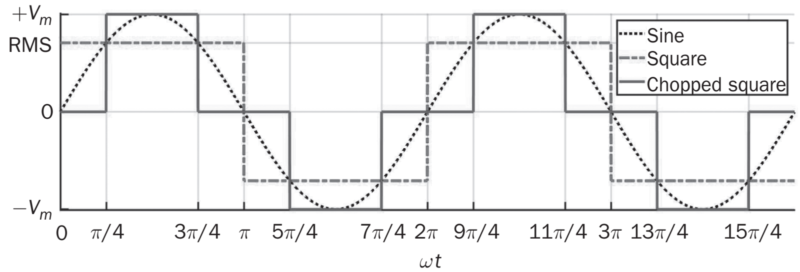



**FIGURE 1.7** Illustration of different AC waveforms.

load. The ripple frequency of the power is shown as $2\omega$, which is the double value of the frequency of $v_{ac}$ and $i_o$. The power waveform indicates the active power measured in watts. The example illustrates the zero value of the reactive power that is measured in VAR.

AC waveform in power electronics is not limited to the ideal sinusoidal wave, as illustrated in Fig. 1.6. The definition of AC signal indicates a periodic waveform with zero-crossings of its current. Different kinds of AC waveforms are commonly produced by the switching operation of power converters. Figure 1.7 illustrates two common types: square waveform and chopped square waveform. They are plotted with the pure sine waveforms for comparison, and indicate the equality of the power consumption effectiveness when they are applied to the same resistive load. Other AC waveforms also appear in power electronics, such as the triangle waveform.

### 1.6.2 Three-Phase AC

Three-phase electric power is the backbone of AC systems in terms of generation, transmission, and distribution. The three-phase AC is commonly represented by three single-phase AC signals, as shown in Fig. 1.8*a*. The source and load share a common neutral point, which is the WYE connection or star connection. The line-to-neutral (LN) voltage and phase current are defined and expressed by (1.3) and (1.4), respectively. Ideally, all

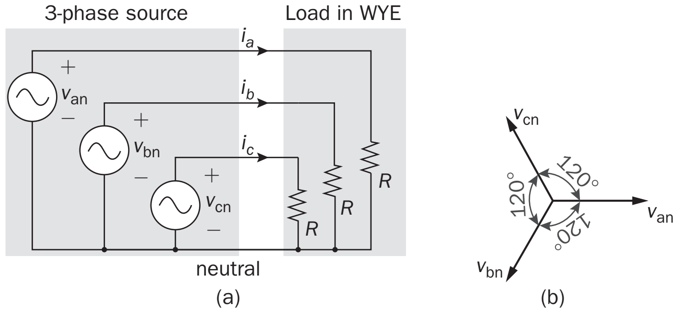



**FIGURE 1.8** Illustration of three-phase source and load in WYE connection: (*a*) circuit; (*b*) phasor.

three-phase waveforms indicated in the circuit should be sinusoidal and share the same frequency and the same amplitude.

$$v_{\text{an}} = V_m \sin(\omega t), v_{bn} = V_m \sin\left(\omega t - \frac{2\pi}{3}\right), v_{cn} = V_m \sin\left(\omega t - \frac{4\pi}{3}\right) \tag{1.3}$$

$$i_a = I_m \sin(\omega t), i_b = I_m \sin\left(\omega t - \frac{2\pi}{3}\right), i_c = I_m \sin\left(\omega t - \frac{4\pi}{3}\right) \tag{1.4}$$

where $I_m = \dfrac{V_m}{R}$, and the phase difference is 120° or $\dfrac{2\pi}{3}$ among the three-phase voltage waveforms. The instantaneous power of each phase is computed by

$$p_a = v_{an} \times i_a = P_m \sin^2(\omega t) \tag{1.5}$$

$$p_b = v_{bn} \times i_b = P_m \sin^2\left(\omega t - \frac{2\pi}{3}\right) \tag{1.6}$$

$$p_c = v_{cn} \times i_c = P_m \sin^2\left(\omega t - \frac{4\pi}{3}\right) \tag{1.7}$$

where $P_m = V_m \times I_m$. The phasor diagram is commonly used to demonstrate three-phase signals, as shown in Fig. 1.8*b*. The phase voltage, current, and power are plotted in time domain and shown in Fig. 1.9. The phase lag of the LN voltage waveforms is measured as $\dfrac{2\pi}{3}$ among the phases A, B, and C.

One important feature of the three-phase power systems is that the sum of the instantaneous power values of $p_a$, $p_b$, and $p_c$ is a straight line, as shown in Fig. 1.10, when the balance of three phases is presented and the power factor is unity. The feature is important for the conversion between DC and three-phase AC. The sum of the three-phase AC power is expressed by

$$\sum(p_a, p_b, p_c) = 1.5P_m \tag{1.8}$$

Another configuration of three-phase power systems is the Δ connection, as shown in Fig. 1.11*a*. The line-to-line (LL) voltages become the direct measurements, which are across the load resistors and symbolized by $v_{ab}$, $v_{bc}$, and $v_{ca}$. The phasor diagram can

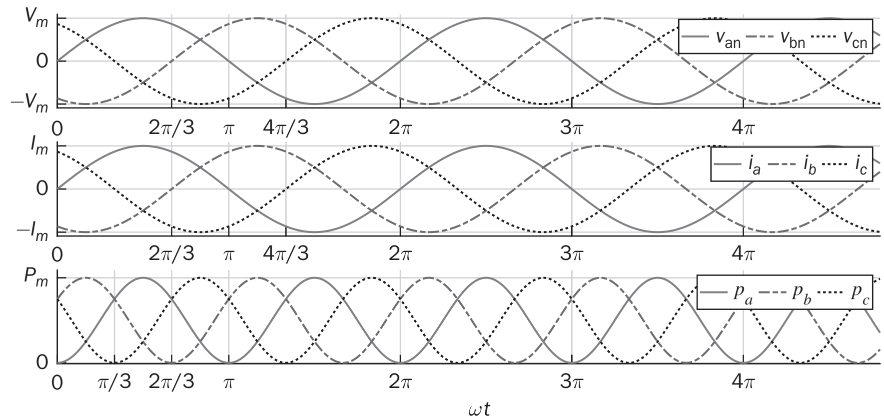



**FIGURE 1.9** Illustration of ideal three-phase waveforms.

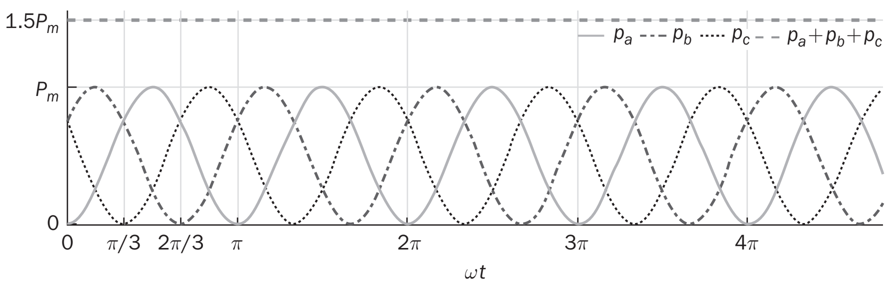



**FIGURE 1.10** Illustration of ideal three-phase waveforms in term of power.

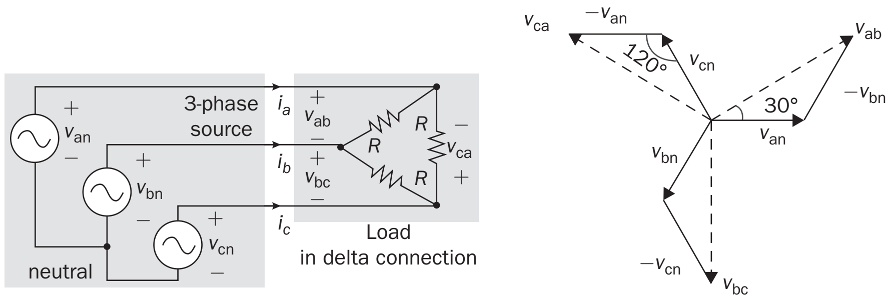
demonstrate the connection between the LN and LL voltages, as illustrated in Fig. 1.11*b*. Mathematically, they are expressed by

$$v_{ab} = v_{an} - v_{bn} = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right) \tag{1.9}$$

$$v_{bc} = v_{bn} - v_{cn} = \sqrt{3}V_m \sin\left(\omega t - \frac{\pi}{2}\right) \tag{1.10}$$

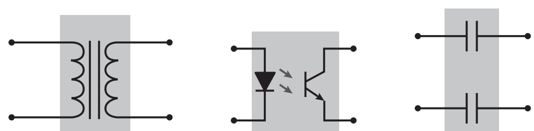
$$v_{ca} = v_{cn} - v_{an} = \sqrt{3}V_m \sin\left(\omega t - \frac{7\pi}{6}\right) \tag{1.11}$$

where the voltage $v_{an} = V_m \sin(\omega t)$ is the reference signal to mathematically present other LN and LL voltage waveforms. The LL and LN voltages show the amplitude difference of $\sqrt{3}$. It is shown that the phase of $v_{ab}$ leads $v_{an}$ by 30° or $\frac{\pi}{6}$, the phase of $v_{bc}$ leads $v_{bn}$ by 30°, and the phase of $v_{ca}$ leads $v_{cn}$ by 30°. The LL voltage waveforms also show the phase difference of $\frac{2\pi}{3}$ among the three phases.




(a) (b)

**FIGURE 1.11** Illustration of three-phase source and load in delta connection: (*a*) circuit; (*b*) phasor.



(a) (b) (c)

**FIGURE 1.12** Galvanic isolation by (*a*) magnetics; (*b*) light; (*c*) capacitor.

## 1.7 Galvanic Isolation

A power conversion shows galvanic isolation when it provides full dielectric isolation. It can be explained that the output power wiring does not electrically contact the input wiring in the conversion system. The key benefit of galvanic isolation in consumer power supplies lies in many safety aspects in response to unpredictable fault conditions. For example, an offline power supply provides low-voltage DC to the motherboard of personal computers. Galvanic isolation becomes important to separate from the hazard voltage level of the main under any faulty condition. In general, galvanic isolation is an effective way to distinguish different voltage levels and prevent electric shock. Furthermore, through galvanic isolation, the functional grounding for various types of sources and loads can be achieved, which leads to improved safety and reliability.

The most common form of isolation for electric power is that of an isolation transformer, based on the magnetic induction, as shown in Fig. 1.12*a*. Transformers can provide very powerful linkage through magnetic field between the windings. The magnetic flux can be built and concentrated by high-permeability materials, such as iron. The recent trend is the wireless power transfer (WPT) technology that relies on magnetic induction to exchange energy among all coupling coils. The WPT technology is popular to charge portable battery–based devices or electric vehicles (EVs), due to the realization of galvanic isolation and the convenience involved. The concept is also used underwater to charge submarine vehicles, which reduces the burden of insulation.

Sensing and control units are commonly based on the ELV implementation that represents a safe voltage level, even for HV industrial applications. Galvanic isolation is required to bridge the significant voltage difference while improving safety as well as minimizing noise coupling. For low-power signal transmission, both magnetic and light effects are commonly used to separate physical circuits and provide galvanic isolation. The optoisolators, also referred to as the optocouplers, are widely used to transmit logic signals through the light path, which is illustrated in Fig. 1.12*b*. On the other hand, based on the magnetic effect, the Hall-effect sensors support galvanic isolation, widely used to measure both AC and DC. Current transformers provide another way to provide galvanic isolation and sense AC for measurement.

Besides the conventional isolation approach, capacitors can be connected in power path to provide galvanic isolation, as shown in Fig. 1.12*c*. The capacitors can exchange signals and provide galvanic isolation. The integrated circuit of isolated amplifiers recently developed a way to safely sense voltage at high levels of more than 1 kV. It is based on the capacitive isolation technology, according to the manufacturer, Texas Instruments (www.ti.com). The device dramatically simplifies the voltage-sensing design and provides essential safety measures. The capacitive isolation can also be used to convert and transmit power.

## 1.8 Fundamental Magnetics

Magnetic components are important in power electronics. However, the subject is usually well covered by textbooks in physics. Thus, this section describes the fundamental principle of magnetics, focusing on the classification and inductor design. In power electronics, the magnetic device mainly supports one or more of the following functions:

- Significant energy storage or buffering in the form of electromagnetics.
- Current smoothing for filtering purpose.
- Power coupling for voltage conversion without galvanic isolation.
- Power coupling for both galvanic isolation and voltage conversion.

### 1.8.1 Physical Laws

Ampere's law can be expressed by (1.12) according to the magnetic demonstration in Fig. 1.13*a*, which indicates the magnetic core, magnetic path, and winding.

$$H(t)l_e = ni(t) \tag{1.12}$$

where $H(t)$ represents the magnetic field strength, with the unit of ampere per meter (A/m). The length of the closed magnetic path is symbolized by $l_e$ in meters. The symbol $n$ indicates the winding turns number. Ampere's law indicates that the current $i(t)$ is

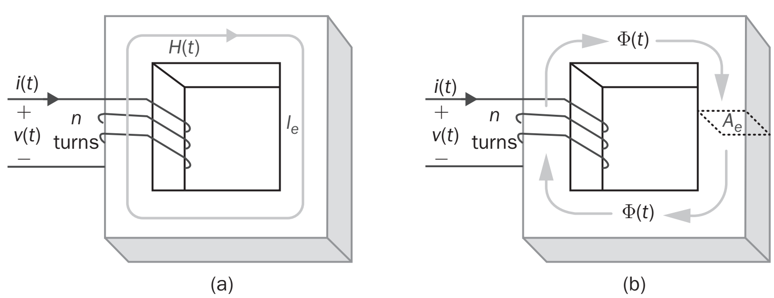



**FIGURE 1.13** Magnetic illustrations of (*a*) Ampere's law and (*b*) Faraday's law.

proportional to the strength of the magnetizing field, $H(t)$, when the parameters of $l_e$ and $n$ are constants.

Faraday's law relates the voltage $v(t)$ induced at a winding to the instant magnetic flux $\Phi(t)$, as expressed in (1.13). Figure 1.13*b* illustrates the configuration that the magnetic flux passes through the interior of the winding. When the flux is uniformly distributed in the magnetic core area, the flux density can be represented by (1.14), where $A_e$ is the cross-sectional area of the magnetic path, and $B(t)$ symbolizes the magnetic flux density. The unit of $B(t)$ is either tesla (T) per m$^2$ or weber (Wb) per m$^2$. Thus, Faraday's law is expressed as (1.15).

$$v(t) = n\frac{d\Phi(t)}{dt} \tag{1.13}$$

$$B(t) = \frac{\Phi(t)}{A_e} \tag{1.14}$$

$$v(t) = nA_e\frac{dB(t)}{dt} \tag{1.15}$$

### 1.8.2 Permeability and Inductance

Faraday's law builds the connection between the voltage $v(t)$ induced in a winding to the total magnetic flux $\Phi(t)$ or flux density $B(t)$ passing through the interior of the winding. Ampere's law relates the current $i(t)$ through a winding to the magnetic field intensity $H(t)$, which is expressed by $H(t) \propto ni(t)$. The electrical characteristic referring to voltage and current is unknown because of the missing link between the $H(t)$ and $B(t)$, as illustrated in Fig. 1.14. It leads to the definition of permeability of magnetic materials.

Characterizing the magnetic field shows the link between the flux density, $B(t)$, and the strength of the magnetizing field, $H(t)$. The term "magnetic permeability" is defined to represent the relation of $B(t)$ and $H(t)$, of which the unit is henry per meter (H/m). The inductor can be simply constructed by a wire coil, as illustrated in Fig. 1.15, which uses air as the medium for magnetic field. This is called an air-core inductor, consisting of a winding of a couple of turns of wire. Without any dedicated magnetic core, the permeability of free space (or vacuum) has been identified as a constant value, which is $\mu_0 = 1.257 \times 10^{-6}$ H/m. The link between $B(t)$ and $H(t)$ is established and expressed as $B(t) = \mu_0 H(t)$ for the air-core inductor.

The circle of magnetic analysis has been completed by the laws of Ampere and Faraday, and the physical value of permeability. The electrical characteristics of the air-core inductor can be derived by (1.12) and (1.15), with respect to the permeability, $\mu_0$. The

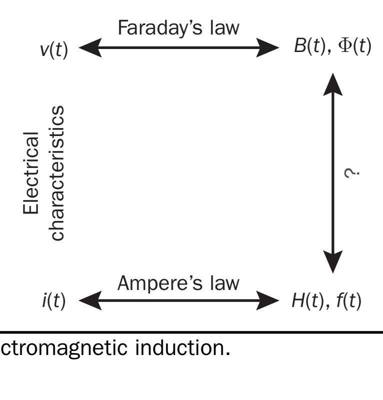



**FIGURE 1.14** Structure of electromagnetic induction.

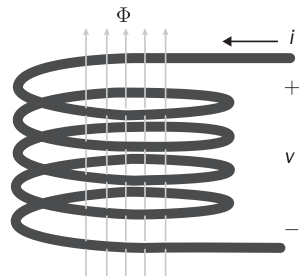



**FIGURE 1.15** Air-core inductor.


**FIGURE 1.16** Magnetic core: (*a*) without winding; (*b*) with winding.

expression results in the derivation of the inductance, $L$, indicated in (1.16). The inductance value is determined by the parameters of the winding turns number, magnetic area, length of magnetic path, and permeability.

$$v(t) = \underbrace{n^2 \frac{A_e \mu_0}{l_e}}_{L} \frac{di(t)}{dt} \tag{1.16}$$

A significant number of winding turns is required to achieve high inductance for the air-core inductor due to the low value of $\mu_0$. The air coil can also produce significant radiation due to the lack of a closed magnetic path. Certain materials show strong coupling and high permeability, which can be utilized to concentrate the magnetic path and construct magnetic cores. Common core materials include solid metal, powdered iron, and ferrite ceramics. The dedicated design of magnetic cores can confine the magnetic field and maximize the available permeability for utilization. One example is shown in Fig. 1.16*a*, which is called the toroidal core. The shape is also referred to "O" or "doughnut" that circumscribes the path of magnetic flux. An inductor is constructed when the winding is foiled by magnetic wire, as shown in Fig. 1.16*b*. The high permeability of the core can improve the inductance density per volume.

Different from the air-core inductor, the permeability is no longer constant and varies from one material to another. The B-H curve is usually plotted to represent the magnetic characteristics and core properties of all different kinds. A typical 4-quadrant graphical representation is illustrated in Fig. 1.17*a*, which shows the features of nonlinearity, time variance, saturation, and hysteresis. Therefore, approximation is required to describe the permeability for design and analyze magnetic cores.

Piecewise linearization can be applied to simplify the link between $B(t)$ and $H(t)$, as illustrated in Fig. 1.17*b*. A group of values of the permeability can be derived along with

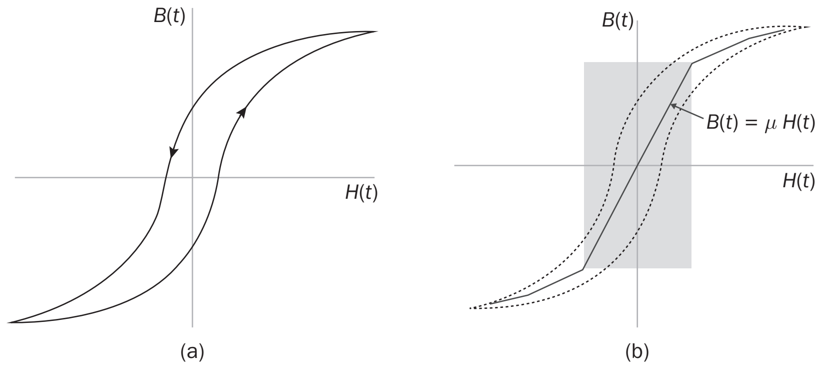



**FIGURE 1.17** B-H curves: (*a*) with hysteresis; (*b*) piecewise linearization.

| Model | Material | $\mu_r$ | $l_e$ (m) | $A_e$ ($m^2$) | $A_L$ |
|---|---|---|---|---|---|
| 0077935A7 | Kool M$\mu$ | 75 | $53.5 \times 10^{-3}$ | $65.4 \times 10^{-6}$ | $94 \pm 8\%$ nH |
| 0L41605TC | Ferrite | 900 | $37.2 \times 10^{-3}$ | $15.6 \times 10^{-6}$ | $475 \pm 25\%$ nH |

*Source*: www.mag-inc.com, December 8, 2018.

**TABLE 1.1** Parameters of Toroidal Cores

the operation range. The permeability value, $\mu$, becomes nominal to represent the linear relation of $B(t)$ and $H(t)$ within a specific range, as indicated in Fig. 1.17*b*. Following the inductor construction in Fig. 1.13, the nominal inductance can be computed by

$$L = n^2 \frac{A_e \mu}{l_e} \tag{1.17}$$

where $\mu$ is the nominal permeability of the applied magnetic core under a specific condition according to the B-H curve.

The highest permeability is near the initial point following the B-H curve, as shown in Fig. 1.17*b*, where the nominal permeability is derived. When saturated, the magnetic core cannot handle the incremental change of applied flux density, followed by a significant drop of permeability. The boundaries for $B$ and $H$ are always clearly defined for magnetic cores. When the operation is out of the limit, the low value of permeability leads to a low value of $L$, which can cause inrush current or even damage to power converters.

The absolute value of permeability is low. Therefore, the permeability of the air, $\mu_0$, is commonly used as a reference to measure magnetic materials. Many magnetic cores are specified by the relative permeability, $\mu_r$, which is expressed by

$$\mu_r = \frac{\mu}{\mu_0} \tag{1.18}$$

### 1.8.3 Magnetic Core and Inductor Design

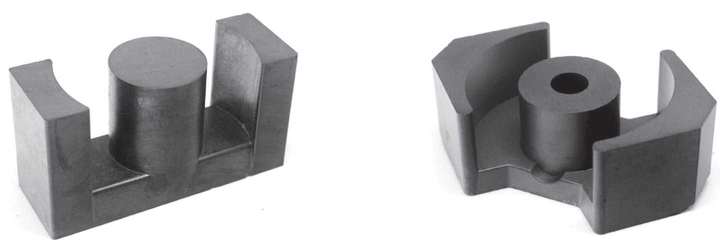
Research of magnetic cores focuses on the improvement of permeability, linear B-H curve, soft saturation, and low core loss. One example of powder cores is shown in

Fig. 1.16. The model number is 0077935A7, which follows the toroidal form. The key parameters are summarized in Table 1.1, sourced from the manufacturer's website www.mag-inc.com. The term "Kool M$\mu$" is the manufacturer trademark that indicates a specially designed and registered core material. It is made of alloy powder with distributed air gaps according to the manufacturer. The nominal value of permeability is shown as the relative value, $\mu_r$. The parameters of $l_e$ and $A_e$ are shown in Table 1.1 sourced from the product datasheet. When a single turn of the winding is applied, as shown in Fig. 1.16*b*, the inductance can be estimated and computed by (1.17) as 94 nH. The value agrees with the parameter given by the product datasheet, which is expressed by $A_L = 94 \pm 8\%$ nH to represent the inductance of the single turn formation. When an inductance, $L$, is specified, the design process for the inductor becomes straightforward since the number of winding turns can be determined by

$$n = \sqrt{\frac{L}{A_L}} \tag{1.19}$$

Ferrite cores show the advantage of high permeability and low cores losses dealing with high frequencies. One model is 0L41605TC, which is listed in Table 1.1. Compared to the powder core, 0077935A7, the ferrite core, 0L41605TC, shows smaller size, but significantly higher permeability, $\mu_r = 900$. However, the ferrite material usually exhibits a sharp saturation curve. Concern should be given to the limitation of operation range in avoidance of core saturation, which poses a potential risk of overcurrent in converter operations. The ferrite-based inductor generally requires an air gap to be added to soften the sudden saturation. Different from the structure of toroidal cores, the majority of core shapes allow construction with a discrete air gap. Figure 1.18 shows the types of ETD and PQ cores. The round center is ideal to adopt bobbins for easy winding and coil implementation. Two pieces are typically required to form a closed magnetic field path with the option of the additional air gap to be implemented. The air gap reduces the permeability and the slope of the B-H loop but enhances field strength and extends the nonsaturation region. In most cases, the shape design of magnetic cores tends to minimize magnetic leakage, which is outside of the dedicated passage of magnetic flux.

The conventional inductor is an independent component to be pre-manufactured and lately connected to a circuit for utilization. Modern power electronics tends to print coil directly on multilayer PCBs to replace the conventional wire coil configuration. The configuration is popular for low-voltage, low-power applications with significantly high switching frequency. When the PCB is ready, the dedicated magnetic cores can be added



(a) (b)

**FIGURE 1.18** Magnetic core shapes: (*a*) ETD; (*b*) PQ.

in an automatic assembly line to complete the full construction of inductors or transformers with other fabrications. The solution provides numerous advantages, including high-level automation, fabrication efficiency, and high power density.

When the turns of a winding are decided, its length can be determined by the specification of the magnetic cores being used. The conduction loss can be used as the reference to select the wire size. As a rule of thumb, the thicker a cable is, the lower power losses it entails, with the downside of increased coil volume. The design should follow the physical limit of the core size and system cost. An iterative process is sometimes required to select the correct core and design a proper inductor to fit design specifications. Litz wire follows the multistrand configuration that is widely used for coils to construct transformers or inductors and reduce the skin effect and proximity effect losses for high-frequency power applications, e.g., >200 kHz.

### 1.8.4 Power Transformer

Inductive coupling leads to the construction of power transformers for galvanic isolation and voltage conversion. The IEC defines the power transformer as "a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power." Since textbooks on electric machines and power systems generally cover the subject of transformers, this section just reviews the fundamental knowledge.

The term is strictly defined and indicates the alternating voltage and current, which should periodically reverse the direction, in contrast to DC. In the early years, power transformers were bulky and hence stationary, and were used in AC electrical networks at different voltage and power levels, ranging from generation, to transmission, to distribution applications. The design is mostly optimized to fit the low-frequency sinusoidal AC power transformation.

A simple power transformer is formed by two coil windings that share with one magnetic core, as shown in Fig. 1.19*a*. Since both windings share the same magnetic flux, Faraday's law can be applied and expressed by (1.20), which leads to the voltage conversion equation in (1.21). The same principle can be applied to a transformer with multiple windings, where the terminal voltages are proportional to the turns of the windings.

$$v_1 = n_1 \frac{d\Phi}{dt}; \quad v_2 = n_2 \frac{d\Phi}{dt} \tag{1.20}$$

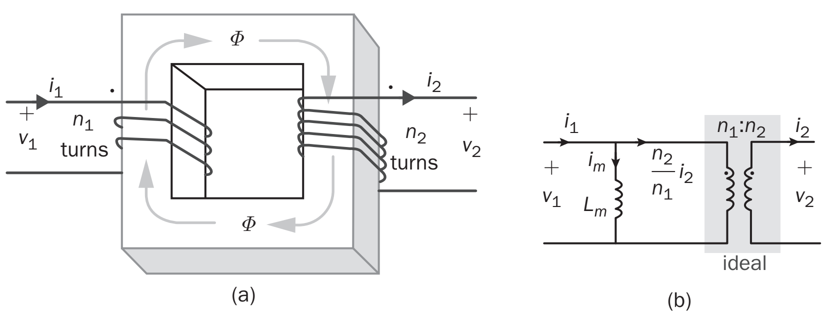



**FIGURE 1.19** Two-winding power transformer: (*a*) illustration; (*b*) equivalent circuit.

$$\frac{v_1}{n_1} = \frac{v_2}{n_2} \tag{1.21}$$

The construction of power transformers cannot avoid the presence of magnetizing inductance, $L_m$, as indicated in the equivalent circuit of Fig. 1.19*b*. The definition of a power transformer is not limited to the function of galvanic isolation. Therefore, one category is the autotransformer, which commonly provides step-down voltage conversion. The voltage conversion ratio depends on the split of the winding turns since the windings share the same magnetic flux. In power electronics, the transformer application does not follow the strict definition or design of power transformers used for the traditional power system. The transformed voltage and current are not limited to the standard sinusoidal AC waveforms. The trends are to operate in high frequency (HF) and to directly accommodate switched waveforms, which can significantly reduce the transformer's size and cost. It serves the same function but differs markedly in design and utilization.

## 1.9 Loss-Free Power Conversion

The loss-free switching concept follows a simple idea: "When electric power is needed, turn on the switch; otherwise, turn it off!" The application of on/off cycle control can be traced back to the old electric cooktop or oven toaster with adjustable temperature. The "click" sound can be frequently heard during cooking. It becomes the early stage of the on/off switching technology to regulate power from the source to the load and control temperature. The operation is theoretically loss-free and then widely extended to the switching concept in modern power electronics. The operation concept can be readily demonstrated by the equivalent circuit shown in Fig. 1.20.

The resistor represents the burning element that converts electric power into thermal energy. The "click" sound results from the switching operation of the single-pole, double-throw (SPDT) relay that is controlled for the switching between "AC" and "BC." The "AC" connection links the source to the load resistor, generates heat, and increases the cooking temperature. On the contrary, the "BC" connection cuts the link from the power source and lower down the cooking temperature. The "BC" connection is essential when inductance presents in the load side. The energy consumption is related to the heat level, which can be regulated by the controllable "on" time of the "AC" connection. The ratio between the "on" and "off" is the control parameter to determine the delivered energy over a certain period. The concept is simple to deliver the desired temperature for proper cooking. The intrinsic disadvantage lies in the signal of $v_o$, which is chopped and discontinuous due to the on/off switching operation. The power quality is considerably low for the load, while having impacts on the source as well. The accumulating

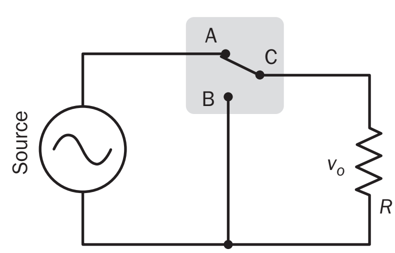



**FIGURE 1.20** Equivalent circuit of timer-controlled burner.

time of the "AC" connection determines the energy dissipating on the load over a particular period regardless of the switching frequency. However, a fast on/off switching is desirable since it can show low up-down ripples regarding the temperature.

The concept of loss-free power conversion leads to modern switching operation of power converters. The electromechanical relay has been replaced by solid-state relays, which are formed by power semiconductors to achieve the same function of on/off switching. Such switches are generally smaller, quieter, faster, of longer cycle life, and easier to drive in comparison with the electromechanical relays. The on/off switching can be combined with low-pass filtering to achieve DC or AC with high power quality. The advances in power semiconductors have provided the technology that is behind the achievement of the wide utilization of solid-state switches in power electronics. The modern semiconductor device is also capable of high-frequency switching, e.g., 1 MHz.

## Bibliography

1. International Standard, *IEC 60038: IEC standard voltages*, International Electrotechnical Commission, 2012.
2. L. W. Nagel, "The 40th Anniversary of SPICE: An IEEE Milestone," *IEEE Solid-State Circuits Magazine*, vol. 3, no. 2, Spring 2011.
3. W. Xiao, *Photovoltaic power systems: modeling, design, and control*, Wiley, 2017.

## Problems

**1.1** Find more power electronics applications in the real world.

**1.2** Following the product data in Table 1.1, determine the inductance values when the the winding turns become 3.

**1.3** Find a magnetic core datasheet; explain all important parameters; use the core to design a 120-μH inductor.

**1.4** Search which industry is using power supplies rated at 400-Hz AC as the fundamental frequency. Explain the constraint and advantage.

**1.5** Discuss why galvanic isolation is important for certain applications.

**1.6** Search online to find the principle of induction cooking and explain the difference between induction cooking and microwave cooking.