1 Introduction

In this chapter we describe power electronics and present a brief introduction to semiconductor switching devices and magnetic components. An introduction to these circuit elements is necessary because we use them in Part I, although we do not discuss them in detail until Part III. We also introduce in this chapter nomenclature that we use throughout the book.

1.1 Power Electronic Circuits

The dominant application of electronics today is to process information. The computer industry is the biggest user of semiconductor devices, and consumer electronics, including cameras and cell phones, is second. While all these applications require power (from a wall plug or a battery), their primary function is to process information; for instance, to take the digital optical signal produced by a cell phone camera and transform it into a photographic image. Power electronic circuits, on the other hand, are principally concerned with processing energy. They convert electrical energy from the form supplied by a source to the form required by a load. For example, the part of a computer that takes the ac mains voltage and changes it to the low-voltage dc required by the logic chips is a power electronic circuit (often abbreviated as *power circuit*). In many applications, the conversion process concludes with mechanical motion. In these cases the power circuit converts electric energy to the form required by the electromechanical transducer, such as a dc or ac motor.

Efficiency is an important concern in any energy processing system, for the difference between the energy into the system and the energy out is usually converted to heat. Although the cost of energy is sometimes a consideration, the most unpleasant consequence of generating heat is that it must be removed from the system. This consideration alone largely dictates the size of power electronic apparatus. A power circuit must, therefore, be designed to operate as efficiently as possible. The efficiency of very large systems exceeds 99%. High efficiency is achieved by using power semiconductor devices (where their voltage is nearly zero when they are on, and their current is nearly zero when they are off) to minimize their dissipation.[†] The only other components in the basic power circuit are inductors, capacitors, and transformers, so the ideal power circuit is lossless.

[†] Exceptions, such as linear voltage regulators, are so few that we do not consider them explicitly in this book.

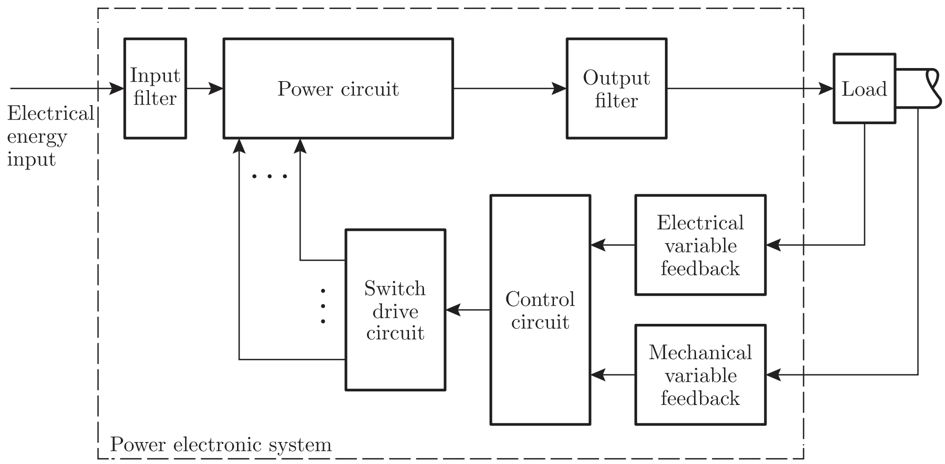

Figure 1.1 A block diagram of a typical power electronic system.

A power electronic system typically consists of much more than a power circuit, as shown in Fig. 1.1. Switching creates waveforms with harmonics that may be undesirable because they interfere with proper operation of the load or other equipment, so filters are often employed at the inputs and outputs of the power circuit. The system load, which may be electrical or electromechanical, is controlled via the feedback of electrical and/or electromechanical variables to a control circuit. This control circuit processes the feedback signals and drives the switches in the power circuit according to the demands of these signals. The system also includes mechanical elements, such as heatsinks and structures to support the physically large components of the power circuit.

In our circuit drawings, we use a capacitor symbol with a curved plate to differentiate it from the symbol for a contactor. We also find it a more elegant symbol than a pair of parallel plates. For electrolytic capacitors, which are polarized, the curved plate represents the negative terminal. We do not worry about this in our diagrams as the type of capacitor is irrelevant.

1.2 Power Semiconductor Switches

The basic semiconductor devices used as switches in power electronic circuits are the bipolar and Schottky diodes, the bipolar junction transistor (BJT), the metal-oxide-semiconductor field-effect transistor (MOSFET), the insulated-gate bipolar transistor (IGBT), and a class of latching bipolar devices known as thyristors, the most common of which is the silicon controlled rectifier (SCR). Their circuit symbols and operating regions in the v–i plane are shown in Fig. 1.2. We discuss these and other hybrid devices in detail in Part III.

What follows is a brief description of the salient operating characteristics of each device shown in Fig. 1.2. This information allows us to present the basic operation of power electronic circuits without first mastering Part III.

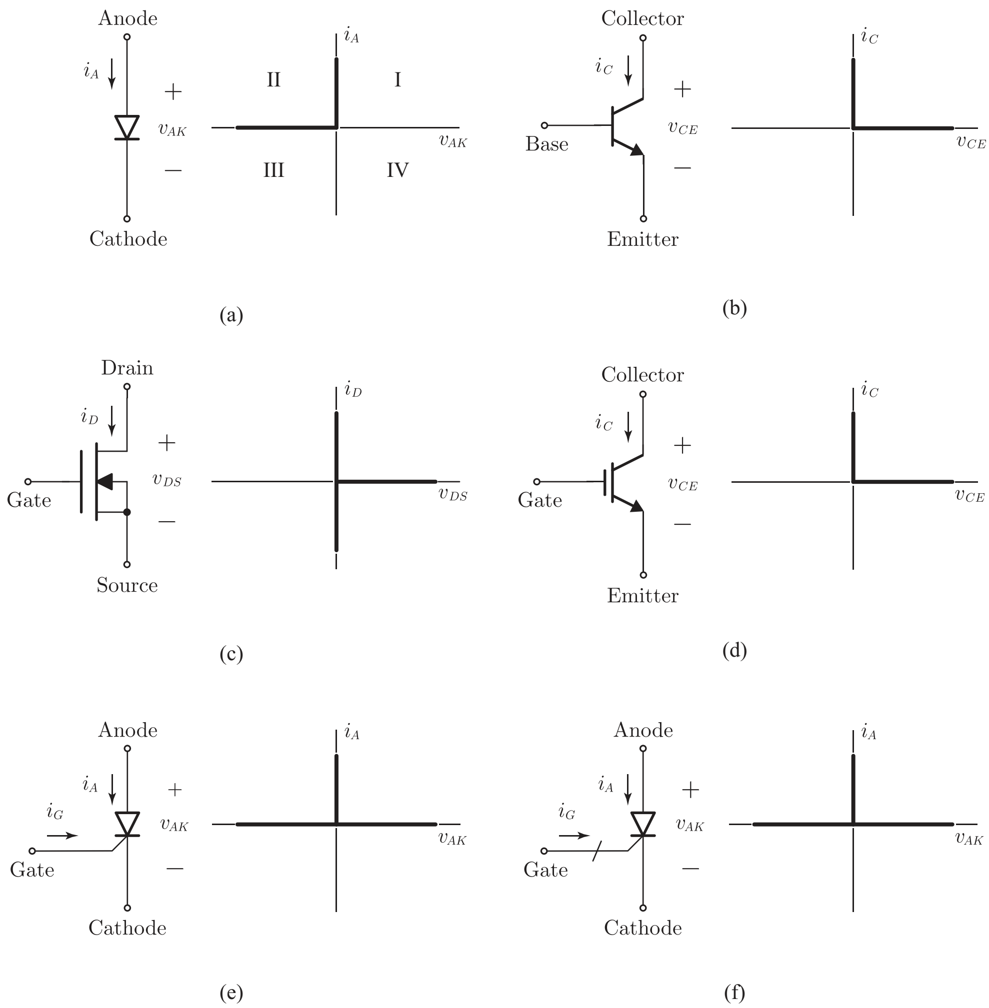

Figure 1.2 Circuit symbols and operating regions for power semiconductor devices: (a) diode; (b) (npn) bipolar junction transistor (BJT); (c) (n-channel) power metal-oxide-semiconductor field-effect transistor (MOSFET); (d) insulated gate bipolar transistor (IGBT); (e) silicon controlled rectifier (SCR); (f) gate turn-off thyristor (GTO).

1.2.1 Diode

The diode, whose symbol and variable definitions are shown in Fig. 1.2(a), is an uncontrollable semiconductor switch. It is uncontrollable because whether it is on or off is determined by the voltages and currents in the network, not by any action we can take. When on, its anode current, i_A, is positive. When off, its anode–cathode voltage, v_{AK}, is negative.† The diode switches in response to the behavior of its terminal variables. If it is off and the circuit causes v_{AK} to try

† The use of "*K*" instead of "*C*" reflects the Greek origin of the word cathode, or *kathodos*, meaning "way down," that is, the negative terminal.

to go positive, the diode will turn on. If on, the diode will turn off if the circuit tries to force i_A to go negative.

1.2.2 Transistor

Transistors, whether of the bipolar or MOS type, are fully controllable switches. They possess a third terminal (the *base* terminal for the BJT and the *gate* terminal for the MOSFET and IGBT) from which we can turn the device on and off. Control of the BJT requires a base current, while the MOSFET and IGBT require a gate voltage. The symbols and terminal variables for the npn BJT, n-channel power MOSFET, and IGBT are shown in Fig. 1.2(b), (c), and (d) respectively.

The BJT and IGBT can carry current in only one direction. For the npn BJT and IGBT shown in the figure, this direction is $i_C > 0$. The power MOSFET, because of its physical structure, can carry current in either direction. The unique structure of the power MOSFET results in a diode, known as the *body diode*, between its source and drain, represented by the arrowhead in the symbol. While this diode allows negative drain current conduction, this negative current can be supported with a lower forward drop by applying a gate signal to the device to turn on the channel and use it instead of the body diode to conduct the current.

When off, all three transistors can support only one polarity of voltage, which, for the transistors shown, are $v_{CE} > 0$ and $v_{DS} > 0$. These voltage and current polarities are reversed for the pnp BJT and the p-channel MOSFET. For reasons discussed in Part III, npn and n-channel devices are the most commonly used types of power transistors. Because of their ease and efficiency of control, and their low on-state voltage, MOSFETs and IGBTs are the dominant form of switch used in power electronic circuits.

1.2.3 Thyristor

The only members of the thyristor family that we describe in this introduction are the SCR and the gate turn-off thyrisor (GTO), whose circuit symbols are shown in Fig. 1.2(e) and (f).

The SCR is a switch that in some ways can be thought of as a “semi-controllable” diode. If no signal is applied to the gate, the device will remain off, independent of the polarity of v_{AK}. To turn the SCR on, a brief pulse of current, i_G, is applied to the gate terminal during a time when $v_{AK} > 0$. This initiates a regenerative turn-on process that quickly latches the SCR in the on state, in which $v_{AK} \approx 0$ and the gate no longer has any control over the device. When in this on state, the SCR can conduct only positive i_A. It turns off when i_A tries to go negative. So once on, the SCR behaves as a diode. In summary, the SCR is a diode whose turn-on can be inhibited by not applying a gate pulse.

The GTO is an SCR which has been constructed to enable a negative gate current to turn it off in the presence of $i_{AK} > 0$. The turn-off gain, defined as the ratio of I_{AK} to the negative gate current required to turn the device off, is typically in the low single digits. Two types of GTOs are available: asymmetrical GTOs, which cannot block a high reverse voltage, and symmetrical GTOs, which can.

1.3 Transformers

Transformers are a prominent feature of power electronic circuits. We treat them extensively in Part III, but the following introduction to their behavior permits us to use them as circuit elements in Parts I and II.

Transformers are employed to provide electric isolation and the step-up or step-down of ac voltages and currents. The *ideal transformer* shown in Fig. 1.3(a) has two windings of N_1 and N_2 turns. Dots indicate the orientation of the windings. If a voltage is applied to one winding so that the dot is positive, the dotted ends of all the other windings (only one in this case) are also positive. If its terminal variables are defined relative to the dots, as shown in Fig. 1.3(a), the ideal transformer has the following terminal relationships:

$$\frac{v_1}{v_2} = \frac{N_1}{N_2}, \tag{1.1}$$

$$\frac{i_1}{i_2} = -\frac{N_2}{N_1}. \tag{1.2}$$

From (1.1) and (1.2), we deduce that $v_1 i_1 = -v_2 i_2$; that is, the instantaneous power into one port is equal to the instantaneous power out of the other. The ideal transformer neither dissipates nor stores energy. A straightforward application of the above relations also shows that if an impedance of value Z_1 is connected to terminals 1–1′, an impedance of value $Z_2 = (N_2/N_1)^2 Z_1$ is measured at terminals 2–2′.

A transformer is ideal if it obeys (1.1) and (1.2), but no practical transformer is ideal. In most transformers, the principal departures from ideal result in some voltage and current being "lost" in the transformation, so terminal variables are not precisely related by (1.1) and (1.2). A model that represents these effects is shown in Fig. 1.3(b). Some of the terminal current i_1' is shunted through the *magnetizing inductance* L_μ and is called the *magnetizing current*. This is the current required to establish the necessary flux in the transformer core. So whereas i_1 and i_2 are still related by (1.1) and (1.2), the real terminal currents i_1' and i_2' are not. Similarly, the real terminal voltages v_1' and v_2' differ from v_1 and v_2 by the drops across $L_{\ell 1}$ and $L_{\ell 2}$, which are called *leakage*

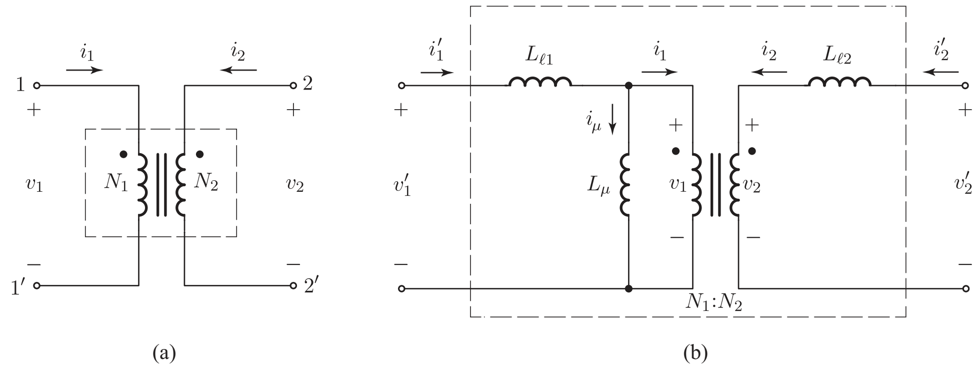

Figure 1.3 (a) The ideal transformer model. (b) A more practical model, with the effects of magnetizing inductance (L_μ) and leakage ($L_{\ell 1}$ and $L_{\ell 2}$) included.

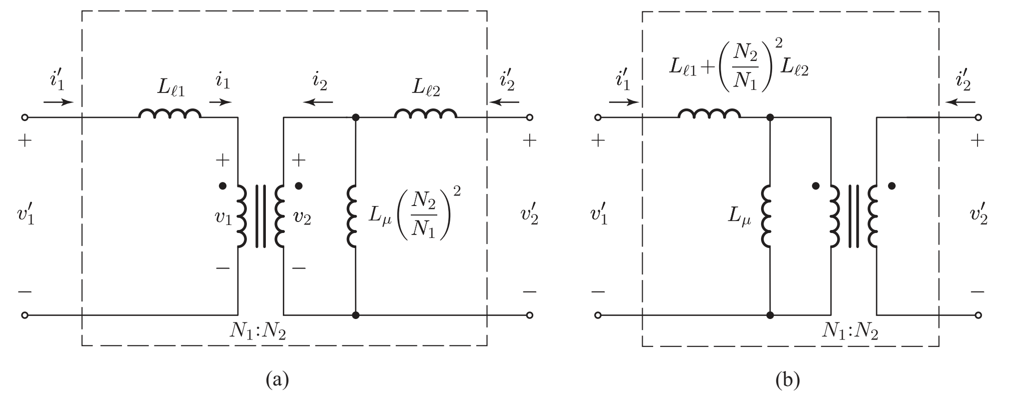

Figure 1.4 (a) The model of Fig. 1.3(b), with the magnetizing inductance placed on the N_2 side of the ideal transformer. (b) The model of Fig. 1.3(b), simplified by reflecting $L_{\ell 2}$ through the ideal transformer and combining it with $L_{\ell 1}$.

inductances. These represent flux linking one winding of the transformer but not the other. In Chapter 18 we describe the physical origins of these effects in much greater detail.

Figure 1.3(b) shows L_μ across the winding N_1. We can, however, *reflect* it through the ideal transformer so that it appears across the N_2 winding, as shown in Fig. 1.4(a). Sometimes we do this because the result is analytically more convenient to use. Although two leakage inductances, one for each winding, are shown in Fig. 1.3(b), they are often combined by reflecting one through the ideal transformer. If the voltage drop across this inductor is small relative to the voltage across L_μ, then L_μ can be moved inside this reflected inductance without introducing much of an error, and the two leakage inductances can be combined. The resulting approximate model is shown in Fig. 1.4(b).

Another useful model transformation is to reflect the entire circuit on one side of the ideal transformer to the other side. A transformation of this kind is shown in Fig. 1.5. There, the N_2 side circuit, C_o and R_o, has been "brought through" the ideal transformer. Of course, the isolation function is lost in the transformation, which makes the technique inappropriate for the analysis of some circuits.

We can calculate or measure the leakage and magnetizing inductances of transformers, and we sometimes construct transformers to have specific values for these parameters. And, even though we have been discussing only two-winding transformers, similar but somewhat more complicated considerations apply to the modeling of transformers with more than two windings. Other practical considerations, such as the resistance of the windings or losses in the core, are represented by the addition of appropriate elements to the model of Fig. 1.3(b).

Figures 1.3(b) and 1.4 show the schematic transformer representation that we use throughout this book: the circuit model being used to describe a transformer is enclosed in a dashed box. The model frequently has an ideal transformer as one of its elements, represented by windings with adjacent double bars. Some schematic conventions utilize the double bars to represent an iron core, but we use the bars to indicate the coupled windings of an ideal transformer when

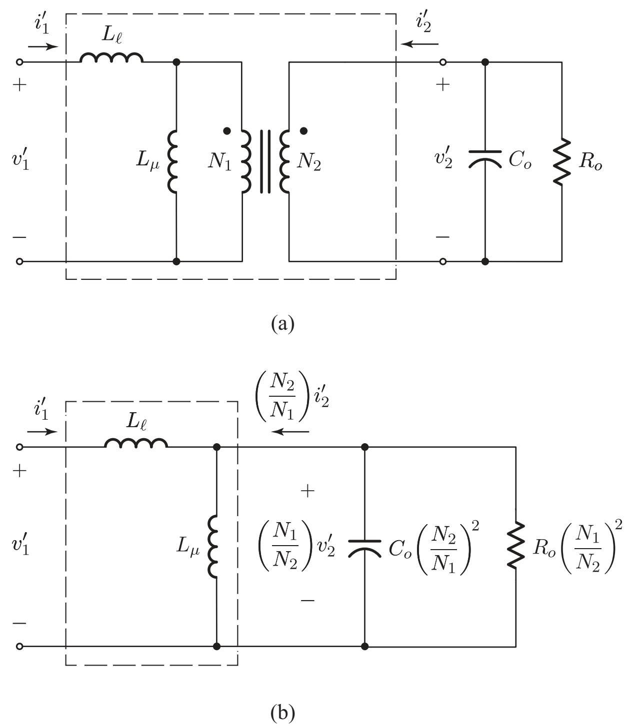

Figure 1.5 (a) A transformer with an *RC* load on the N_2 side. (b) The circuit of (a) with all the N_2 side components reflected to the N_1 side so that the ideal transformer can be eliminated from the transformer model.

it appears inside a dashed box. This convention avoids ambiguity and schematic clutter when more than two windings are involved.

1.4 Nomenclature

Because we discuss several different kinds of variables, we establish some notation and definitions now to permit a quick entry into the subject, and to avoid confusion later.

- Variables that may be time dependent are represented by lowercase names, such as v_1. When necessary for clarification, the time dependence is explicitly indicated, as in $v_1(t)$.
- Variables that are held constant are represented by uppercase names, such as V_1 or V_{dc}.
- The *average value* or *dc component* of a variable that varies periodically in time is denoted by angle brackets around the variable, for example $\langle v_o(t)\rangle = V_o$. Since this average value is a constant, it is represented by an uppercase name.
- The *local average* is defined for a possibly non-periodic waveform, say $x(t)$. It is the average over a time window of fixed length that moves with t; the window is usually chosen to be short

relative to the timescales of interest. The particular version defined in Chapter 12 is denoted by an overbar, so $\overline{x}(t)$.

- Perturbations around a constant value are indicated by a tilde, for instance $\widetilde{v}_C = v_C - V_C$.
- The *root mean square* (rms) value of a periodic variable $v(t)$ with period T is denoted by V_{rms} and defined as $V_{\mathrm{rms}} = \sqrt{(1/T)\int_0^T v^2(\tau)\,d\tau}$. The integral may be taken over any contiguous interval of length T.
- Harmonic components of a (non-sinusoidal) periodic waveform are indicated by an additional subscript representing the harmonic number, for example $v_a = v_{a_1} + v_{a_3} + v_{a_5} + \cdots$.
- A sinusoidal function $v(t)$ can be written in the form

$$v(t) = V\cos(\omega t + \phi) = \mathrm{Re}\left(Ve^{j\phi}e^{j\omega t}\right) = \mathrm{Re}\left(\widehat{V}e^{j\omega t}\right),$$

where "Re" denotes the real part of the complex number that follows it. The *complex amplitude* of $v(t)$ is the complex number $\widehat{V} = Ve^{j\phi}$, and (particularly when plotted in the complex plane) is also termed the *phasor* associated with the sinusoid.

1.5 Bibliographies

We include an annotated bibliography at the end of most chapters. It provides sources of additional information on topics that you might want to pursue further.

1.6 Problems

Each chapter includes end-of-chapter problems that are designed to introduce variations or extensions of the chapter's material, or to provide students the opportunity to examine more closely concepts or circuits introduced in the chapter. They are not simply exercises in applying formulas. Further practice and confidence in applying and extending the material in a chapter can be obtained by filling in details of the derivations and examples, or by developing parallel results for circuits or converters in the same family or category as those explicitly treated in the chapter.