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Power electronic devices, circuits, topology, and control

1.1 Power electronics

Power electronics is a branch of engineering that combines the generation, transformation, and distribution of electrical energy through electronic means. In 1974, W. Newell described power electronics as a combination of electrical engineering, electronics, and control theory, which has been widely accepted today [1].

Power electronics has merged into various residential, commercial, and industrial domains. Application of power electronics encompasses renewable energy, transportation, defense, communication, manufacturing, utilities, and appliances. In the renewable energy field, power electronics covers distributed generation, control of electric power quality, wind power generation, and solar energy conversion. Modern power electronics consists of the research and development of novel power electronic semiconductors, new topologies, and new control algorithms. Power electronics is an interdisciplinary subject that involves traditional electrical engineering, electromagnetics, microelectronics, control, thermal fluid dynamics, and computer science.

More specifically, research in power electronics includes but is not limited to:

1. Theory, manufacture, and application of power electronic semiconductor devices.
2. Power electronic circuits, devices, systems and their relevant modeling, simulation, and computer-aided design.
3. Prediction and improvement of system reliability.

Transients of Modern Power Electronics, First Edition. Hua Bai and Chris Mi.

4. Motor drive design, traction, and automation control.
5. Techniques for electromagnetic design and measurement.
6. Power electronics-based flexible AC transmission systems (FACTSs).
7. Advanced control techniques.

The study of power semiconductor devices is the foundation of modern power electronics. It began with the introduction of thyristors in the late 1950s. Today there are several types of power semiconductor devices available for power electronics applications, including gate turn-off thyristors (GTOs), power Darlington transistors, power metal oxide semiconductor field effect transistors (MOSFETs), insulated-gate bipolar transistors (IGBTs), and integrated-gate commutated thyristors (IGCTs). Recently, new materials with wideband energy gaps, such as silicon carbide (SiC) and gallium arsenide (GaS), are leading the direction of next-generation power semiconductor devices.

With the development of computer science and control theory, power electronics began to be utilized for industrial applications, for instance in motor drive and traction applications. Various remarkable control algorithms, such as field-oriented control (FOC) and direct torque control (DTC), have been developed for induction motor drives and permanent magnet motor drives [2–5].

With the development of power electronic technology, especially the maturity of high-voltage and high-power semiconductors, power electronics began to play an active role in power systems, improving their performance, cost, and controllability. FACTS is a typical example of power electronics in power system applications. The static reactive-power compensator (STATCOM) can eliminate excessive reactive power in the system so as to make the local power system more robust, environmentally friendly, and flexible [6–8].

Power supply is another area for the most popular power electronics applications. Spanning a wide range of power ratings, from ultralow power of a few milliwatts to several megawatts, and from a few volts to more than a thousand volts, power supplies based on power electronics occupy a large amount of market share. DC–DC converters [9], DC–AC inverters [10], AC–DC rectifiers [11], and AC–AC cyclo-converters [12] are typical of this field. Research in these power electronic technologies helps diversify topologies and the control methods. Furthermore, all of these topologies can be mathematically described, modeled, and simulated. For example, in order to mitigate thermal generation by the switching losses in hard-switched converters, soft-switching techniques were developed where nearly all circuits have their own unique topology mathematically modeled according to their own operation modes [13–17]. Advanced control algorithms and diverse topologies can all be validated through the use of sophisticated analytical and numerical analysis tools, especially after the feasibility and accuracy of such tools have been validated widely in consumer and industrial applications.

1.2 The evolution of power device technology

Power semiconductors are the fundamental building blocks of power electronics. Each generation of semiconductors determines its corresponding generation of power electronic technology. The first power electronic device ever created was the mercury arc rectifier in 1900. The grid-controlled vacuum rectifier, ignitron, and thyratron followed later. These devices were found in numerous applications in industrial power control until 1950. At this time, the invention of the transistor in 1948 marked a revolution in the field of electronics. It also paved the way for the introduction of the silicon-controlled rectifier, announced by General Electric in 1957, commonly known nowadays as the thyristor.

All of these semiconductor devices can be classified as the following three types:

1. **Uncontrolled devices:** devices that do not need any trigger signals to control their on/off action, such as a rectifying diode.
2. **Semi-controlled devices:** devices that can be triggered on but cannot be turned off through control signals. A typical example is a thyristor, where the only way to turn it off is to reverse the polarity of the voltage across it and wait until the current reaches zero.
3. **Fully controlled devices:** also known as self-controlled devices, these devices can be turned on and off by the gate signals. Typical examples include bipolar junction transistors (BJTs), IGBTs, MOSFETs, GTOs, and IGCTs.

The common aspects of thyristors and GTOs are their high power ratings (most recently reaching over 6000 V/6000 A) and slow switching speed. They have always been the primary choice in high-voltage and high-power inverters (voltage source or current source inverters) until IGCTs emerged. Due to their slow switching speed, the switching frequency of thyristors and GTOs cannot be too high, otherwise a large switching loss will eventually damage the device. In medium-voltage applications, thyristors and GTOs have been replaced by high-voltage IGBTs or IGCTs. However, in high-voltage DC applications, thyristors and GTOs still dominate.

BJTs and MOSFETs were developed simultaneously in the late 1970s. BJTs are current-controlled devices while MOSFETs are voltage-controlled devices. Power BJTs have gradually been phased out while MOSFETs and IGBTs have become dominant in power electronics, especially in low- to medium-power applications. Compared to BJTs, MOSFETs can operate at higher switching frequencies while having lower switching losses. The only disadvantage of MOSFETs is their higher on-state voltage compared to that of IGBTs.

An IGBT is basically a combination of a BJT and a MOSFET [18]. It has been an important milestone in the history of power semiconductor devices. Its switching frequency can be much higher than that of BJTs, and its electrical capabilities are much higher than those of MOSFETs. Currently, IGBTs can reach 6000 V/600 A or 3500 V/1200 A. The operational details of IGBTs will be further explained in the next few chapters.

IGCTs were introduced by ABB in 1997 [19]. Presently they can reach 4500 V/4000 A. Essentially, a gate-controlled thyristor (GCT) is a four-layer thyristor, being simple to turn on but difficult to turn off. However, with the introduction of "integrated gates," the turn-off process is accelerated by shifting all the current from the GCT to its gate. Therefore, in the turn-off process, an IGCT behaves as a transistor. The advantages of IGCTs over GTOs include: faster switching, uniform temperature distribution within the junction, and snubber-free operation. One of the IGCT's disadvantages is that a short circuit is formed across its terminals during failure, which is not desirable in most power electronics applications.

Power semiconductor device development now extends beyond just semiconductor design. With the increase in various power electronics applications, more and more power devices tend to integrate gate-drive circuits, overcurrent protection, and other additional functions inside the module. Thus intelligent power modules (IPMs) have emerged for up to several hundred kilowatts for IGBTs [20]. IGCTs are typical IPMs. An IGCT integrates the gate with a GCT. Some types of IGCTs can even process self-diagnosis and feed back their status to the microcontroller.

The above semiconductors are silicon based. It is expected that in the future silicon devices will still keep their dominance. However, other materials have shown promise as well. For example, the silicon carbide (SiC) semiconductor has a wider bandgap (3.0 eV for 6H-SiC), higher saturation velocity (2×10^7 cm/s), higher thermal conductivity (3.3–4.9 W/cm K), lower on-state resistance (1 mΩ/cm^2), and higher breakdown electric field strength (2.4 MV/cm) [21]. Therefore, SiC-based power devices are expected to show superior performance compared to traditional silicon (Si) power switches. Since SiC power devices can operate at higher switching frequencies, the size of passive components (inductors and capacitors) can be reduced significantly in SiC-based power electronic converters. The associated heat sink size will also be reduced due to the lower losses compared to a conventional power electronic converter. Higher junction temperatures will result in much simpler cooling mechanisms. It is predicted that SiC devices will have a significant impact on the next generation of power electronic systems.

1.3 Power electronic circuit topology

Power semiconductor switches are the fundamental building blocks of power electronic converters. Switching actions are the core of power electronic converters.

1.3.1 Switching

Switches are the components responsible for controlling energy flow in power electronics. Consider an IGBT as an example. When the gate is supplied with a voltage higher than its turn-on threshold, the collector and emitter will show a low impedance between its terminals, therefore the device will have an "on state" equivalent to a closed switch. When the gate voltage is lower than its turn-on threshold, high impedance will be present between the collector and emitter, preventing current flow and transitioning to an "off state." Switching is the repetitive action of changing the semiconductor switch from an on state to an off state and vice versa. By controlling the state of the power switches, the energy flow is controlled through different paths.

Figure 1.1 shows a typical buck converter topology. The buck or step-down topology converts an input DC voltage to a lower output DC voltage. This is accomplished by controlling its main switching device, rerouting the flow of energy, and converting from a higher voltage to a lower voltage.

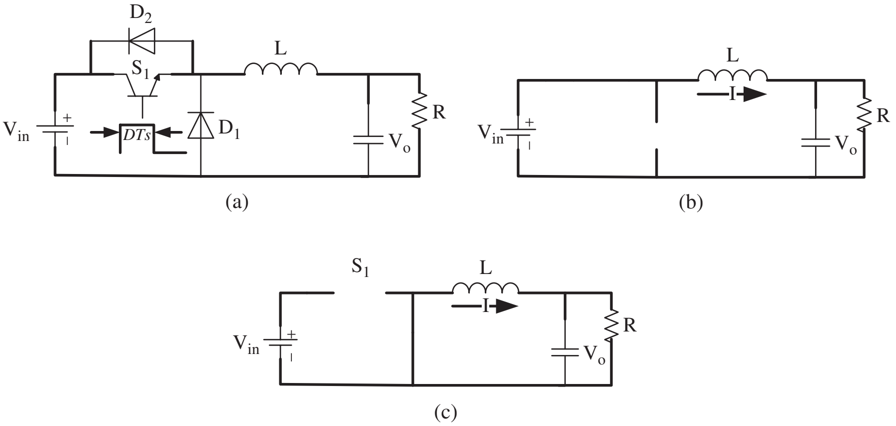


Figure 1.1 A buck circuit and its topology under different operation modes: (a) a buck converter, (b) topology when S_1 *is on, and (c) topology when* S_1 *is off.*

The buck converter consists of a primary power input V_{in}, an active switch S_1 (parallel diode D_2 is temporarily neglected), a clamping diode D_1, an inductor L, and an output capacitor holding voltage V_o which is assumed to be constant. All elements are shown in Figure 1.1a. R is added as a load to the output of the circuit. In this topology, D is the switch-on/off duty cycle and T_s is the switching period. When S_1 is on, the equivalent circuit is illustrated in Figure 1.1b where the current of the inductor increases linearly. The voltage drop across L is $V_{in} - V_o$. When S_1 is off, the equivalent circuit is shown in Figure 1.1c where the inductor current decreases linearly. Since current through the inductor cannot stop instantaneously, the inductor voltage will reverse its direction, therefore forcing the clamping diode to conduct. The voltage drop across L is now $-V_o$. By switching on and off alternately, the inductor average current is maintained and keeps up with the output power requirements.

For the purpose of analyzing this topology, the switching actions are assumed to take place in a negligible time interval. Therefore the switching process is divided into two independent states. Based on this premise, the buck converter shown in Figure 1.1a is mathematically modeled as follows.

When S_1 is on,

$$L\frac{di}{dt} = V_{in} - V_o \tag{1.1}$$

When S_1 is off,

$$L\frac{di}{dt} = 0 - V_o \tag{1.2}$$

It is observed that the switching action only provides a possible alternative for energy flow. It does not have to change the circuit topology and thereby the energy loop. For example, in Figure 1.1a, if, for some reason, the initial current in the inductor flows in the opposite direction, the current flow is always through D_2 regardless of the on or off state of S_1.

1.3.2 Basic switching cell

Figure 1.2 shows two basic switching cells defined in [22] a P cell and an N-cell. Each cell consists of one active switch, one diode and one current load; (+) stands for the positive DC-bus voltage and (−) represents the negative DC-bus voltage; (→) means current flows out of the bridge and (←) for current flowing into the bridge. For the P-cell, the active switching device is connected to the positive terminal (+). The cathode of the diode and the other node of the active switch are connected to the load. This is the opposite for the N-cell, which is shown as Figure 1.2b.

All power electronic converters are different combinations of the above basic cells. The reason lies in the theory of energy continuity. When an active switch is turned off, an alternative loop is needed to exhaust the excessive energy. Therefore an auxiliary diode should exist to commute the current. This diode is also called a freewheeling diode.

1.3.3 Circuit topology of power electronics

Power electronic circuits convert electrical energy from one form to another. In [23], a power electronic circuit is defined as “the part of a system that actually manipulates the flow of energy.” It also provides “an interface between two other systems.”

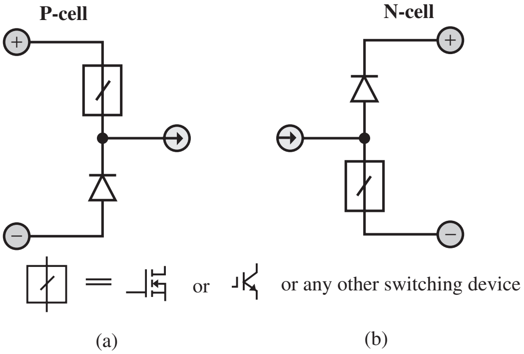


Figure 1.2 Basic switching cells: (a) a P-cell and (b) an N-cell. © [2009] IEEE. Reprinted, with permission, from IPEMC 2009.

In the theoretical analysis of power electronics, the components of power electronic systems and connections are considered lossless. With this assumption, circuit topologies and the theoretical investigation of the power electronic circuits can be greatly simplified.

In the domain of power electronics, topology stands for the specific position of each component and its electrical relationships. Junctions, loops, and simplified symbols of the components are the major elements of power electronics topologies.

Due to the existence of semiconductor switches, power electronics topologies have their own peculiarities, such as:

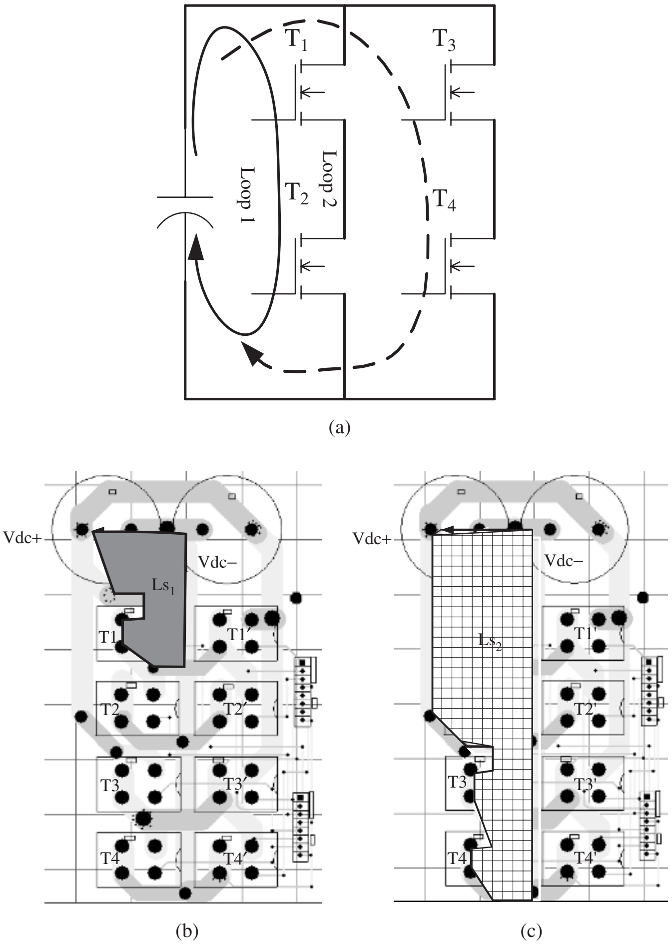
1. **Time variant:** the operation of the circuit is different depending on whether the switch is on or off as shown in Figure 1.1. Considering the configuration of Figure 1.1b as A and that of Figure 1.1c as B, as the time step to analyze the topology is reduced, some intermediate processes need to be taken into account, such as the switching process of the switches. Therefore a potential configuration C exists between A and B, where some other parameters, for example, the junction capacitance and stray inductance, should be considered. This will be illustrated in later chapters.

2. **Space variant:** if the wire connections are regarded as ideal conductors, the physical location of the circuit components has no effect on the circuit topology. However, in many specific applications where a more detailed analysis is needed, those connections cannot be regarded as ideal wires. Stray inductance and capacitance need to be included in the circuits.

In Figure 1.3, an H-bridge inverter is shown. Leg 1 comprises T_1 and T_2, and leg 2 comprises T_3 and T_4. The physical placement of these devices is shown in Figure 1.3b, where leg 2 is more distant away from the DC-bus capacitor than leg 1. Therefore the stray inductance of loop 2 is larger than loop 1.

Based on the above analysis, the electrical behavior is different when the parasitic/stray elements are included. There is also a big difference when the concept of topology is used in the investigation of transient processes, as defined in [24].

For the two bridges of three-level converters, the traditional topology assumes that the semiconductors, such as IGCTU1 and IGCTV1 in Figure 1.4, are subject to the same voltage stress in the switching-off process. However, in Figure 1.4, large amounts of stray inductances are present in the commutating process. They exist in the loop made of snubber diodes (Ls_1–Ls_6), clamping diodes, IGCTs, and so on. Due to the different configuration of the loops and different distances from the snubber circuit, the parasitic inductances of the commutating loop

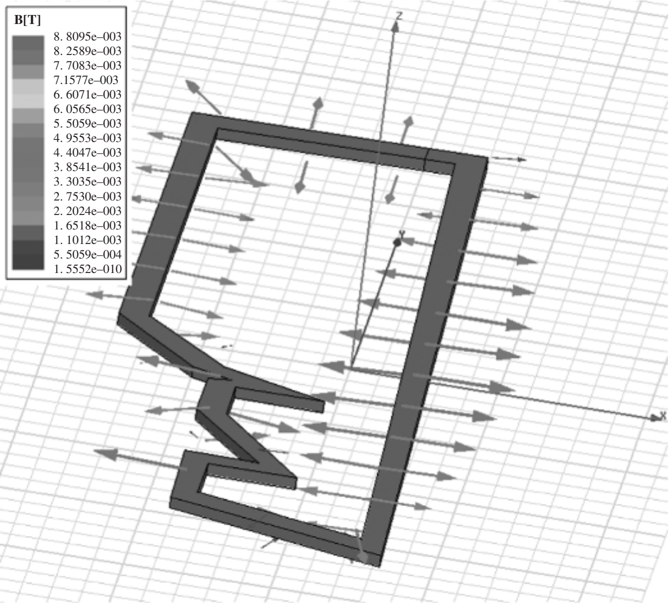


(a)

(b)

(c)

Figure 1.3 H-bridge loops and their stray inductance: (a) H-bridge, showing loop 1 and loop 2, (b) stray inductance of loop 1, (c) stray inductance of loop 2, and (d) finite-element-method analysis for loop 2.



(d)

Figure 1.3 (continued)

for different IGCTs vary, in the case of figure shown, being $L_1 = 350\,\text{nH}$ and $L_2 = 267\,\text{nH}$. The reason why $L_2 < L_1$ is because the snubber circuit is closer to bridge V and more distant away from bridge U. Note that Figure 1.4 is only a schematic representation and does not show the real distribution of components and loops in three dimensions. The unequal distance to the snubber circuit generates the voltage spikes undertaken by IGCTs.

In order to achieve high-efficiency energy conversion, not only the control algorithm, but also the energy loop and the energy storage should be optimized. These parasitic loops will present some side effects, as illustrated in the following chapters.

1.4 Pulse-width modulation control

Circuit topology provides an effective way to analyze power electronic systems. The switches in the topology are controlled through triggering the gate signals which in the real world are typically digital pulses generated by microcontrollers with certain control algorithms. Among all the signal modulation schemes, pulse-width modulation (PWM) is the most popular strategy and involves modulation of the duty cycle to produce the required voltage, current, or power to the load [25]. Particularly in the domain of power supply and motor control, PWM plays a dominant role.

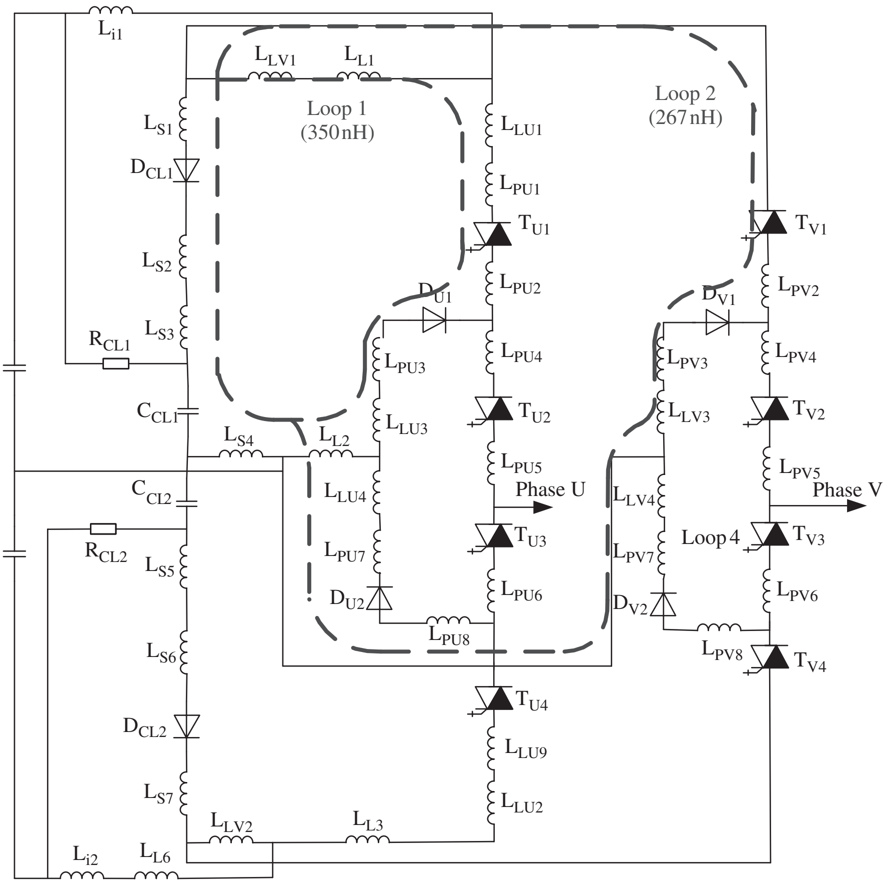


Figure 1.4 Transient commutating topology.

PWM utilizes a pulse sequence whose pulse width is varied over time or over different switching cycles, resulting in the variation of the average value of the waveform. Consider a square waveform as shown in Figure 1.5a, which has a minimum value $y_{\min}$, a maximum value $y_{\max}$, and a duty ratio D. The average value of the waveform is then

$$\begin{aligned}\bar{y} &= \frac{1}{T}\left(\int_0^{DT} y_{\max}\,dt + \int_{DT}^{T} y_{\min}\,dt\right)\\ &= \frac{DTy_{\max} + (T - DT)\,y_{\min}}{T} \\ &= Dy_{\max} + (1 - D)\,y_{\min}\end{aligned} \tag{1.3}$$

Suppose $y_{\min} = 0$ and $y_{\max} = 1$; then Equation 1.3 turns out to be $\bar{y} = D$.

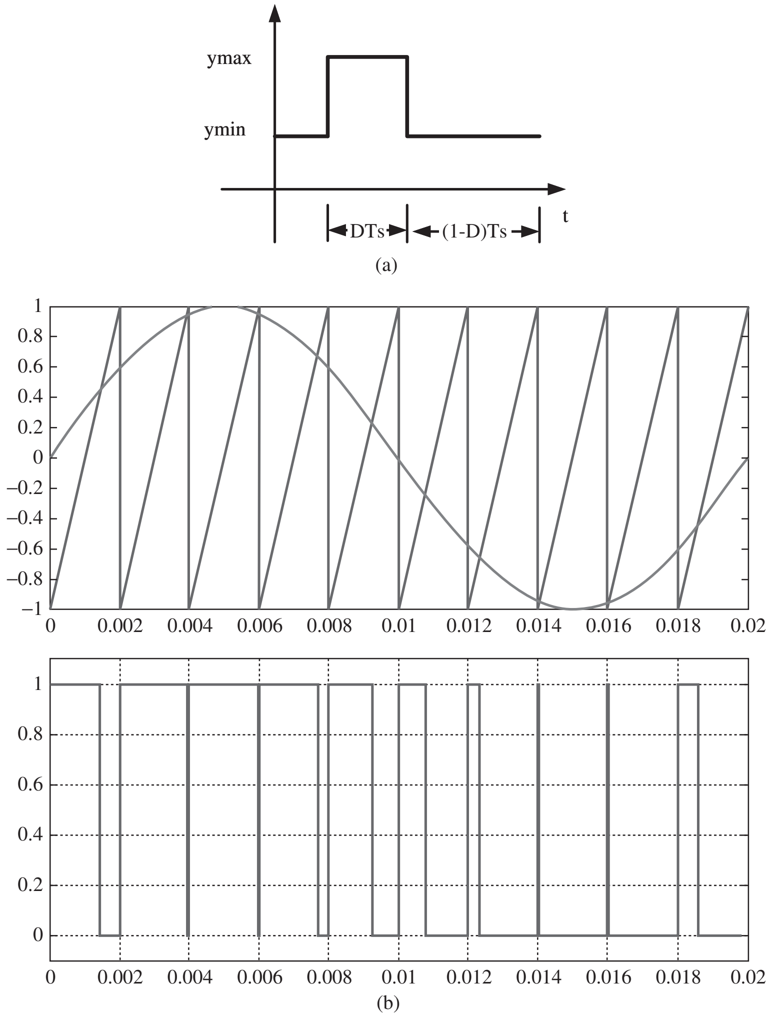


Figure 1.5 Illustration of PWM methods: (a) a signal with duty ratio D *and (b) PWM waveforms.*

The simplest way to generate a PWM signal is the sine-triangle PWM method, which adopts a sinusoidal waveform as the reference signal, a sawtooth or a triangular waveform as the carrier waveform, and a comparator. When the value of the reference signal is more than the carrier waveform, the PWM signal output will be in a high-state, otherwise it will be in a low-state, as shown in Figure 1.5b.

Delta modulation is another method of PWM control, where the output signal is restrained by two limits, that is, the upper limit and the lower limit. The offset between these two limits is a constant. Once the output signal reaches one of the limits, the PWM signal changes state, as shown in Figure 1.6. More details can be found in [26].

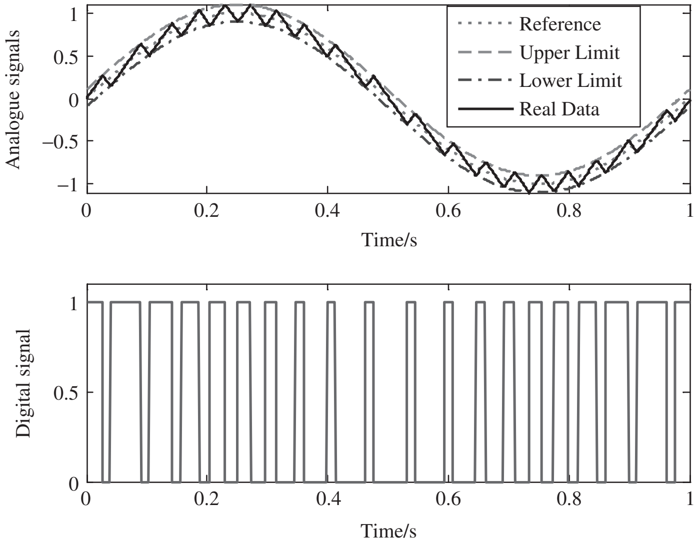


Figure 1.6 Delta PWM.

Sigma−delta is the third method of PWM control, shown in Figure 1.7, where the output signal is subtracted from a reference signal to form an error signal [27]. This error is integrated, and when the integral of the error exceeds the limits, the output changes state.

Space vector modulation is a PWM control algorithm for multi-phase AC wave generation, in which the reference signal is sampled regularly [28, 29]. After each sample, non-zero active switching vectors adjacent to the reference vector and one or more of the zero switching vectors are selected for the appropriate fraction of the sampling period in order to synthesize the reference signal [30]. The detailed theory of space vector PWM and its application in three-level DC−AC inverters will be explained in Chapters 4 and 5.

There are analogue integrated circuits (ICs) on the market that perform these PWM control methods, with low power and reduced component count as their main advantages. However, they lack flexibility in configurability. Many digital circuits (e.g., microcontrollers) are capable of generating PWM signals. They typically use a counter that increments periodically and is reset at the end of every period of the PWM. When the counter value reaches a configurable reference value, the PWM output changes state from high to low or vice versa. An example of a PWM-capable microcontroller is the TMS320F2XX from Texas Instruments (or TI).

When incrementing counters work in microcontrollers, the PWM method used is the intersecting method. The comparator function is performed by comparing

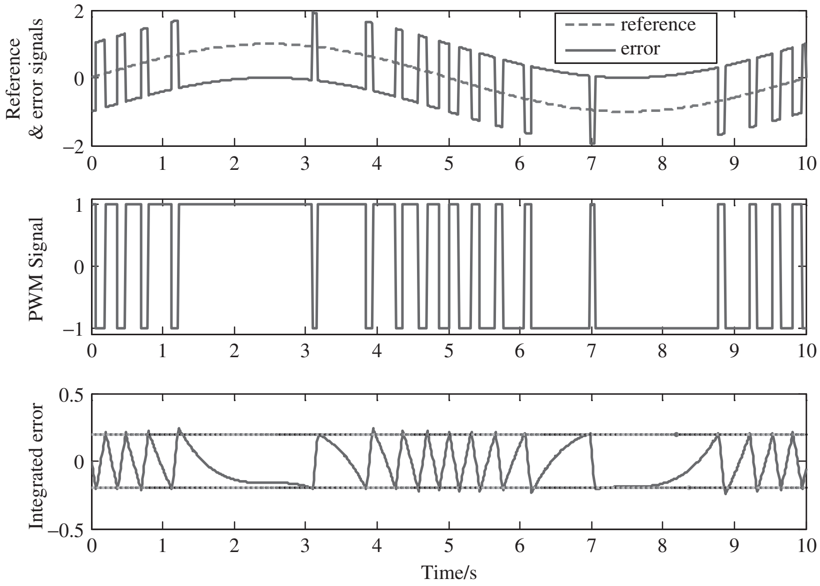


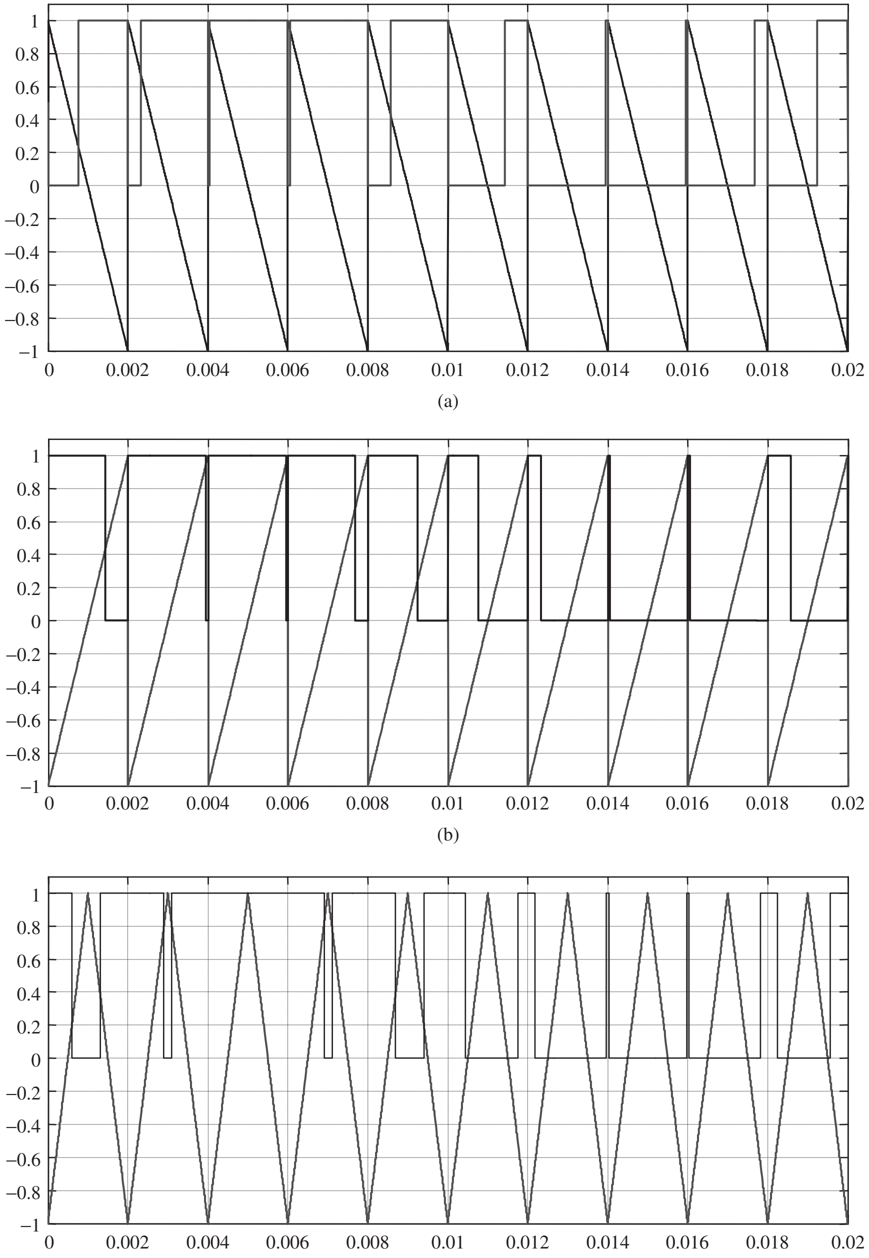
Figure 1.7 Sigma–delta PWM.

the current counter value to a reference value, both digitally. The duty cycle can no longer vary continuously due to the limited counter resolution. Therefore, the duty cycle varies in discrete steps. For example, if the maximum counter value is 256, the duty cycle resolution is 0.39%.

Three types of PWM are possible (Figure 1.8), whose difference lies only in the different sawtooth or triangular carrier signals applied to generate the PWM waveforms using the intersecting method:

1. Center-aligned PWM, where all PWM signals generated have their centers aligned.
2. Leading edge aligned, where the rising edges of all PWM signals generated are aligned.
3. Trailing edge aligned, where the falling edges of all PWMs are aligned.

High-frequency PWM output (PWM voltage) can be easily realized using power semiconductor switches. The PWM signals are used to control the state of the switches which directly determine the load voltage/current. The switches are either off (not conducting any current) or on (have no voltage drop across them with ideal switches). The product of current and voltage defines the instantaneous power dissipated inside the switch, thus no power is dissipated in an ideal switch [30]. However, semiconductor switches are always not ideal, although the losses of these devices are relatively small compared to the power they can deliver to the load. Additional control strategies, such as soft-switching control, can be



(a)

(b)

(c)

Figure 1.8 Three types of PWM signals: leading edge modulation, trailing edge modulation, and centered pulses (from top to bottom).

used to achieve very high efficiency for power converters, even at very high frequencies.

PWM is also often used to control the supply of electric power to another system. For example, induction motors used for pumps and blowers mostly employ a specific type of PWM control with a power converter. These power converters receive energy from the AC grid, rectify the AC input to a DC voltage, and then invert to a variable voltage, variable frequency (VVVF) AC voltage by means of PWM control [31]. Controlling the speed of the motor is done inside the microcontrollers by changing the modulation index and the frequency of the pulse sequences. By chopping the DC-bus voltage with the appropriate duty cycle, the output will be at the desired level. The voltage and current ripple are usually filtered with an inductor and/or a capacitor.

1.5 Typical power electronic converters and their applications

Power electronic converters are found in many applications where there is a need to change the form of electrical energy (i.e., voltage, current, or frequency). The ratings of power converters range from a few milliwatts (e.g., in a mobile/cell phone) to hundreds of megawatts (e.g., in a high-voltage DC transmission system). In contrast to electronic systems concerned with transmitting and processing signals and data which carry very large amounts of information with small amounts of energy, power electronics systems handle a large amount of electrical energy along with information. The power conversion systems can be classified according to the types of input and output:

- **AC to DC (rectifier):** converts AC input to DC output. This takes place in electronic devices and systems that use DC power as the power supply with only AC source available.
- **DC to AC (inverter):** converts DC input to AC output, with fixed or variable frequency and voltage. Typical applications are an uninterruptable power supply (UPS), emergency lighting, and motor control.
- **DC to DC (chopper):** converts a DC voltage to a different DC voltage. DC sources include batteries, photovoltaic arrays, and fuel cells. Buck, boost, buck–boost, Cuk circuit, half-bridge DC–DC, and full-bridge DC–DC are typical examples.
- **AC to AC (cyclo-converter):** converts one form of AC voltage to another AC voltage with a different frequency or voltage.

An AC–DC converter (rectifier) is typically found in many consumer electronic devices and residential applications, for example, cellular phones, televisions, computers, washers, dryers, air-conditioners, automobiles, and so on. The power range is typically from tens of watts to several hundred watts.

Variable speed drives (VSDs) are typical DC-AC converters which are used to control electric motors, including induction, DC, and permanent magnet motors. The power rating of VSDs varies from a few hundred watts to tens of megawatts.

It is worthwhile to point out that, in some applications, more than one conversion system is used. For example, battery chargers take the input voltage from the AC grid, rectify it to a DC voltage, and then convert the DC voltage to another DC voltage at a different level. Similarly, variable speed drive (VSD) systems also employ AC input, rectify it to DC, and convert back to another AC with different frequency and voltage to drive AC motors.

1.6 Transient processes in power electronics and book organization

Transient processes in power electronic converters occur in multiple forms. The common aspects are the short-timescale and large-energy exchange in these transient processes. With this in mind, Chapter 2 will categorize the research on power electronics into the macroscopic and microscopic domains. The perspective of this book is microscopic research in power electronics, and the main focus of the following chapters will range from devices and topology to circuits and systems.

In Chapter 3, the transients in power electronic devices are described. Three of the most widely used devices including Si IGBT, Si IGCT, and SiC JFET, are modeled.

As one of the most interesting applications, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have attracted a lot of attention lately. Chapter 4 will discuss the application of power electronics in EVs and HEVs. An inverter-fed drive system and battery chargers will be detailed.

In Chapter 5, alternative energies with power electronics will be addressed. Solar energy, wind energy, and fuel cells are the three main subjects. Power electronic converters are needed to control their variable output and provide high-efficiency energy. The critical transient processes in these applications will be analyzed.

As another typical example, the battery management system in the HEV and plug-in HEV (PHEV) will be addressed in Chapter 6. This system is highly related to power electronics to balance the energy distribution among the battery cells in the same string. The energy flow in the battery management system will be described.

While Chapter 2 analyzes the transients at the device level, Chapters 4–6 study them at the system level. Chapters 7 and 8 will combine the device-level with the system-level perspectives. The influence of three typical microscopic factors, dead band, minimum pulse width, and modulated error in power electronic systems, will be demonstrated in detail.

Finally, chapter 9 looks at the future trends of power electronics, including devices, topology, packaging, systems and applications. The impact of new devices and topology on the transients of power electronics are discussed.

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