CHAPTER 1

Power Electronic Converters

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This introductory chapter provides a background to the subject of the book. Fundamental principles of electric power conditioning are explained using a hypothetical generic power converter. Ac to dc, ac to ac, dc to dc, and dc to ac power electronic converters are described, including select operating characteristics and equations of their most common representatives.

1.1 PRINCIPLES OF ELECTRIC POWER CONDITIONING

Electric power is supplied in a "raw," fixed-frequency, fixed-voltage form. For small consumers, such as homes or small stores, usually only the single-phase ac voltage is available, whereas large energy users, typically industrial facilities, draw most of their electrical energy via three-phase lines. The demand for conditioned power is growing rapidly, mostly because of the progressing sophistication and automation of industrial processes. Power conditioning involves both *power conversion*, ac to dc or dc to ac, and *control*. Power electronic converters performing the conditioning are highly efficient and reliable.

Power electronic converters can be thought of as networks of semiconductor power switches. Depending on the type, the switches can be uncontrolled, semicontrolled, or fully controlled. The state of uncontrolled switches, the *power diodes*, depends on the operating conditions only. A diode turns on (closes) when positively biased and it turns off (opens) when the conducted current changes its polarity to negative. Semicontrolled switches, the *SCRs* (silicon controlled rectifiers), can be turned on by a gate current signal, but they turn off just like the diodes. Most of the existing power switches are fully controlled, that is, they can both be turned on and off by appropriate voltage or current signals.

Principles of electric power conversion can easily be explained using a hypothetical "generic power converter" shown in Fig. 1.1. It is a simple network of five switches, S0 through S4, of which S1 opens and closes simultaneously with S2, and S3 opens and closes simultaneously with S4. These four switches can all be open (OFF), but they may not be all closed (ON) because they would short the supply source. Switch S0 is only closed when all the other switches are open. It is assumed that the switches open and close instantly, so that currents flowing through them can be redirected without interruption.

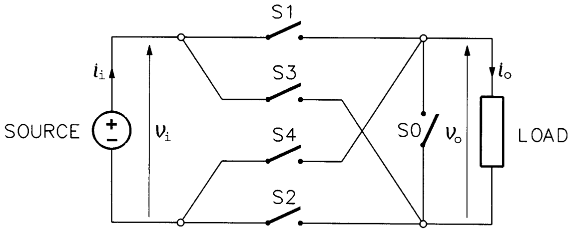


FIGURE 1.1
Generic power converter.

The generic converter can assume three states only: (1) State 0, with switches S1 through S4 open and switch S0 closed, (2) State 1, with switches S1 and S2 closed and the other three switches open, and (3) State 2, with switches S3 and S4 closed and the other three switches open. Relations between the output voltage, v_o, and the input voltage, v_i, and between the input current, i_i, and output current, i_o, are

$$v_o = \begin{cases} 0 & \text{in State } 0 \\ v_i & \text{in State } 1 \\ -v_i & \text{in State } 2 \end{cases} \tag{1.1}$$

and

$$i_i = \begin{cases} 0 & \text{in State } 0 \\ i_o & \text{in State } 1 \\ -i_o & \text{in State } 2. \end{cases} \tag{1.2}$$

Thus, depending on the state of generic converter, its switches connect, cross-connect, or disconnect the output terminals from the input terminals. In the last case (State 0), switch S0 provides a path for the output current (load current) when the load includes some inductance, L. In absence of that switch, interrupting the current would cause a dangerous impulse overvoltage, $Ldi_o/dt \to -\infty$.

Instead of listing the input–output relations as in Eqs. (1.1) and (1.2), the so-called *switching functions* (or *switching variables*) can be assigned to individual sets of switches. Let $a = 0$ when switch S0 is open and $a = 1$ when it is closed, $b = 0$ when switches S1 and S2 are open and $b = 1$ when they are closed, and $c = 0$ when switches S3 and S4 are open and $c = 1$ when they are closed. Then,

$$v_o = \bar{a}(b - c)v_i \tag{1.3}$$

and

$$i_i = \bar{a}(b - c)i_o. \tag{1.4}$$

The ac to dc power conversion in the generic converter is performed by setting it to State 2 whenever the input voltage is negative. Vice-versa, the dc to ac conversion is realized by periodic repetition of the State 1–State 2– . . . sequence (note that the same state sequence appears for the ac to dc conversion). These two basic types of power conversion are illustrated in Figs. 1.2 and 1.3. Thus, electric power conversion is realized by appropriate operation of switches of the converter.

Switching is also used for controlling the output voltage. Two basic types of voltage control are *phase control* and *pulse width modulation*. The phase control consists of delaying States 1

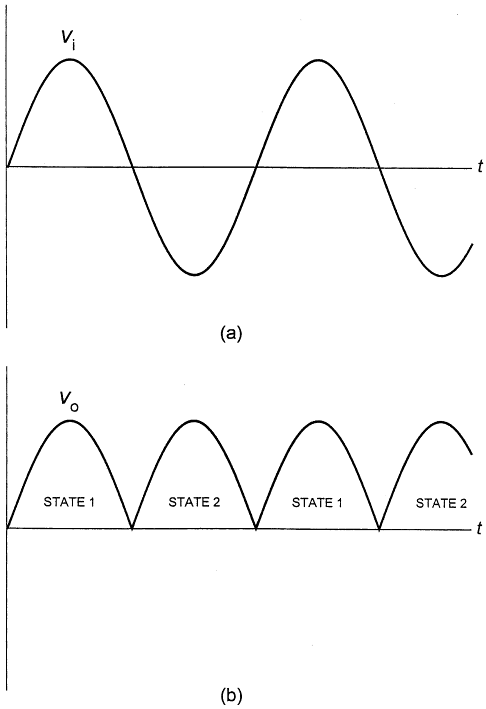


FIGURE 1.2
Ac to dc conversion in the generic power converter: (a) input voltage, (b) output voltage.

and 2 and setting the converter to State 0. Figure 1.4 shows the generic power converter operating as an ac voltage controller (ac to ac converter). For 50% of each half-cycle, State 1 is replaced with State 0, resulting in significant reduction of the rms value of output voltage (in this case, to $1/\sqrt{2}$ of rms value of the input voltage). The pulse width modulation (PWM) also makes use of State 0, but much more frequently and for much shorter time intervals. As shown in Fig. 1.5 for the same generic ac voltage controller, instead of removing whole "chunks" of the waveform, numerous "slices" of this waveform are cut out within each switching cycle of the converter. The *switching frequency*, a reciprocal of a single switching period, is at least one order of magnitude higher than the input or output frequency.

The difference between phase control and PWM is blurred in dc to dc converters, in which both the input and output frequencies are zero, and the switching cycle is the operating cycle. The dc to dc conversion performed in the generic power converter working as a *chopper* (dc to dc converter) is illustrated in Fig. 1.6. Switches S1 and S2 in this example operate with the *duty ratio* of 0.5, reducing the average output voltage by 50% in comparison with the input voltage. The duty ratio of a switch is defined as the fraction of the switching cycle during which the switch is ON.

To describe the magnitude control properties of power electronic converters, it is convenient to introduce the so-called *magnitude control ratio*, *M*, defined as the ratio of the actual useful output voltage to the maximum available value of this voltage. In dc-output converters, the useful output voltage is the dc component of the total output voltage of the converter, whereas in ac-output ones, it is the fundamental component of the output voltage. Generally, the magnitude control ratio can assume values in the -1 to $+1$ range.

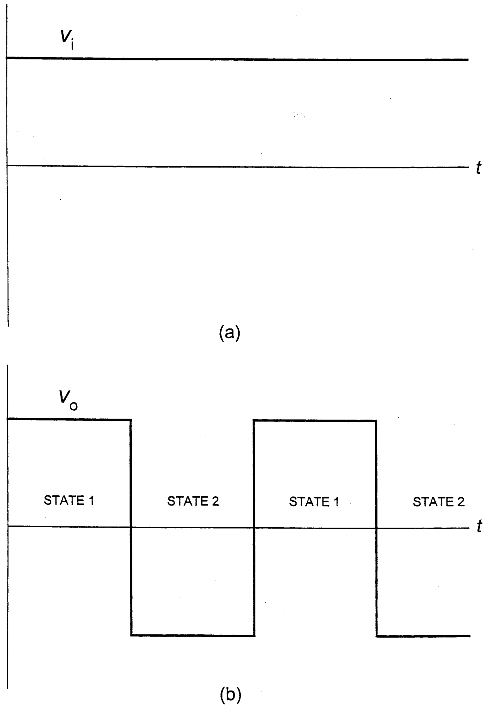


FIGURE 1.3
Dc to ac conversion in the generic power converter: (a) input voltage, (b) output voltage.

In practical power electronic converters, the electric power is supplied by voltage sources or current sources. Each of these can be of the uncontrolled or controlled type, but a parallel capacitance is a common feature of the voltage sources while a series inductance is typical for the current sources. The capacitance or inductance is sufficiently large to prevent significant changes of the input voltage or current within an operating cycle of the converter. Similarly, loads can also have the voltage-source or current-source characteristics, resulting from a parallel capacitance or series inductance. To avoid direct connection of two capacitances charged to different voltages or two inductances conducting different currents, a voltage-source load requires a current-source converter and, vice versa, a current-source load must be supplied from a voltage-source converter. These two basic source-converter-load configurations are illustrated in Fig. 1.7.

1.2 AC TO DC CONVERTERS

Ac to dc converters, the *rectifiers*, come in many types and can variously be classified as uncontrolled versus controlled, single-phase versus multiphase (usually, three-phase), half-wave versus full-wave, or phase-controlled versus pulse width modulated. Uncontrolled rectifiers are based on power diodes; in phase-controlled rectifiers SCRs are used; and pulse width modulated

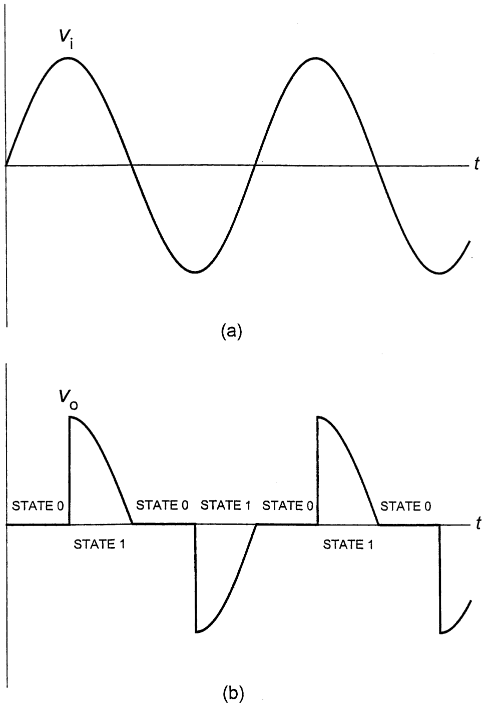


FIGURE 1.4
Phase control of output voltage in the generic power converter operating as an ac voltage controller: (a) input voltage, (b) output voltage.

rectifiers require fully controlled switches, such as *IGBTs* (insulated gate bipolar transistors) or *power MOSFETs*.

The two most common rectifier topologies are the single-phase bridge and three-phase bridge. Both are full-wave rectifiers, with no dc component in the input current. This current is the main reason why half-wave rectifiers, although feasible, are avoided in practice. The single-phase and three-phase diode rectifiers are shown in Fig. 1.8 with an RLE (resistive–inductive–EMF) load. At any time, one and only one pair of diodes conducts the output current. One of these diodes belongs to the common-anode group (upper row), the other to the common-cathode group (lower row), and they are in different legs of the rectifier. The line-to-line voltage of the supply line constitutes the input voltage of the three-phase rectifier, also known as a *six-pulse rectifier*. The single-phase bridge rectifier is usually referred to as a *two-pulse rectifier*.

In practice, the output current in full-wave diode rectifiers is continuous, that is, it never drops to zero. This mostly dc current contains an ac component (ripple), dependent on the type of rectifier and parameters of the load. Output voltage waveforms of rectifiers in Fig. 1.8 within a single period, T, of input frequency are shown in Fig. 1.9, along with example waveforms of the output current. The average output voltage (dc component), V_o, is given by

$$V_o = \frac{2}{\pi} V_{i,p} \approx 0.63 V_{i,p} \tag{1.5}$$

for the two-pulse diode rectifier and

$$V_o = \frac{3}{\pi} V_{i,p} \approx 0.95 V_{i,p} = 0.95 V_{LL,p} \tag{1.6}$$

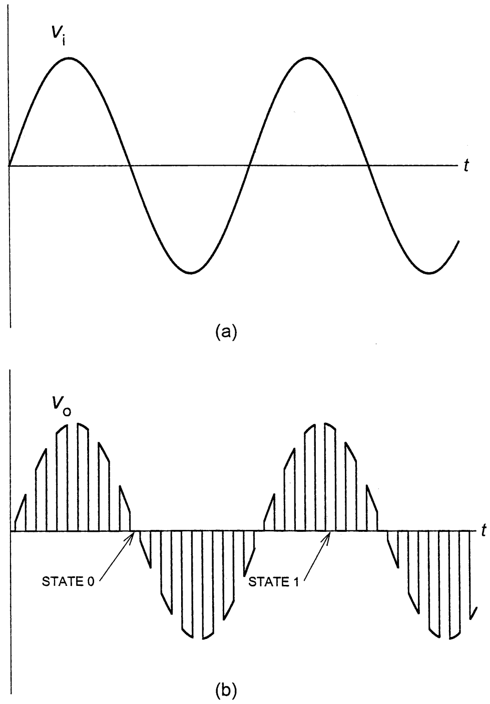


FIGURE 1.5
PWM control of output voltage in the generic power converter operating as an ac voltage controller: (a) input voltage, (b) output voltage.

for the six-pulse diode rectifier. Here, $V_{i,p}$ denotes the peak value of input voltage, which, in the case of the six-pulse rectifier, is the peak line-to-line voltage, $V_{LL,p}$.

In phase-controlled rectifiers shown in Fig. 1.10, diodes are replaced with SCRs. Each SCR must be turned on (fired) by a gate signal (firing pulse) in each cycle of the supply voltage. In the angle domain, ωt, where ω denotes the supply frequency in rad/s, the gate signal can be delayed by α_f radians with respect to the instant in which a diode replacing a given SCR would start to conduct. This delay, called a *firing angle*, can be controlled in a wide range. Firing pulses for all six SCRs are shown in Fig. 1.11. Under the continuous conductance condition, the average output voltage, $V_{o(con)}$, of a controlled rectifier is given by

$$V_{o(con)} = V_{o(unc)} \cos(\alpha_f) \tag{1.7}$$

where $V_{o(unc)}$ denotes the average output voltage of an uncontrolled rectifier (diode rectifier) of the same type. It can be seen that $\cos(\alpha_f)$ constitutes the magnitude control ratio of phase-controlled rectifiers. Example waveforms of output voltage in two- and six-pulse controlled rectifiers are shown in Fig. 1.12, for the firing angle of 45°.

As in uncontrolled rectifiers, the output current is basically of the dc quality, with certain ripple. The *ripple factor*, defined as the ratio of the rms value of the ac component to the dc component, increases with the firing angle. At a sufficiently high value of the firing angle, the continuous current waveform breaks down into separate pulses. The conduction mode depends on the load EMF, load angle, and firing angle. The graph in Fig. 1.13 illustrates that relation for a six-pulse rectifier: for a given firing angle, the continuous conduction area lies below the line representing this angle. For example, for load and firing angles both of 30°, the load EMF

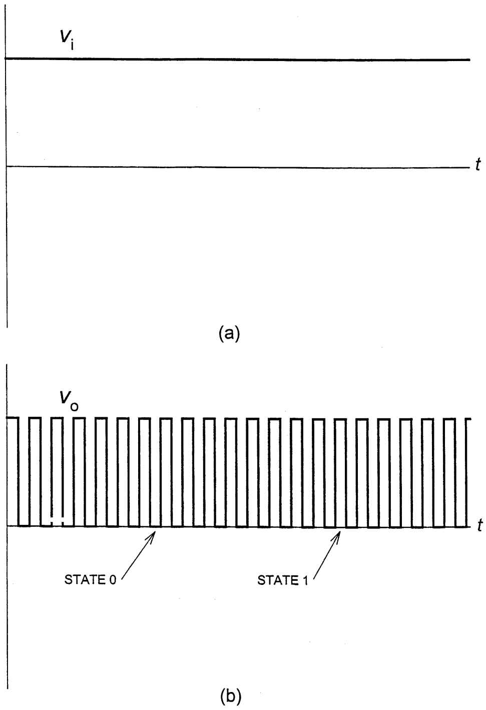


FIGURE 1.6
PWM control of output voltage in the generic power converter operating as a chopper: (a) input voltage, (b) output voltage.

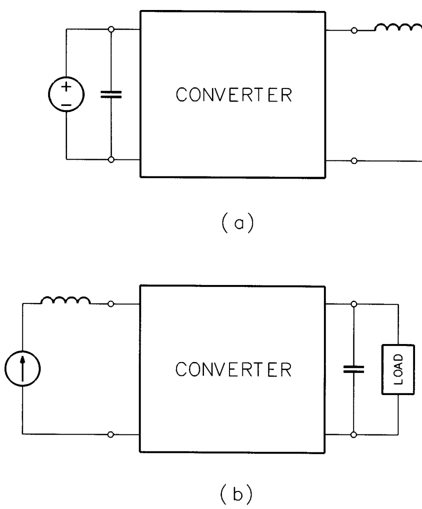
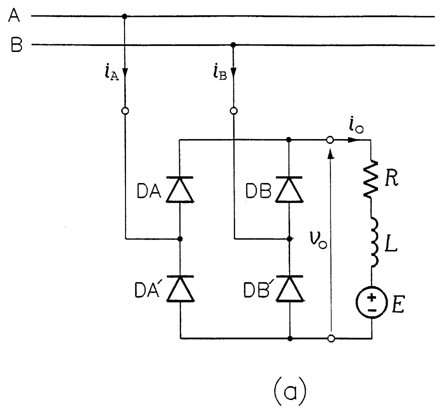


FIGURE 1.7
Two basic source-converter-load configurations: (a) voltage-source converter with a current-source load, (b) current-source converter with a voltage-source load.



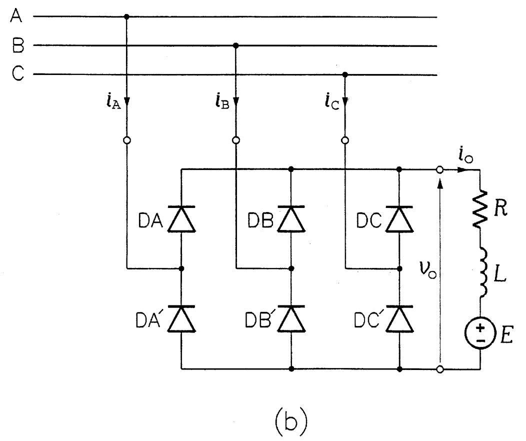


FIGURE 1.8
Diode rectifiers: (a) single-phase bridge, (b) three-phase bridge.

coefficient, defined as the ratio of the load EMF to the peak value of line-to-line input voltage, must not be greater than 0.75.

Equation (1.7) indicates that the average output voltage becomes negative when $\alpha_f > 90°$. Then, as the output current is always positive, the power flow is reversed, that is, the power is transferred from the load to the source, and the rectifier is said to operate in the inverter mode. Clearly, the load must contain a negative EMF as a source of that power.

Figure 1.14 shows four possible *operating quadrants* of a power converter. In Quadrants 1 and 3, the rectifier transfers electric power from the source to the load, while Quadrants 2 and 4 represent the inverter operation. A single controlled rectifier can only operate in Quadrants 1 and 4, that is, with a positive output current. As illustrated in Fig. 1.15a, the current can be reversed using a cross-switch between a rectifier and a load, typically a dc motor. In this way, the rectifier and load terminals can be connected directly or cross-connected. This method of extending operation of the rectifier on Quadrants 2 and 3 is only practical when the switch does not have to be used frequently as, for example, in an electric locomotive. Therefore, a much more common solution consists in connecting two controlled rectifiers in antiparallel, creating the so-called *dual converter* shown in Fig. 1.15b.

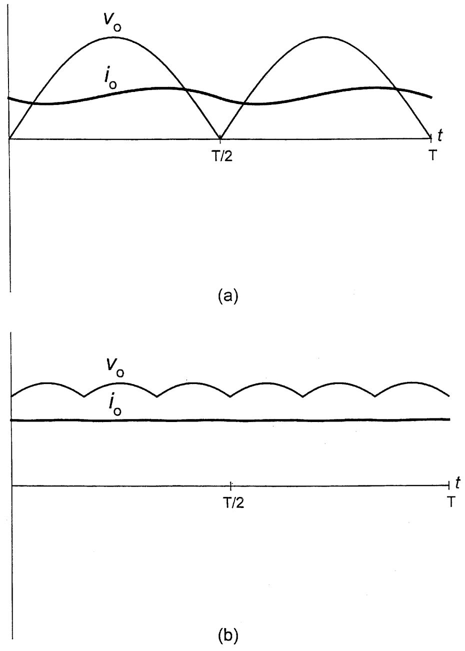


FIGURE 1.9
Output voltage and current waveforms in diode rectifiers: (a) single-phase bridge, (b) three-phase bridge.

There are two types of dual converters. Figure 1.16 shows the *circulating current-free dual converter*, that is, a rectifier in which single SCRs have been replaced with antiparallel SCR pairs. This arrangement is simple and compact, but it has two serious weaknesses. First, to prevent an interphase short circuit, only one internal rectifier can be active at a given time. For example, with TB1 and TC1′ conducting, TC2′ is forward biased and, if fired, it would short lines B and C. This can easily be prevented by appropriate control of firing signals, but when a change in polarity of the output current is required, the incoming rectifier must wait until the current in the outgoing rectifier dies out and the conducting SCRs turn off. This delay slows down the response to current control commands, which in certain applications is not acceptable. Secondly, as in all single phase-controlled rectifiers, if the firing angle is too large and/or the load inductance is too low, the output current becomes discontinuous, which is undesirable. For instance, such a current would generate a pulsating torque in a dc motor, causing strong acoustic noise and vibration.

In the *circulating current-conducting dual converter*, shown in Fig. 1.17, both constituent rectifiers are active simultaneously. Depending on the operating quadrant, one rectifier works with the firing angle, $\alpha_{f,1}$, less than 90°. The other rectifier operates in the inverter mode with the firing angle, $\alpha_{f,2}$, given by

$$\alpha_{f,2} = \beta - \alpha_{f,1} \tag{1.8}$$

where β is a controlled variable. It is maintained at a value of about 180°, so that both rectifiers produce the same *average* voltage. However, the *instantaneous* output voltages of the rectifiers are not identical, and their difference generates a current circulating between the rectifiers. If the rectifiers were directly connected as in Fig. 1.15b, the circulating current, limited by the resistance of wires and conducting SCRs only, would be excessive. Therefore, reactors are

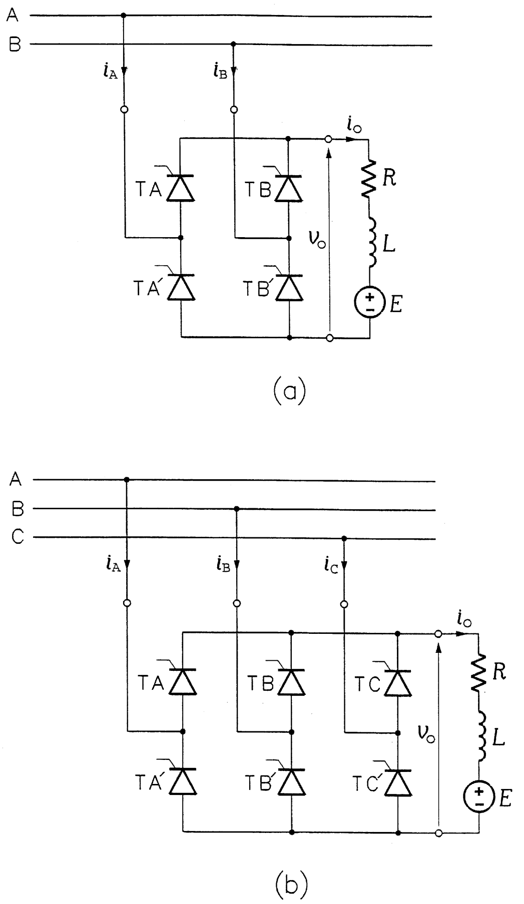


FIGURE 1.10
Phase-controlled rectifiers: (a) single-phase bridge, (b) three-phase bridge.

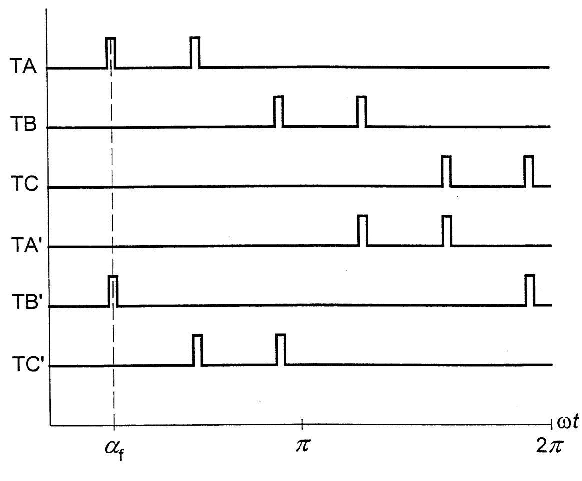


FIGURE 1.11
Firing pulses in the phase-controlled six-pulse rectifier.

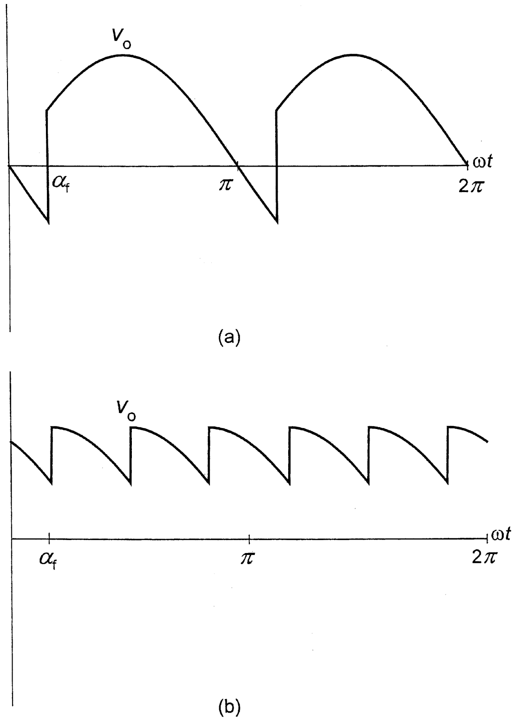


FIGURE 1.12
Output voltage waveforms in phase-controlled rectifiers: (a) single-phase bridge, (b) three-phase bridge (firing angle of 45°).

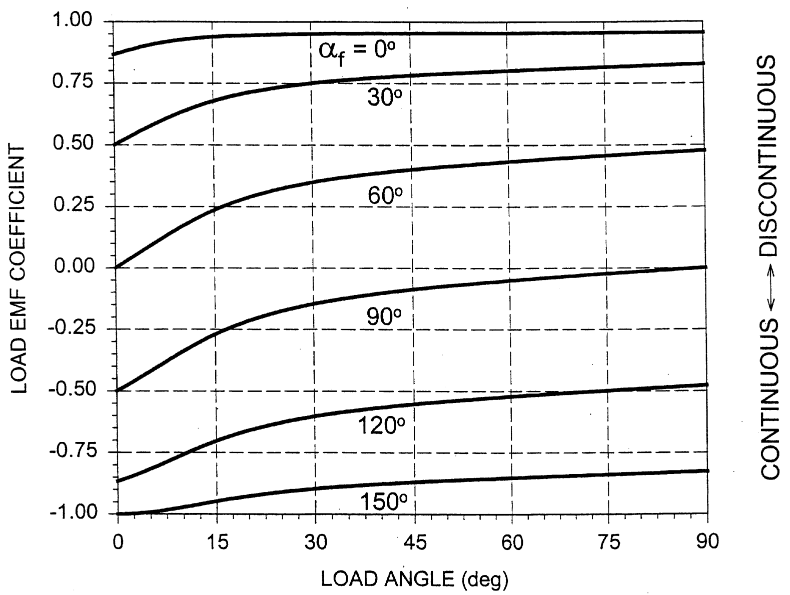


FIGURE 1.13
Diagram of conduction modes of a phase-controlled six-pulse rectifier.

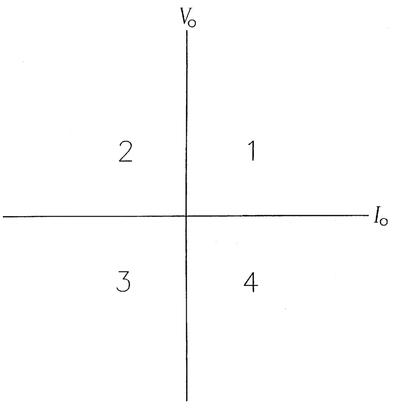


FIGURE 1.14
Operating quadrants of a controlled rectifier.

placed between the rectifiers and the load, strongly reducing the ac component of the circulating current.

The circulating current is controlled in a closed-loop control system which adjusts the angle β in Eq. (1.8). Typically, the circulating current is kept at the level of some 10% to 15% of the rated current to ensure continuous conduction of both constituent rectifiers. The converter is thus seen to employ a different scheme of operation from the circulating current-free converter. Even when the load consumes little power, a substantial amount of power enters one rectifier and the difference between this power and the load power is transferred back to the supply line by the second rectifier. Reactors L_3 and L_4 can be eliminated if the constituent rectifiers are supplied from isolated sources, such as two secondary windings of a transformer.

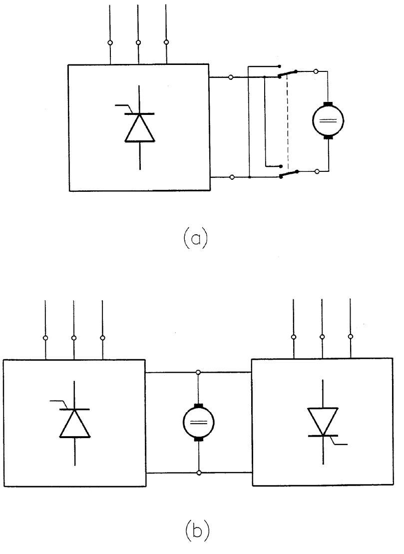


FIGURE 1.15
Rectifier arrangements for operation in all four quadrants: (a) rectifier with a cross-switch, (b) two rectifiers connected in antiparallel.

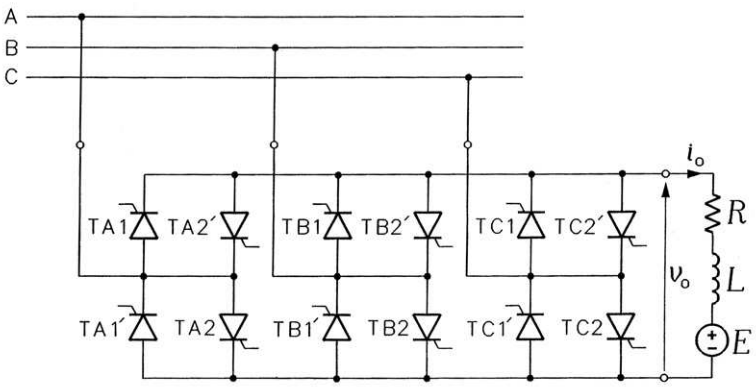


FIGURE 1.16
Circulating current-free dual converter.

Both the uncontrolled and phase-controlled rectifiers draw square-wave currents from the supply line. In addition, the input power factor is poor, especially in controlled rectifiers, where it is proportional to $\cos(\alpha_f)$. These flaws led to the development of *PWM rectifiers*, in which waveforms of the supply currents can be made sinusoidal (with certain ripple) and in phase with the supply voltages. Also, even with very low values of the magnitude control ratio, continuous output currents are maintained. Fully controlled semiconductor switches, typically IGBTs, are used in these rectifiers.

A voltage-source PWM rectifier based on IGBTs is shown in Fig. 1.18. The diodes connected in series with the IGBTs protect the transistors from reverse breakdown. Although the input current, i_a, to the rectifier is pulsed, most of its ac component come from the input capacitors, while the current, i_A, drawn from the power line is sinusoidal, with only some ripple. Appropriate control of rectifier switches allows obtaining a unity input power factor. Example waveforms of the output voltage, v_o, output current, i_o, and input currents, i_a and i_A, are shown in Figs. 1.19 and 1.20, respectively.

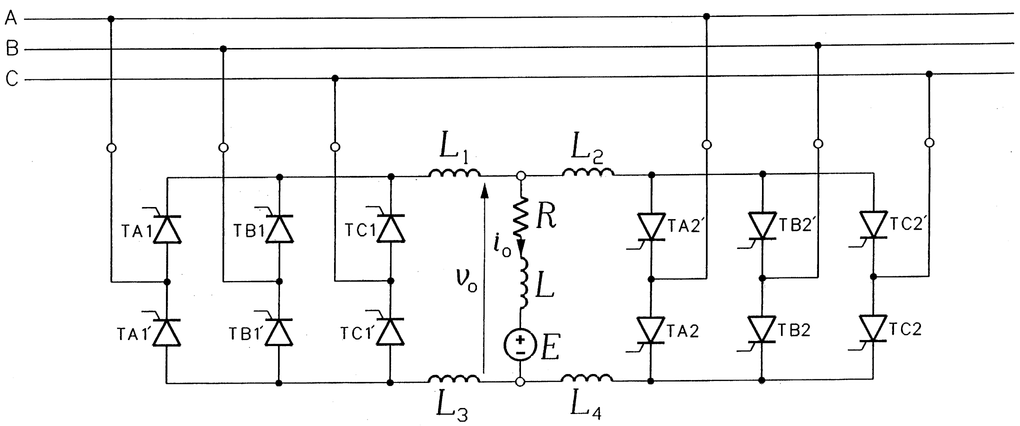


FIGURE 1.17
Circulating current-conducting dual converter.

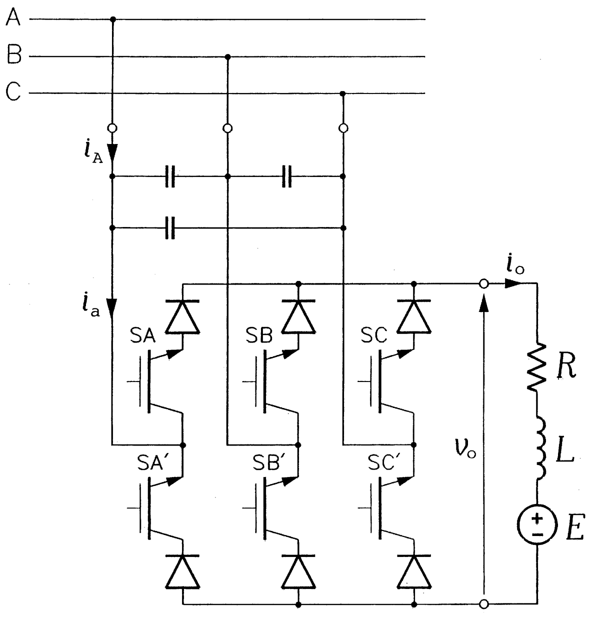


FIGURE 1.18
Voltage-source PWM rectifier.

The *voltage-source PWM rectifier* is a *buck-type converter*, that is, its maximum available output voltage (dependent on the PWM technique employed) is less than the peak input voltage. In contrast, the *current-source PWM rectifier* shown in Fig. 1.21 is a *boost-type* ac to dc converter, whose output voltage is higher than the peak input voltage. Figure 1.22 depicts example waveforms of the output voltage and current and the input current of the rectifier.

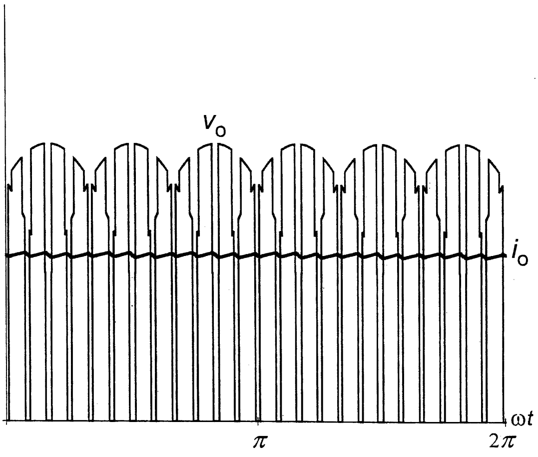


FIGURE 1.19
Output voltage and current waveforms in a voltage-source PWM rectifier.

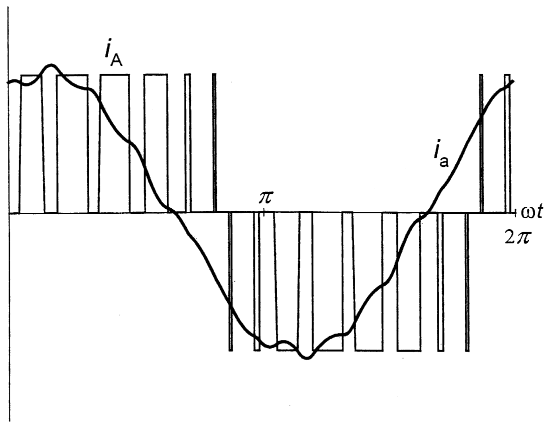


FIGURE 1.20
Input current waveforms in a voltage-source PWM rectifier.

The amount of ripple in the input and output currents of the PWM rectifiers described depends on the switching frequency and size of the inductive and capacitive components involved. In practice, PWM rectifiers are typically of low and medium power ratings.

1.3 AC TO AC CONVERTERS

There are three basic types of ac to dc converters. The simplest ones, the *ac voltage controllers*, allow controlling the output voltage only, while the output frequency is the same as the input frequency. In *cycloconverters*, the output frequency can be controlled, but it is at least one order of magnitude lower than the input frequency. In both the ac voltage controllers and cycloconverters, the maximum available output voltage approaches the input voltage. *Matrix*

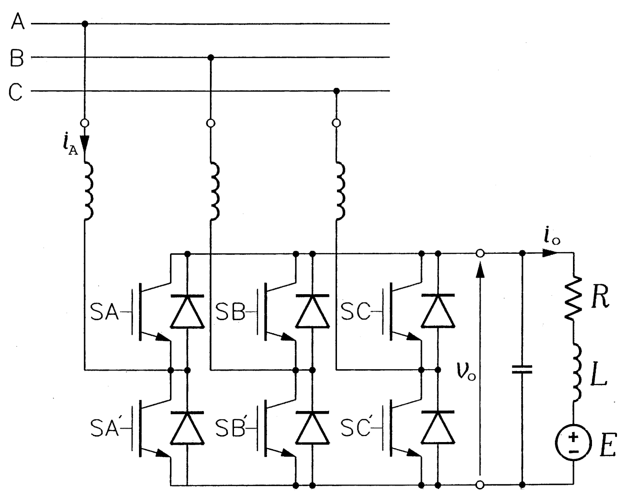


FIGURE 1.21
Current-source PWM rectifier.

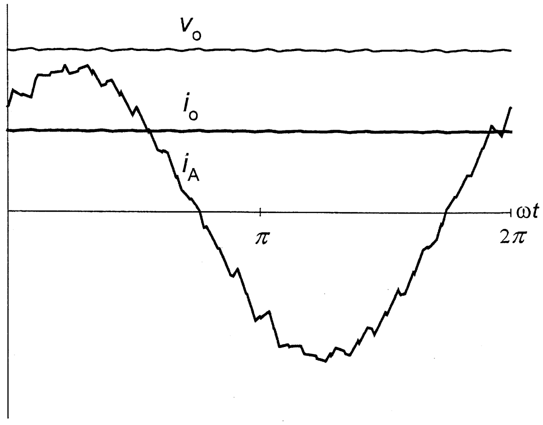


FIGURE 1.22
Waveforms of the output voltage and current and the input current in a current-source PWM rectifier.

converters are most versatile, with no inherent limits on the output frequency, but the maximum available output voltage is about 15% lower than the input voltage.

A pair of semiconductor power switches connected in antiparallel constitutes the basic building block of ac voltage controllers. Phase-controlled converters employ pairs of SCRs, SCR-diode pairs, or *triacs*. A single-phase ac voltage controller is shown in Fig. 1.23 and example waveforms of the output voltage and current in Fig. 1.24. The rms output voltage, V_o, is given by

$$V_o = V_i \sqrt{\frac{1}{\pi}\left\{\alpha_e - \alpha_f - \frac{1}{2}[\sin(2\alpha_e) - \sin(2\alpha_f)]\right\}} \tag{1.9}$$

where α_e denotes the so-called *extinction angle*, dependent on the firing angle, α_f, and load angle, φ. The precise value of φ is usually unknown and changing. Consequently, as shown in Fig. 1.25, only an envelope of control characteristics, $M = f(\alpha_f)$, where $M = V_o/V_i$, can accurately be determined.

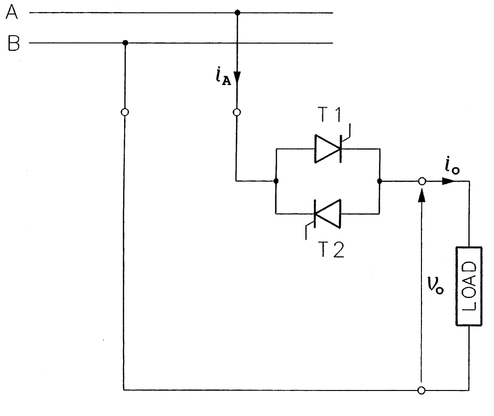


FIGURE 1.23
Phase-controlled single-phase ac voltage controller.

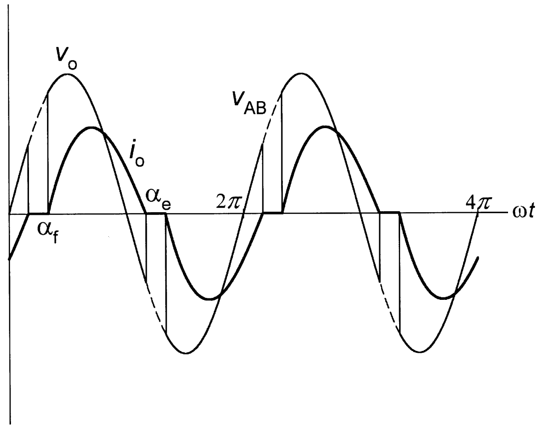


FIGURE 1.24
Output voltage and current waveforms in a phase-controlled single-phase ac voltage controller (firing angle of 60°).

The output voltage equals the input voltage, and the current is continuous and sinusoidal, when $\alpha_f = \varphi$. This can easily be done by applying a packet of narrowly spaced firing pulses to a given switch at the instant of zero-crossing of the input voltage waveform. The first pulse which manages to fire the switch appears at $\omega t \approx \varphi$, and the ac voltage controller becomes a *static ac switch*, which can be turned off by cancelling the firing pulses.

Several topologies of phase-controlled three-phase ac voltage controllers are feasible, of which the most common, *fully controlled* controller, usually based on triacs, is shown in Fig. 1.26.

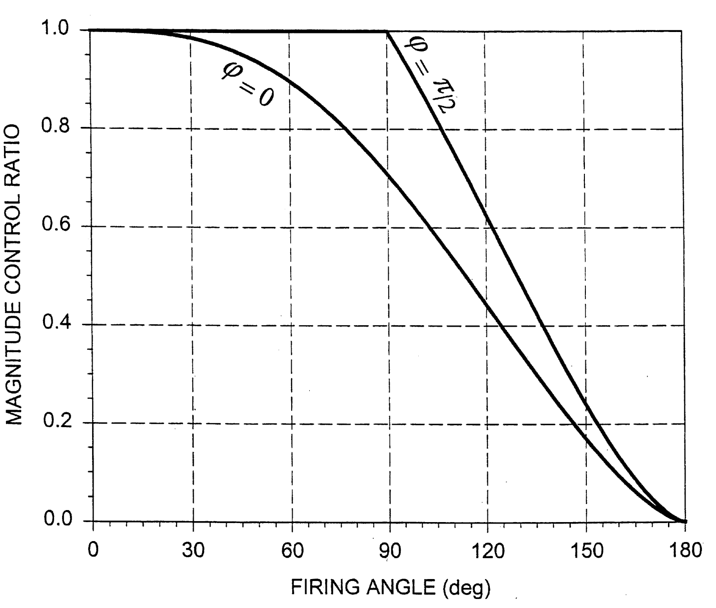


FIGURE 1.25
Envelope of control characteristics of a phase-controlled single phase ac voltage controller.

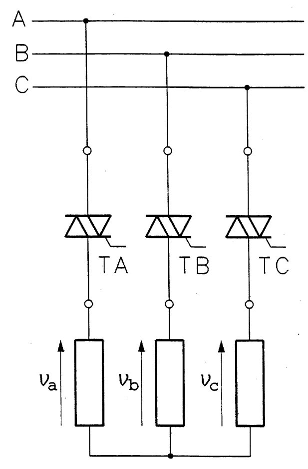


FIGURE 1.26
Phase-controlled, fully controlled three-phase ac voltage controller.

If switching functions, a, b, and c, are assigned to each triac, output voltages, v_a, v_b, and v_c, of the controller are given by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} a & -b & c \\ -a & b & -c \\ -a & -b & c \end{bmatrix} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \tag{1.10}$$

where v_A, v_B, and v_C are line-to-ground voltages of the supply line. Analysis of operation of the fully controlled controller is rather difficult since, depending on the load and firing angle, the controller operates in one of three modes: (1) Mode 1, with two or three triacs conducting; (2) Mode 2, with two triacs conducting; and (3) Mode 3, with none or two triacs conducting. The output voltage waveforms are complicated, as illustrated in Fig. 1.27 for voltage v_a of a controller with resistive load and a firing angle of 30°. The waveform consists of segments of the v_A, $v_{AB}/2$, and $v_{AC}/2$ voltages. The envelope of control characteristics of the controller is shown in Fig. 1.28.

Four other topologies of the phase-controlled three-phase ac voltage controller are shown in Fig. 1.29. If ratings of available triacs are too low, actual SCRs must be used. In that case, an SCR-diode pair is employed in each phase of the controller. Such a *half-controlled* controller is shown in Fig. 1.29a. If the load is connected in delta, the three-phase ac voltage controller can have the topology shown in Fig. 1.29b. The triacs (or SCR–diode pairs) can also be connected after the load, as in Figs. 1.29c and 1.29d.

Similarly to phase-controlled rectifiers, phase-controlled ac voltage controllers draw distorted currents from the supply line, and their input power factor is poor. Again, as in the rectifiers, these characteristics can significantly be improved by employing pulse width modulation. Pulse width modulated ac voltage controllers, commonly called *ac choppers*, require fully controlled power switches capable of conducting current in both directions. Such switches can be assembled from transistors and diodes; two such arrangements are shown in Fig. 1.30.

The *PWM ac voltage controller*, also known as *ac chopper*, is shown in Fig. 1.31 in the single-phase version. For simplicity, and to stress the functional analogy to the generic converter, the bidirectional switches are depicted as mechanical contacts. When the main switch, S1, is

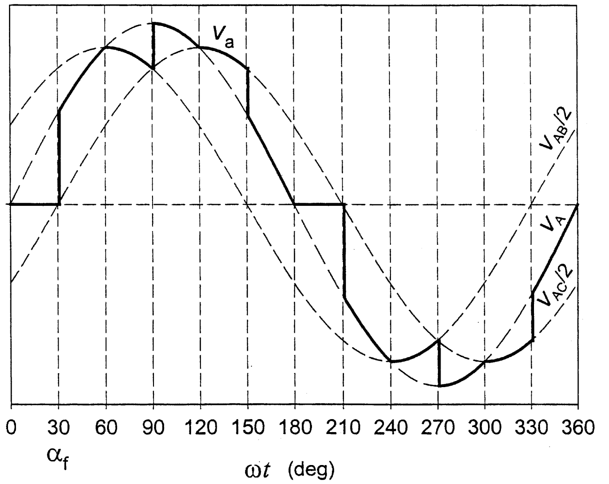


FIGURE 1.27
Waveform of the output voltage in a fully controlled three-phase ac voltage controller (resistive load, firing angle of 30°).

chopping, that is, turning on and off many times per cycle, the current drawn from the LC input filter is interrupted. Therefore, another switch, S2, is connected across the load. It plays the role of the freewheeling switch S0 in the generic power converter in Fig. 1.1. Switches S1 and S2 are operated complementarily: when S1 is turned on, S2 is turned off and vice versa. Denoting the duty ratio of switch S1 by D_1, the magnitude control ratio, M, taken as ratio of the rms output voltage, V_o, to rms input voltage, V_i, equals $\sqrt{D_1}$.

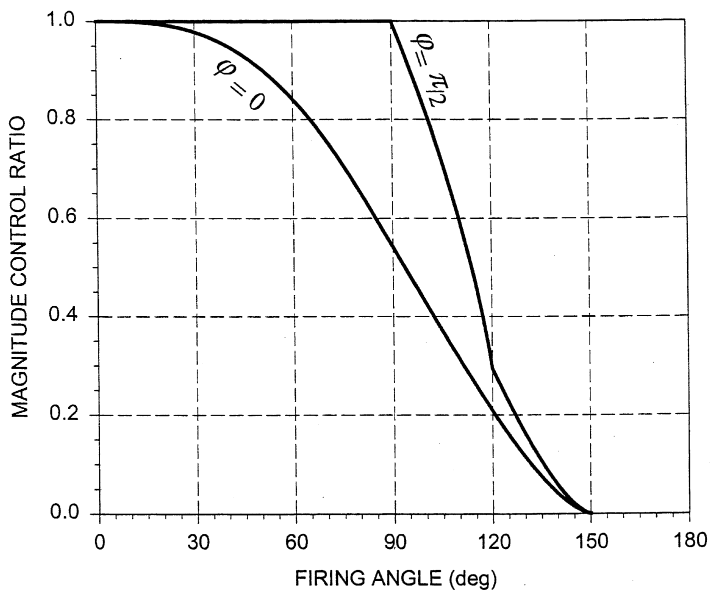


FIGURE 1.28
Envelope of control characteristics of the fully controlled three-phase ac voltage controller.

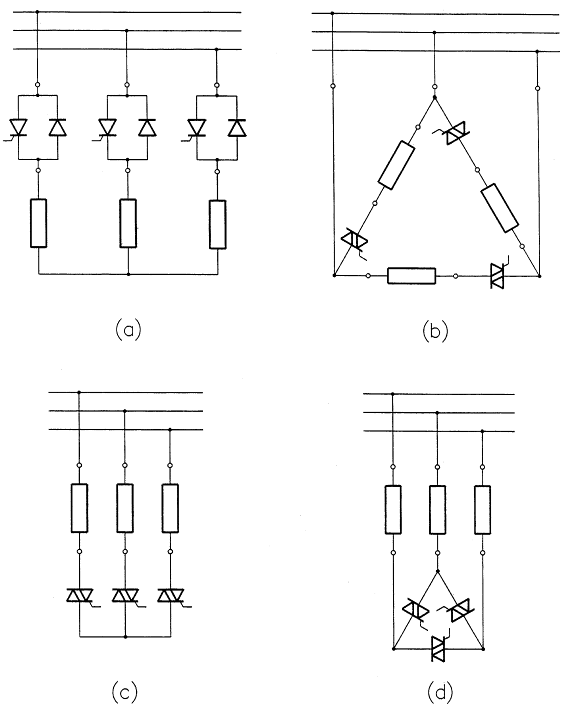


FIGURE 1.29
Various topologies of phase-controlled three-phase ac voltage controllers: (a) half-controlled, before-load, (b) delta-connected, before-load, (c) wye-connected after-load, (d) delta-connected, after-load.

Example waveforms of the output voltage, v_o, and current, i_o, of the ac chopper are shown in Fig. 1.32. The high-frequency component of the pulsed input current, i_a, is mostly supplied by the filter capacitors, so that the current, i_A, drawn from the power line is similar to that of the PWM voltage-source rectifier (see Fig. 1.20). Analogously to the single-phase ac chopper in Fig. 1.31, three-phase ac choppers can be obtained from their phase-controlled counterparts by replacing each triac with a fully controlled bidirectional switch. A similar switch must be connected in parallel to each phase load to provide an alternative path for the load current when the load is cut off from the supply source by the main switch.

The dual converter in Fig. 1.17 can be operated as a single-phase cycloconverter by varying the firing angle $\alpha_{f,1}$ in accordance with the formula

$$\alpha_{f,1}(t) = \cos^{-1}[M \sin(\omega_o t)] \tag{1.11}$$

where the magnitude control ratio, M, represents the ratio of the peak value of the fundamental output voltage to the maximum available dc voltage of the constituent rectifiers. The output frequency, ω_o, must be significantly lower than the supply frequency, ω. Example waveforms of the output voltage of such cycloconverter are shown in Fig. 1.33 for $\omega_o/\omega = 0.2$ and two values of M: 1 and 0.5.

Two three-phase six-pulse cycloconverters are shown in Fig. 1.34. The cycloconverter with isolated phase loads in Fig. 1.34a is supplied from a single three-phase source. If the loads are interconnected, as in Fig. 1.34b, individual phases of the cycloconverter must be fed from separate sources, such as isolated secondary windings of the supply transformer. Practical

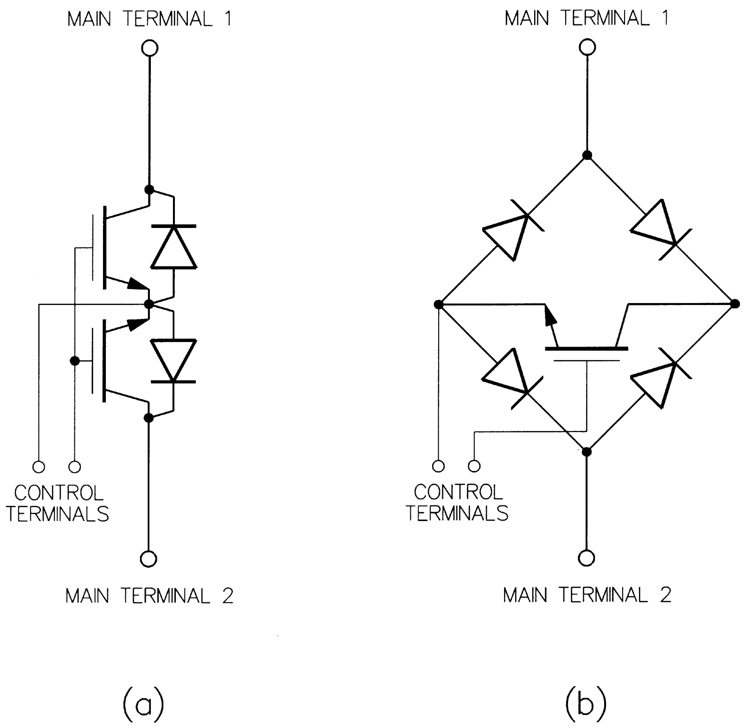


FIGURE 1.30
Fully controlled bidirectional power switch assemblies: (a) two transistors and two diodes, (b) one transistor and four diodes.

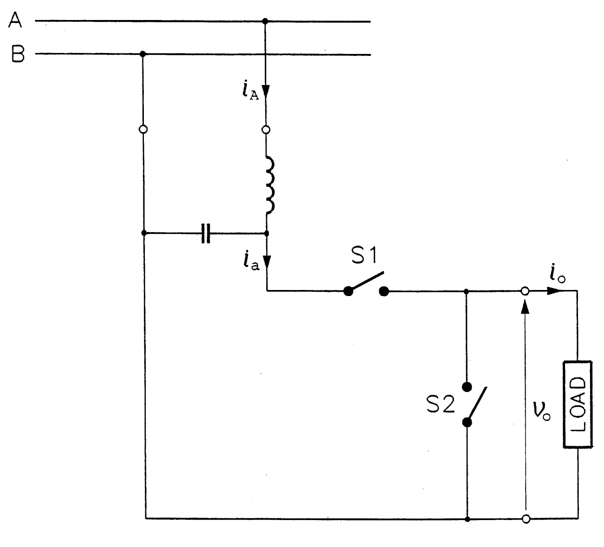


FIGURE 1.31
Single-phase ac chopper.

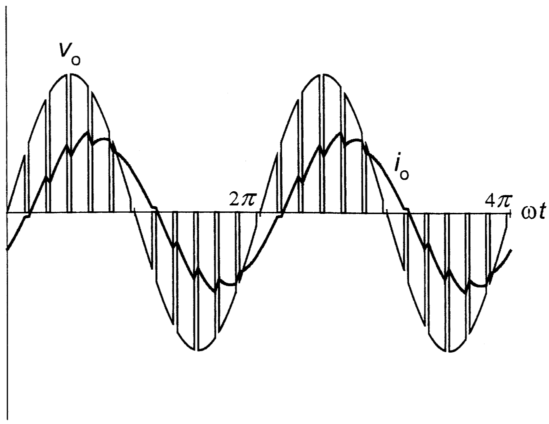


FIGURE 1.32
Output voltage and current waveforms in an ac chopper.

cycloconverters are invariably high-power converters, typically used in adjustable-speed synchronous motor drives requiring sustained low-speed operation.

The matrix converter, shown in Fig. 1.35 in the three-phase to three-phase version, constitutes a network of bidirectional power switches, such as those in Fig. 1.30, connected between each of the input terminals and each of the output terminals. In this respect, the matrix converter

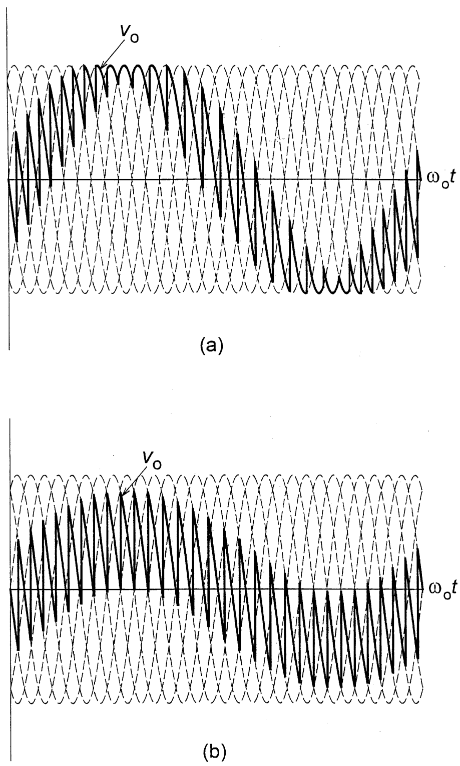
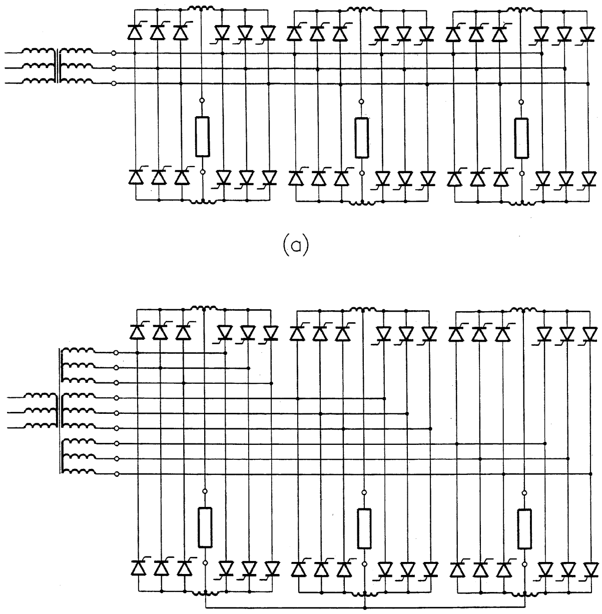


FIGURE 1.33
Waveforms of output voltage in a six-pulse cycloconverter: (a) $M = 1$, (b) $M = 0.5$ ($\omega_o/\omega = 0.2$).



(a)

(b)

FIGURE 1.34
Three-phase six-pulse cycloconverters: (a) with isolated phase loads, (b) with interconnected phase loads.

constitutes an extension of the generic power converter in Fig. 1.1. The voltage of any input terminal can be made to appear at any output terminal (or terminals), while the current in any phase of the load can be drawn from any phase (or phases) of the supply line. An input LC filter is employed to screen the supply system from harmonic currents generated by the converter, which operates in the PWM mode. The load inductance assures continuity of the output currents. Although, with the 9 switches, the matrix converter can theoretically have 512 states, only 27 states are permitted. Specifically, at any time, one and only one switch in each row must be closed. Otherwise, the input terminals would be shorted or the output currents would be interrupted.

The voltages, v_a, v_b, and v_c, at the output terminals are given by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} x_{Aa} & x_{Ba} & x_{Ca} \\ x_{Ab} & x_{Bb} & x_{Cb} \\ x_{Ac} & x_{Bc} & x_{Cc} \end{bmatrix} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \tag{1.12}$$

where x_{Aa} through x_{Cc} denote switching functions of switches S_{Aa} through S_{Cc}, and v_A, v_B, and v_C are the voltages at the input terminals. In turn, the line-to-neutral output voltages, v_{an}, v_{bn}, and v_{cn}, can be expressed in terms of v_a, v_b, and v_c as

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}. \tag{1.13}$$

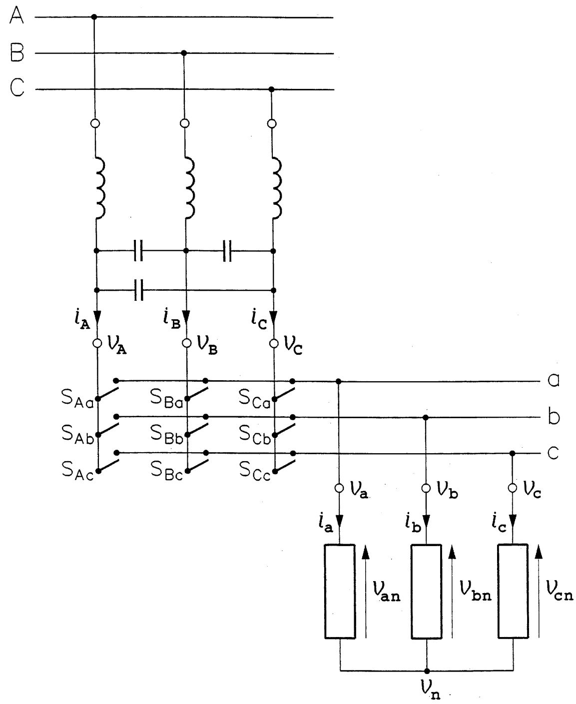


FIGURE 1.35
Three-phase to three-phase matrix converter.

The input currents, i_A, i_B, and i_C, are related to the output currents, i_a, i_b, and i_c, as

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} x_{Aa} & x_{Ab} & x_{Ac} \\ x_{Ba} & x_{Bb} & x_{Bc} \\ x_{Ca} & x_{Cb} & x_{Cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \tag{1.14}$$

Fundamentals of both the output voltages and input currents can successfully be controlled by employing a specific, appropriately timed sequence of the switching functions. As a result of such control, the fundamental output voltages acquire the desired frequency and amplitude, while the low-distortion input currents have the required phase shift (usually zero) with respect to the corresponding input voltages.

Example waveforms of the output voltage and current are shown in Fig. 1.36. For reference, waveforms of the line-to-line input voltages are shown, too. The output frequency, ω_o, in Fig. 1.36a is 2.8 times higher than the input frequency, ω, while the ω_o/ω ratio in Fig. 1.36b is 0.7. Respective magnitude control ratios, M, are 0.8 and 0.4.

Apart from the conceptual simplicity and elegance, matrix converters have not yet found widespread application in practice. Two major reasons are the low voltage gain, limited to $\sqrt{3}/2 \approx 0.866$, and unavailability of fully controlled bidirectional semiconductor switches.

1.4 DC TO DC CONVERTERS

Dc to dc converters, called *choppers*, are supplied from a dc voltage source, typically a diode rectifier and a *dc link*, as shown in Fig. 1.37. The dc link consists of a large capacitor connected

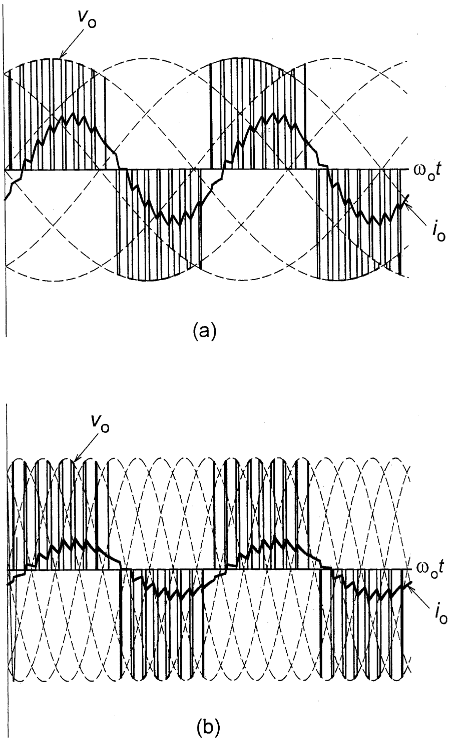


FIGURE 1.36
Output voltage and current waveforms in a matrix converter: (a) $\omega_o/\omega = 2.8, M = 0.8$; (b) $\omega_o/\omega = 0.7, M = 0.4$.

across the input terminals of the chopper and, often but not necessarily, a series inductance. The capacitor smooths the dc voltage produced by the rectifier and serves as a source of the high-frequency ripple current drawn by the chopper. The inductor provides an extra screen for the supply power system against the high-frequency currents. All choppers are pulse width modulated, the phase control being infeasible with both the input and output voltages of the dc type.

Most choppers are of the step-down (buck) type, that is, the average output voltage, V_o, is always lower than the input voltage, V_i. The *first-quadrant chopper*, based on a single fully

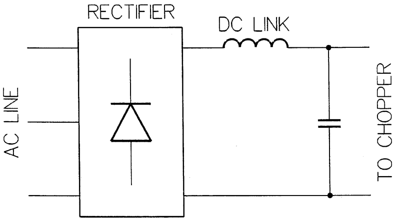


FIGURE 1.37
Dc voltage source for choppers.

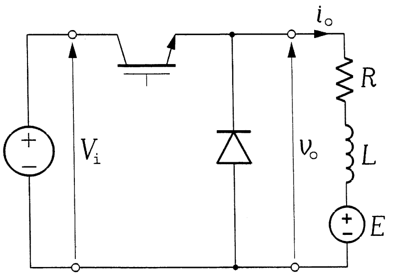


FIGURE 1.38
First-quadrant chopper.

controlled switch and a freewheeling diode, is shown in Fig. 1.38. Both the output voltage, v_o, and current, i_o, can only be positive. The average output voltage is given by

$$V_o = DV_i \tag{1.15}$$

where D denotes the duty ratio of the switch. The magnitude control ratio, M, is defined here as V_o/V_i and it equals D. Example waveforms of v_o and i_o are shown in Fig. 1.39, with M changing from 0.5 to 0.75. As in all PWM converters, the output voltage is pulsed, but the output current is continuous thanks to the load inductance. The current ripple is inverse proportional to the switching frequency, f_{sw}. Specifically, the rms value, $I_{o,ac}$, of the ac component of the output current is given by

$$I_{o,ac} = \frac{|M|(1-|M|)}{2\sqrt{3}Lf_{sw}} V_i \tag{1.16}$$

where L denotes inductance of the load.

The reason for the absolute value, $|M|$, of the magnitude control ratio appearing in Eq. (1.16) is that this ratio in choppers can assume both the positive and negative values. In particular, $M > 0$ indicates operation in the first and third quadrant (see Fig. 1.14), while $M < 0$ is specific for choppers operating in the second and fourth quadrant. The most versatile dc to dc converter, the four-quadrant chopper shown in Fig. 1.40, can, as its name indicates, operate in all four quadrants.

In the first quadrant, switch S4 is turned on all the time, to provide a path for the output current, i_o, while switch S1 is chopping with the duty ratio D_1. The remaining two switches, S2 and S3, are OFF. In the second quadrant, it is switch S2 that is chopping, with the duty ratio D_2, and all the other switches are OFF. Analogously, in the third quadrant, switch S1 is ON, switch S3 is chopping with the duty ratio D_3 and, in the fourth quadrant, switch S4 is chopping with the

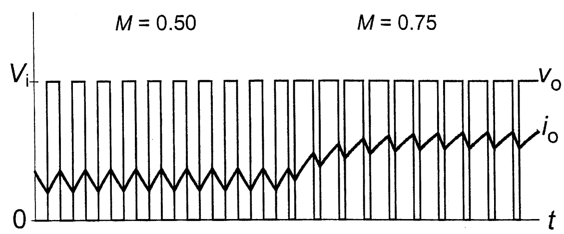


FIGURE 1.39
Example waveform of output voltage and current in a first-quadrant chopper.

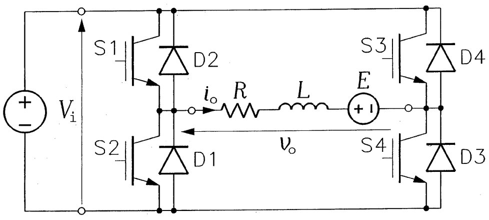


FIGURE 1.40
Four-quadrant chopper.

duty ratio D_4. When a chopping switch is OFF, conduction of the output current is taken over by a respective freewheeling diode, for instance, D1 in the first quadrant of operation. The magnitude control ratio, M, is given by

$$M = \begin{cases} D_1 & \text{in Quadrant 1} \\ 1 - D_2 & \text{in Quadrant 2} \\ -D_3 & \text{in Quadrant 3} \\ D_4 - 1 & \text{in Quadrant 4.} \end{cases} \tag{1.17}$$

If the chopper operates in Quadrants 2 and 4, the power flows from the load to the source, necessitating presence of an EMF, E, in the load. The EMF must be positive in Quadrants 1 and 2, and negative in Quadrants 3 and 4. For sustained operation of the chopper with a continuous output current, the magnitude control ratio must be limited in dependence on the ratio E/V_i as illustrated in Fig. 1.41. These limitations, as well as Eq. (1.17), apply to all choppers.

Any less-than-four-quadrant chopper can easily be obtained from the four-quadrant topology. Consider, for instance, a two-quadrant chopper, capable of producing an output voltage of both polarities, but with only a positive output current. Clearly, this converter can operate in the first and fourth quadrants. Its circuit diagram, shown in Fig. 1.42, is determined by eliminating switches S2 and S3 and their companion diodes, D2 and D3, from the four-quadrant chopper circuit in Fig. 1.40.

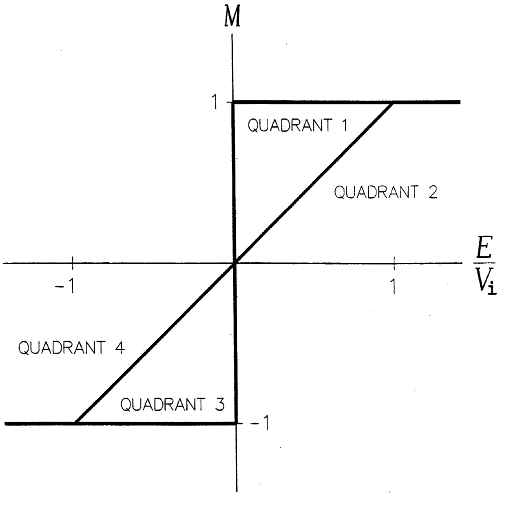


FIGURE 1.41
Allowable ranges of the magnitude control ratio in a four-quadrant chopper.

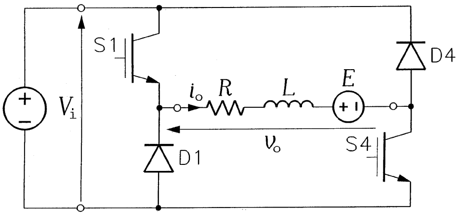


FIGURE 1.42
First-and-fourth-quadrant chopper.

A step-up (boost) chopper, shown in Fig. 1.43, produces a pulsed output voltage, whose amplitude, $V_{o,p}$, is higher than the input voltage. If a sufficiently large capacitor is connected across the output terminals, the output voltage becomes continuous, with $V_o \approx V_{o,p} > V_i$. When switch S is turned on, the input inductor, L_c, is charged with electromagnetic energy, which is then released into the load by turning the switch off. The magnitude control ratio, M, defined as $V_{o,p}/V_i$, in an ideal (lossless) step-up chopper is given by

$$M = \frac{1}{1 - D} \tag{1.18}$$

where D denotes the duty ratio of the switch. In real choppers, the value of M saturates at a certain level, usually not exceeding 10 and dependent mostly on the resistance of the input inductor. Example waveforms of the output voltage and current in a step-up chopper without the output capacitor are shown in Fig. 1.44.

1.5 DC TO AC CONVERTERS

Dc to ac converters are called *inverters* and, depending on the type of the supply source and the related topology of the power circuit, they are classified as *voltage-source inverters* (VSIs) and *current-source inverters* (CSIs). The simplest, single-phase, half-bridge, VSI is shown in Fig. 1.45. The switches may not be ON simultaneously, because they would short the supply source. There is no danger in turning both switches off, but the output voltage, v_o, would then depend on the conducting diode, that is, it could not be determined without some current sensing arrangement. Therefore, only two states of the inverter are allowed. Consequently, a single switching function, a, can be assigned to the inverter. Defining it as

$$a = \begin{cases} 0 & \text{if SA} = \text{ON} \quad \text{and} \quad \text{SA}' = \text{OFF} \\ 1 & \text{if SA} = \text{OFF} \quad \text{and} \quad \text{SA}' = \text{ON}, \end{cases} \tag{1.19}$$

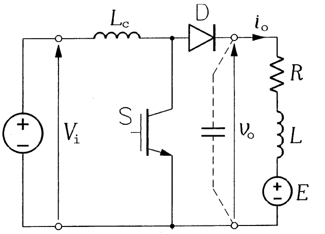


FIGURE 1.43
Step-up chopper.

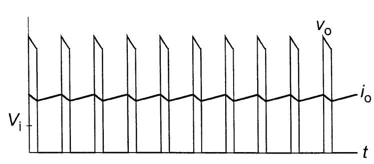


FIGURE 1.44
Output voltage and current waveforms in a step-up chopper ($D = 0.75$).