CHAPTER 13.2

NATURALLY COMMUTATED CONVERTERS

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INTRODUCTION

The applications for this family of naturally commutated converters embrace a very wide range, including dc power supplies for electronic equipment, battery chargers, dc power supplies delivering many thousands of amperes for electrochemical and other industrial processes, high-performance reversing drives for dc machines rated at thousands of horsepower, and high-voltage dc transmission at the gigawatt power level.

The basic feature common to this class of converters is that one set of terminals is connected to an ac voltage source. The ac source causes natural commutation of the converter power electronic devices. In these converters, a second set of terminals operates with dc voltage and current. This class of converters is divided in function depending on the direction of power flow. In *ac-to-dc rectification*, the ac source, typically the utility line voltage, supplies power to the converter, which in turn supplies power to a dc load. In *dc-to-ac inversion*, a dc source, typically a battery or dc generator, provides power to the converter, which in turn transfers the power to the ac source, again, usually the utility line voltage. Because natural commutation synchronizes the power semiconductor device turn on and turn off to the ac source, this converter is also known as a *synchronous inverter* or a *line-commutated inverter*. This process is different from supplying power to an ac load, which usually requires forced commutation.

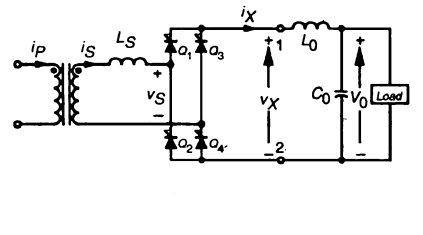
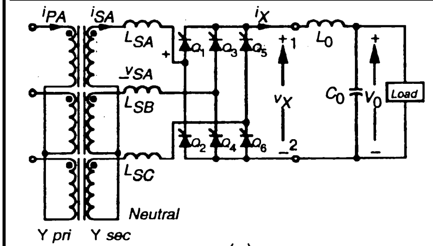
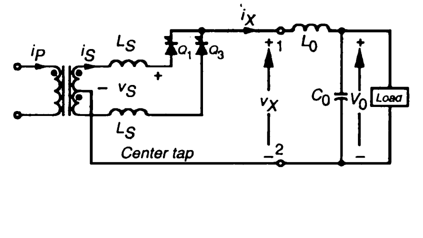
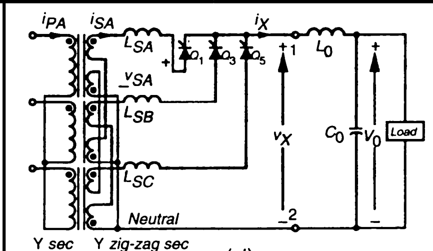
The power electronic devices in these converters are typically either *silicon controlled rectifiers* (SCRs) *diodes*. To simplify the discussion that follows, the SCRs and diodes are assumed to (1) conduct forward current with zero forward voltage drop, (2) block reverse voltage with zero leakage current, and (3) switch instantaneously between conduction and blocking. Furthermore, stray resistive loss is ignored and balanced three-phase ac sources are assumed.

Converter Topologies

Basic Topologies**.** The number of different converter topologies is very large (Schaeffer, 1965; Pelly, 1971; Dewan, 1975; Rashid, 1993). Using SCRs as the power electronic devices, Table 13.2.1 illustrates four basic topologies from which many others are derived. These ac-to-dc converters are rectifiers that provide a dc voltage V_O to a load. The rectifier often uses an output filter inductor L_O and capacitor C_O, but one or the other or both are often omitted. Rectifiers are usually connected to the ac source through a transformer. Note that the transformer is often utility equipment, located separately from the rectifier. The transformer adds a series leakage inductance L_S, which is often detrimental to rectifier operation.

Rectifier topologies are classified by whether the rectifier operates from a single- or three-phase source and whether the rectifier uses a bridge connection or transformer midpoint connection. The *single-phase bridge rectifier* shown in Table 13.2.1*a* requires four SCRs and a two-winding transformer. The *single-phase midpoint*

TABLE 13.2.1 Basic Converter Topologies

	Single-phase source	Three-phase source
Bridge	 (*a*)	 (*c*)
Midpoint	 (*b*)	 (*d*)

rectifier shown in Table 13.2.1*b* requires only two SCRs but requires a transformer with a center-tapped secondary to provide the midpoint connection. The *three-phase bridge rectifier* shown in Table 13.2.1*c* requires six SCRs and three two-winding transformers. The *three-phase midpoint rectifier* shown in Table 13.2.1*d* requires three SCRs and three transformers using a Y-connected "zig-zag" secondary. The Y-connected secondary provides the necessary midpoint connection and the zig-zag winding prevents unidirectional secondary winding currents from causing magnetic saturation of the transformers.

The bridge rectifier is better suited to using the simple connection provided by the typical utility transformer. For the same power delivered to the load, the bridge rectifier often requires a smaller transformer. Therefore, in the absence of other constraints, the bridge rectifier is often preferred over the midpoint rectifier.

Pulse Number. Converters are also classified by their pulse number q, an integer that is the number of current pulses appearing in the rectifier output current waveform i_X per cycle of the ac source voltage. Higher pulse number rectifiers generally have higher performance but usually with a penalty of increased complexity. Of the rectifiers shown in Table 13.2.1, both single-phase rectifiers are two-pulse converters ($q = 2$) with one current pulse in i_X for each half-cycle of the ac source voltage. The three-phase midpoint rectifier is a three-pulse converter ($q = 3$) with one current pulse in i_X for each cycle of each phase of the three-phase ac source voltage. The three-phase bridge rectifier is a six-pulse converter ($q = 6$) with one current pulse in i_X for each half cycle of each phase of the three-phase ac source voltage.

BASIC CONVERTER OPERATION

Given a certain operating point, rectifier operation and performance are dramatically influenced by the values of source inductance L_S, output filter inductance L_O, and output filter capacitance C_O.

Operation with Negligible Ac Source Inductance. Figures 13.2.1 and 13.2.2 show example time waveforms for the single- and three-phase bridge rectifiers of Table 13.2.1*a* and 13.2.1*c*, respectively. In these

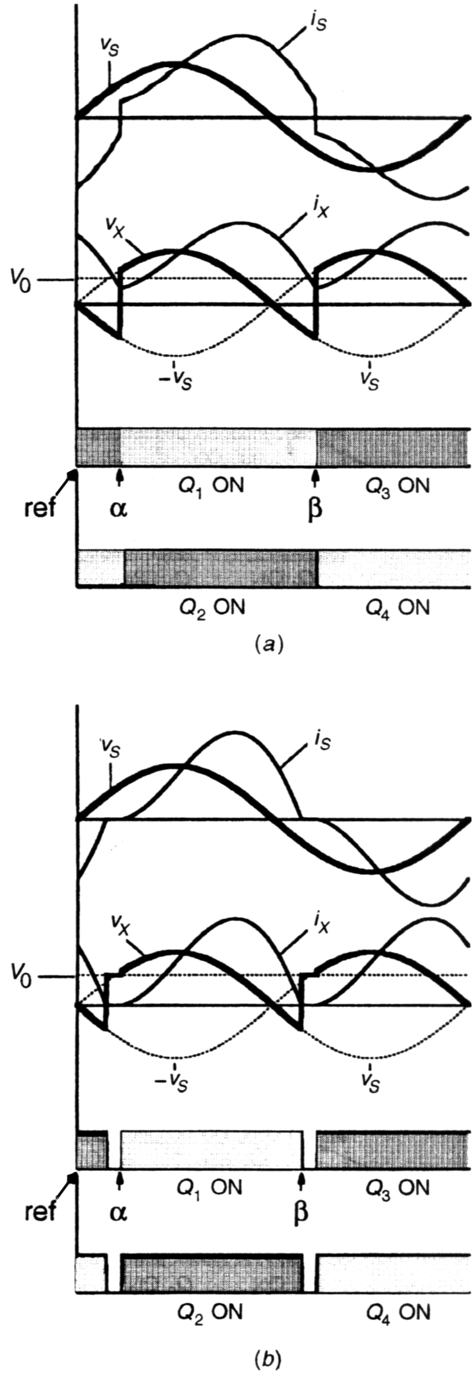


FIGURE 13.2.1 Time waveforms for single-phase bridge rectifier with $\alpha = 40°$: (*a*) CCM and (*b*) DCM.

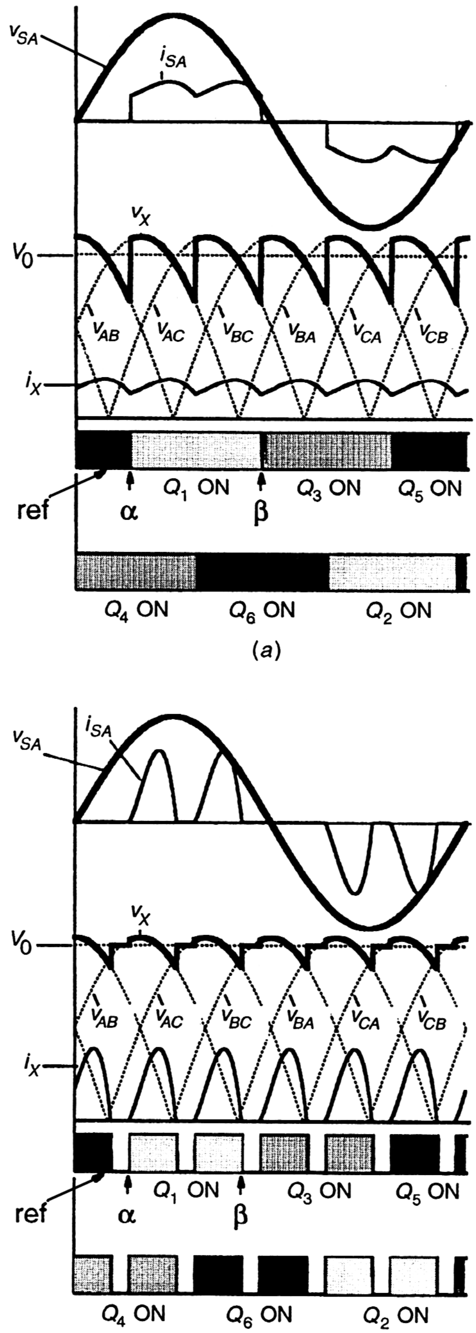


FIGURE 13.2.2 Time waveforms for three-phase bridge rectifier with $\alpha = 20°$: (*a*) CCM and (*b*) DCM.

examples L_S is comparatively small and its influence is neglected. The value of C_O is relatively large so that the ripple in the output voltage V_O is relatively small. Operation of single- and three-phase phase-controlled rectifiers is described in detail in (Kelley, 1990).

Figure 13.2.1*a* shows time waveforms for the single-phase bridge rectifier when the current i_X in L_O flows continuously without ever falling to zero. The rectifier is said to be operating in the *continuous conduction mode* (CCM). The CCM occurs for relatively large L_O, heavy loads, and small α. Figure 13.2.1*b* shows time waveforms for the single-phase bridge rectifier when i_X drops to zero twice each cycle and the rectifier is said to be operating in the *discontinuous conduction mode* (DCM). The DCM occurs for relatively small L_O, light loads, and large α.

Figure 13.2.1 also shows the conduction intervals for SCRs Q_1 to Q_4 and the rectifier voltage, v_X. A controller, not shown in Fig. 13.2.1, generates gating pulses for the SCRs. The controller gates each SCR at a *firing angle* α (alpha) with respect to a *reference* that is the point in time at which the SCR is first forward biased. The SCR ceases conduction at the *extinction angle* β (beta). The reference, α, and β for Q_1 are illustrated in Fig. 13.2.1. The SCR *conduction angle* γ (gamma) is the difference between β and α. In DCM the SCR ceases conduction because i_X falls naturally to zero, while in the CCM the SCR ceases conduction even though i_X is not zero because the opposing SCR is gated and begins conducting i_X. Therefore in CCM, γ is limited to a maximum of one-half of an ac source voltage cycle, while in DCM γ depends on L_O, load, and α.

Note that v_X equals v_S when Q_1 and Q_4 are conducting and that v_X equals $-v_S$ when Q_2 and Q_3 are conducting. The output filter L_O and C_O reduces the ripple in v_X and delivers a relatively ripple-free voltage V_O to the load. The firing angle α determines the composition of v_X and ultimately the value of V_O. Increasing α reduces V_O and is the mechanism by which the controller regulates V_O against changes in ac source voltage and load. This method of output voltage regulation is referred to as *phase control*, and a rectifier using it is said to be a *phase-controlled rectifier*.

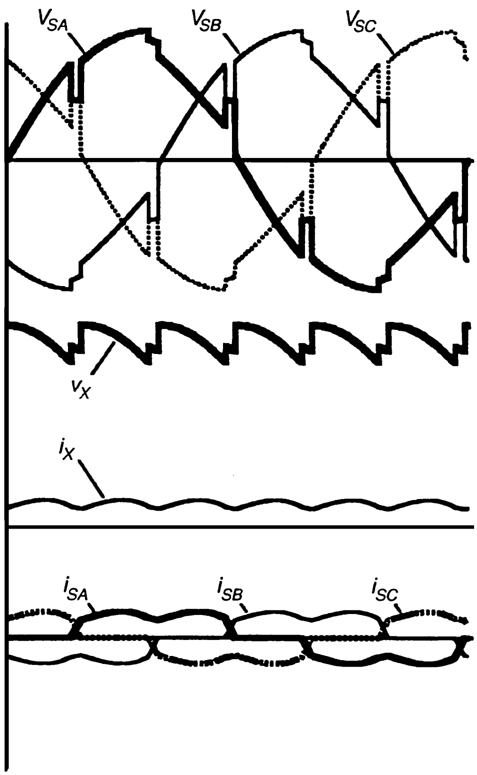


FIGURE 13.2.3 Time waveforms for three-phase bridge rectifier with appreciable L_S.

Since in CCM the conduction angle is always one half of a source voltage cycle, the dc output voltage is easily found from v_X as

$$V_O = \frac{2}{\pi}\sqrt{2}\,V_S \cos\alpha \tag{1}$$

where V_S is the rms value of the transformer secondary voltage v_S. Unfortunately, the conduction angle in DCM depends on L_O, the load, and α, and V_O cannot be calculated except by numerical methods.

For the three-phase bridge rectifier, Figures 13.2.2*a* and 13.2.2*b* show time waveforms for CCM and DCM, respectively. Operation is similar to the single-phase rectifier except that v_X equals each of the six line-to-line voltages—v_{AB}, v_{AC}, v_{BC}, v_{BA}, v_{CA}, and v_{CB}—in succession. In CCM, the SCR conduction angle γ is one-third of an ac source voltage cycle, and in DCM γ depends on L_O, load, and α. In CCM the dc output voltage V_O is found from v_X as

$$V_O = \frac{3}{\pi}\sqrt{3}\,\sqrt{2}\,V_S \cos\alpha \tag{2}$$

where V_S is the rms value of the transformer secondary line-to-neutral voltage. In DCM, the value of V_O must be calculated by numerical means. To produce a ripple-free output voltage V_O, the time waveform of v_X for the three-phase rectifier naturally requires less filtering than the time waveform of v_X for the single-phase rectifier.

Therefore, if a three-phase ac source is available, a three-phase rectifier is always preferred over a single-phase rectifier.

Operation with Appreciable Ac Source Inductance. The preceding discussion assumes that the value of L_S is small and does not influence circuit operation. In practice the effect of L_S must often be considered. The three-phase rectifier CCM time waveforms of Fig. 13.2.2 are repeated in Fig. 13.2.3 but for an appreciable L_S. Since i_X is always nonzero in CCM, the principal effect of L_S is to prevent instantaneous transfer of i_X from one transformer secondary winding to the next transformer secondary winding as the SCRs are gated in succession. This process is called *commutation* and the interval during which it occurs is called *commutation overlap*.

For example, at some point in time Q_1 is conducting i_{SA} equal to i_X and Q_3 is gated by the controller. Current i_{SA} through Q_1 falls while i_{SB} through Q_3 rises. During this interval both Q_1 and Q_3 conduct simultaneously and the sum of i_{SA} and i_{SB} is equal to i_X. As a result transformer secondary v_{SA} is directly connected to transformer secondary v_{SB} effectively creating a line-to-line short circuit. This connection persists until i_{SA} falls to zero and Q_1 ceases conduction. The duration of the connection is the *commutation angle* μ (mu). During this interval v_{SA} experiences a positive-going voltage "notch" while v_{SB} experiences a negative-going voltage notch. The enclosed area of the positive-going notch equals the enclosed area of the negative-going notch and represents the flux linkage or "volt seconds" necessary to produce a change in current through L_S equal to i_X. If L_O is sufficiently large so that i_X is relatively constant with value I_X during the time that both SCRs conduct, then the notch area is used to find

$$\cos\alpha - \cos(\mu + \alpha) = \sqrt{\frac{2}{3}}(2\pi f\, L_S I_X / V_S) \tag{3}$$

which can be solved numerically for μ. Note that the commutation angle is always zero in DCM since i_X is zero when each SCR is gated to begin conduction.

CONVERTER POWER FACTOR

Source Current Harmonic Composition. The time waveforms of the prior section show that the rectifier is a nonlinear load that draws a highly distorted nonsinusoidal waveform i_S. Fourier series is used to decompose i_S into a fundamental-frequency component with rms value $I_{S(1)}$ and phase angle $\phi_{S(1)}$ with respect to v_S, and into harmonic-frequency components with rms value $I_{S(h)}$ where h is an integer representing the harmonic number. In general, the $I_{S(h)}$ are zero for even h. Furthermore, depending on converter pulse number q, certain $I_{S(h)}$ are also zero for some odd h. Apart from $h = 1$ for which $I_{S(1)}$ is always nonzero, the $I_{S(h)}$ are nonzero for

$$h = kq \pm 1 \; (k \text{ integer} \geq 1) \tag{4}$$

Therefore harmonic currents for certain harmonic numbers are eliminated for higher pulse numbers. For example, the single-phase bridge rectifier with $q = 2$ produces nonzero $I_{S(h)}$ for $h = 1, 3, 5, 7, 9, \ldots$, while the three-phase bridge rectifier with $q = 6$ produces nonzero $I_{S(h)}$ for $h = 1, 5, 7, 11, 13, \ldots$. If rectifier operation is unbalanced, then harmonics are produced for all h. An unbalanced condition can result from asymmetrical gating of the SCRs or from voltage or impedance unbalance of the ac source. The effect is particularly pronounced for three-phase rectifiers with a comparatively small L_O and a comparatively large C_O since these rectifiers act like "peak detectors" and C_O charges to the point where V_O approaches the peak value of the line-to-line voltage. One phase needs to be only several percent below the other two phases for it to conduct a greatly reduced current and shift most of the current to the other two phases. An unbalanced condition is always evident from the waveform of i_X because the heights of the pulses are not all the same.

Power Factor. The rms value I_S of i_S is found from

$$I_S = \sqrt{I_{S(1)}^2 + \sum_{h>1} I_{S(h)}^2} \tag{5}$$

The ac source is rated for apparent power S, which is the product of V_S and I_S (in volt-amperes, VA). However, the source delivers real input power P_I (in watts, W), which the rectifier converts to dc and supplies to the load. The *total power factor PF* is the ratio of the real input power and the apparent power supplied by the ac source

$$PF = \frac{P_I}{S} = \frac{P_I}{V_S I_S} \tag{6}$$

and measures the fraction of the available apparent power actually delivered to the rectifier. The source voltage v_S is an undistorted sine wave only if L_S is negligible. In this case power is delivered only at the fundamental frequency so that

$$P_I = V_S I_{S(1)} \cos \phi_{S(1)} \tag{7}$$

Note that the harmonics $I_{S(h)}$ draw apparent power from the source by increasing I_S but do not deliver real power to the rectifier. Using this assumption, the expression for power factor reduces to

$$PF = \cos \phi_{S(1)} \frac{I_{S(1)}}{I_S} \tag{8}$$

The *displacement power factor* $\cos\phi_{S(1)}$ is the traditional power factor used in electric power systems for sinusoidal operation and is unity when the fundamental of i_S is in phase with v_S. The *purity factor* $I_{S(1)}/I_S$ is unity when i_S is a pure sine wave and the rms values of $I_{S(h)}$ are zero so that I_S equals $I_{S(1)}$. The distortion of i_S is often and equivalently represented by the *total harmonic distortion for current* THD_i

$$THD_i = 100\frac{\sqrt{\sum_{h>1} I_{S(h)^2}}}{I_{S(1)}} = 100\sqrt{\frac{1}{(I_{S(1)}/I_S)^2} - 1} \quad \text{(expressed in percent)} \tag{9}$$

The purity factor $I_{S(1)}/I_S$ is also called the distortion power factor, which is easily confused with the total harmonic distortion THD_i.

The theoretical maximum power factor for the single-phase bridge rectifier is 0.90, which occurs for $\alpha = 0°$ and usually requires an uneconomically large value of L_O. The actual power factor often ranges from 0.5 to 0.75. The theoretical maximum power factor for the three-phase bridge rectifier is 0.96 which also occurs for $\alpha = 0°$. Because the three-phase bridge rectifier requires less filtering, it is often possible to approach this theoretical maximum power factor with an economical value of L_O. However, for cost reasons, L_O is often omitted in both the single- and three-phase rectifiers which dramatically reduces the power factor and leaves it to depend on the value of L_S.

Source Voltage Distortion and Power Quality. The time waveforms of Fig. 13.2.3 show that with appreciable L_S the rectifier distorts the voltage source v_S supplying the rectifier. Fourier series is also used to represent v_S as a fundamental voltage of rms value $V_{S(1)}$ and harmonic voltages of rms value $V_{S(h)}$. The distortion of v_S is often represented by the total harmonic distortion for voltage THD_v

$$THD_v = 100\frac{\sqrt{\sum_{h>1} V_{S(h)^2}}}{V_{S(1)}} \quad \text{(expressed in percent)} \tag{10}$$

Note that the definition of power factor (Eq. (7)) is valid for appreciable L_S and distorted v_S but (Eq. (8)) is strictly valid only when L_S is negligible and v_S is undistorted.

Voltage distortion can cause problems for other loads sharing the rectifier ac voltage source. Computer-based loads, which have become very common, appear to be particularly sensitive. Issues of this kind have been receiving increased attention and fall under the general heading of *power quality*. Increasingly strict power factor and harmonic current limits are being placed on ac-to-dc converters (IEEE-519, 1992; IEC-1000, 1995). In particular, limits on the total harmonic distortion of the current THD_i, the rms values $I_{S(h)}$ of the harmonics, and the rms values of the harmonics relative to the fundamental $I_{S(h)}/I_{S(1)}$ are often specified. These limits present new challenges to the designers of ac-to-dc converters.

ADDITIONAL CONVERTER TOPOLOGIES

This section summarizes the large number of converters that are based on the rectifiers of Table 13.2.1. These converters are shown in Table 13.2.2.

Uncontrolled Diode Rectifier. Replacing SCRs with diodes produces an uncontrolled rectifier as shown in Table 13.2.2*a*. In contrast to the SCRs, which are gated by a controller, the diodes begin conduction when initially forward biased by the circuit so that an uncontrolled diode rectifier behaves like a phase-controlled rectifier operated with $\alpha = 0°$. Details of uncontrolled diode rectifier operation are described in Kelley (1992).

Half-Controlled Bridge Rectifier. In the half-controlled bridge rectifier the even-numbered SCRs (Q_2 and Q_4 for the single-phase rectifier, and Q_2, Q_4, and Q_6 for the three-phase rectifier) are replaced with diodes as shown in Table 13.2.2*b*. The remaining odd-numbered SCRs (Q_1 and Q_3 for the single-phase rectifier, and Q_1, Q_3, and Q_5 for the three-phase rectifier) are phase controlled to regulate the dc output voltage V_O. This substitution is advantageous because diodes are cheaper than SCRs and the cathodes of the remaining SCRs are connected to a common point that simplifies SCR gating.

Note that the diodes begin conduction when first forward biased while the SCRs begin conduction only after being gated while under forward bias. As a result, during a certain portion of each cycle, i_X *freewheels* through the series connection of a diode and SCR, thereby reducing i_S to zero. For example, in the single-phase bridge rectifier i_X freewheels through Q_1 and D_2 for one part of the cycle and through Q_3 and D_4 for another part of the cycle. In the three-phase rectifier i_X freewheels through Q_1 and D_2, Q_3 and D_4, and Q_5 and D_6 during different parts of the cycle. This freewheeling action prevents v_X from changing polarity and improves rectifier power factor as α increases and V_O decreases.

Freewheeling Diode. The same effect is achieved if a *freewheeling diode* D_X is connected across terminals 1 and 2 of the rectifier as shown in Table 13.2.2*c*. The freewheeling diode is used with both the bridge and midpoint rectifier connections.

Dc Motor Drive. Any of the phase-controlled rectifiers described above can be used as a dc motor drive by connecting the motor armature across terminals 1 and 2 as shown in Table 13.2.2*d.* Phase control of SCR firing angle α controls motor speed.

Battery Charger. Phase-controlled rectifiers are widely used as battery chargers as shown in Table 13.2.2*e*. Phase control of SCR firing angle α regulates battery charging current.

Line Commutated Inverter. A line-commutated inverter transfers power from the dc terminals 1 and 2 of the converter to the ac source. As shown in Table 13.2.2*f*, the dc terminals are connected to a dc source of power such as a dc generator or a battery. The polarity of each SCR is reversed and the rectifier is operated with $\alpha >$ 90°. This circuit is called a line-commutated inverter or a synchronous inverter. Note that the half-controlled bridge and the freewheeling diode cannot be used with a line-commutated inverter because they prevent a change in the polarity of v_X.

Operation with $\alpha > 90°$ causes the majority of the positive half cycle of i_S to coincide with the negative half cycle of v_S. Similarly, the negative half cycle of i_S coincides with the positive half cycle of v_S. It is this mechanism that, on average, causes power flow from the dc source into the ac source. In principal α could approach 180°, but in practice α must be limited to 160° or less to permit sufficient time for the SCRs to stop conducting and regain forward voltage blocking capability before forward voltage is reapplied to them. This requirement is particularly important when L_S is appreciable.

TABLE 13.2.2 Additional Converter Topologies

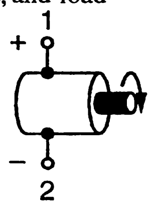
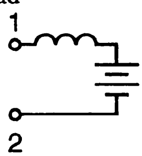
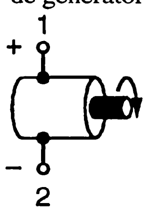
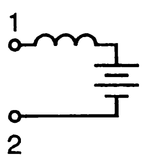
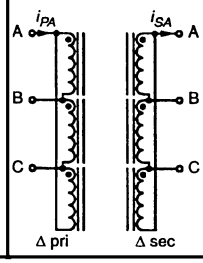
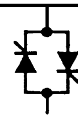
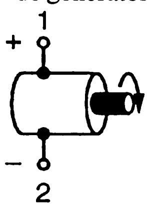
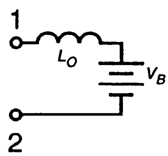
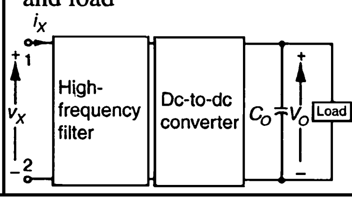
	Single-Phase Source	Three-Phase Source
(*a*) Uncontrolled diode rectifier	Replace all SCRs with diodes	
(*b*) Half-controlled bridge rectifier	Replace SCRs Q_2, Q_4 with diodes D_2, D_4	Replace SCRs Q_2, Q_4, Q_6 with diodes D_2, D_4, D_6
(*c*) Freewheeling diode	Retain L_O, C_O, and load, adding diode D_X 	
(*d*) Dc motor drive	Replace L_O, C_O, and load with dc motor 	
(*e*) Battery charger	Replace L_O, C_O, and load with L_O and battery 	
(*f*) Line commutated inverter	Reverse polarity of all SCRs changing to Replace L_O, C_O, and load with dc generator or battery and L_O  	

TABLE 13.2.2 Additional Converter Topologies (*Continued*)

<table>
<tr><th></th><th>Single-Phase Source</th><th>Three-Phase Source</th></tr>
<tr><td>(g) Alternate three-phase transformer connections</td><td>Not applicable</td><td>Replace Y primary and/or secondary with Δ primary and/or secondary

</td></tr>
<tr><td>(h) Bidirectional converter</td><td colspan="2">Replace all SCRs  with two SCRs in antiparallel 
Replace L_O, C_O, and load with dc generator 

or battery and L_O 
</td></tr>
<tr><td>(i) Active power factor correction</td><td colspan="2">Replace all SCRs  with diodes 
Replace L_O, C_O, and load with high-frequency filter, dc-to-dc converter, C_O and load

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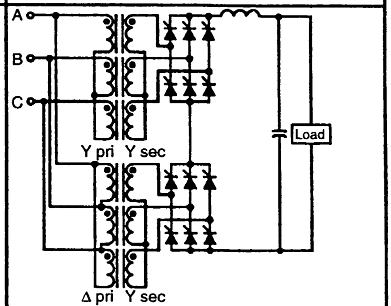
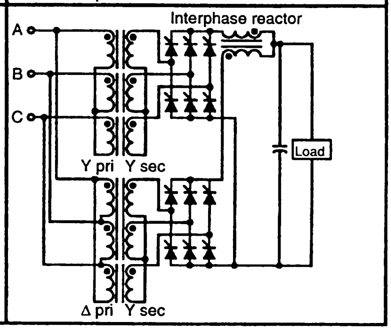
(*Continued*)

TABLE 13.2.2 Additional Converter Topologies (*Continued*)

	Single-Phase Source	Three-Phase Source
(*j*) Series-connected 12-pulse rectifier	Not-applicable	
(*k*) Parallel-connected 12-pulse rectifier	Not-applicable	

Alternate Three-Phase Transformer Connections. Both primary and secondary transformer windings may be either Y-connected or Δ-connected, as shown in Table 13.2.2*g* except for the midpoint connection, which requires a Y-connected secondary winding. If the connection is Y-Y or Δ-Δ the waveform of secondary current i_S is scaled by the transformer turn ratio to become the waveform of primary current i_P. Therefore, the secondary current fundamental $I_{S(1)}$ and harmonics $I_{S(h)}$, when scaled by the turn ratio, become the primary fundamental $I_{P(1)}$ and harmonics $I_{P(h)}$.

Similarly, if the transformer connection is Y-Δ or Δ-Y, the secondary current fundamental $I_{S(1)}$ and harmonics $I_{S(h)}$, when scaled by the turn ratio, become the primary fundamental $I_{P(1)}$ and harmonics $I_{P(h)}$. However, the Y-Δ and Δ-Y transformer connections introduce different phase shifts for each harmonic so that the primary current waveform i_P differs in shape from the secondary current wave-form i_S. Rectifier power factor remains unchanged; however, this phase shift is used to produce harmonic cancellation in rectifiers with high pulse numbers as described subsequently.

Bidirectional Converter. Many applications require bidirectional power flow from a single converter. Table 13.2.2*h* illustrates one example in which a phase-controlled rectifier is, effectively speaking, connected in parallel with a line commutated inverter by replacing each SCR with a *pair* of SCRs connected in antiparallel. The load is replaced either by a battery or by a dc motor. In the bidirectional converter, one polarity of SCRs is used to transfer energy from the ac source to the battery or motor while the opposite polarity of SCRs is used to reverse the power flow and transfer energy from the battery or motor to the ac source.

For example, using the battery, the converter operates as a battery charger to store energy when demand on the utility is low and at a subsequent time the converter operates as a line commutated inverter to supply energy when demand on the utility is high. Using a dc motor, the converter operates as a dc motor drive to supply power to a rotating load. Depending on the direction of motor rotation and on which polarity of SCRs is used, the bidirectional converter can both brake the motor efficiently by returning the energy stored in the rotating momentum back to the ac source and subsequently reverse the motors direction of rotation.

Active Power Factor Corrector. In many instances the basic converter topologies of Table 13.2.1 and the additional converter topologies of Table 13.2.2*a* to 13.2.2*g* cannot meet increasingly strict power factor and harmonic current limits without the addition of expensive passive filters operating at line frequency. The active power factor corrector, illustrated in Table 13.2.2*i*, is one solution to this problem (Rippel, 1979; Kocher, 1982; Latos, 1982). The output filter inductor L_O is replaced by a high-frequency filter and a dc-to-dc converter. The dc-to-dc converter uses high-frequency switching and a fast control loop to actively control the waveshape of i_X, and therefore control the waveshape of i_S, for near unity displacement power factor and near unity purity factor resulting in near unity power factor ac-to-dc conversion (Huliehel, 1992). A high-frequency filter is required to prevent dc-to-dc converter switching noise from reaching the ac source.

A slower control loop regulates V_O against changes in source voltage and load. Because the dc-to-dc converter regulates V_O over a wide range of source voltage, the active power factor corrector can be designed for a *universal input* that allows the corrector to operate from nearly any ac voltage source. The active power factor corrector is used most commonly for lower powers.

Higher Pulse Numbers. When strict power factor and harmonic limits are imposed at higher power levels, and the active factor corrector cannot be used, the performance of the basic rectifier is improved by increasing the pulse number q and elimination of current harmonics $I_{S(h)}$ for certain harmonic numbers as shown by Eq. (4). Table 13.2.2*j* and 13.2.2*k* illustrate two examples based on the three-phase six-pulse bridge rectifier ($q = 6$) of Table 13.2.1*c*. The six-pulse rectifiers are shown connected in series in Table 13.2.2*j* and in parallel in Table 13.2.2*k*. The parallel connection in Table 13.2.2*k* requires an *interphase reactor* to prevent commutation of the SCRs in one rectifier from interfering with commutation of the SCRs in the other rectifier. The interphase reactor also helps the two rectifiers share the load equally.

Both approaches use a Y-Y transformer connection to supply one six-pulse rectifier and a Δ-Y transformer connection to supply the second six-pulse rectifier. The primary-to-secondary voltage phase shift of the Δ-Y transformer means the two rectifiers operate out of phase with each other producing 12-pulse operation ($q = 12$). As described previously, the Δ-Y transformer also produces a secondary-to-primary phase shift of the current harmonics. As a result, at the point of connection to the ac source, harmonics from the Δ-Y connected six-pulse rectifier cancel the harmonics from the Y-Y connected six-pulse rectifier for certain harmonic numbers. For example, the harmonics cancel for $h = 5$ and 7, but not for $h = 11$ and 13. Thus the total harmonic distortion for current THD_i and the total power factor for the 12-pulse converter is greatly improved in comparison to either six-pulse converter alone. The 12-pulse output voltage ripple filtering requirement is also greatly reduced compared to a single six-pulse rectifier. This principle can be extended to even higher pulse numbers by using additional six-pulse rectifiers and transformer phase-shift connections.

High Voltage Dc Transmission. High Voltage dc (HVDC) Transmission is a method for transmitting power over long distances while avoiding certain problems associated with long distance ac transmission. This requirement often arises when a large hydroelectric power generator is located a great distance from a large load such as a major city. The hydroelectric generator's relatively low ac voltage is stepped up by a transformer, and a phase-controlled rectifier converts it to a dc voltage of a megavolt or more. After transmission over a long distance, a line commutated inverter and transformer convert the dc back to ac and supply the power to the load. Alternately, the rectifier and inverter are co-located and used as a tie between adjacent utilities. The arrangement can be used to actively control power flow between utilities and to change frequency between adjacent utilities operating at 50 and 60 Hz.

With power in the gigawatt range, this is perhaps the highest power application of a power electronic converter. To ensure a stable system, the control algorithms of the rectifier and inverter must be carefully coordinated. Note that since the highest voltage rating of an individual SCR is less than 10 kV, many SCRs are connected in series to form a *valve* capable of blocking the large dc voltage. Both the rectifier and inverter use a high pulse number to minimize filtering at the point of connection to the ac source.

REFERENCES

Dewan, S. B., and A. Straughen, "Power Semiconductor Circuits," Wiley, 1975.

Huliehel, F. A., F. C. Lee, and B. H. Cho, "Small-signal modeling of the single-phase boost high power factor converter with constant frequency control," *Record of the 1992 IEEE Power Electronics Specialists Conference (PESC '92)*, pp. 475–482, June 1992.

IEC-1000 Electromagnetic Compatibility (EMC), Part 3: Limits, Section 2: Limits for Harmonic Current Emissions (formerly IEC-555-2), 1995.

IEEE Standard 519, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," 1992.

Kelley, A. W., and W. F. Yadusky, "Phase-controlled rectifier line-current harmonics and power factor as a function of firing angles and output filter inductance," *Proc. IEEE Applied Power Electronics Conf.,* pp. 588–597, March 1990.

Kelley, A. W., and W. F. Yadusky, "Rectifier design for minimum line-current harmonics and maximum power factor," *IEEE Trans. Power Electronics*, Vol. 7, No, 2, pp. 332–341, April 1992.

Kocher, M. J., and R. L. Steigerwald, "An ac-to-dc converter with high-quality input waveforms," *Record of the 1982 IEEE Power Electronics Specialists Conference (PESC '82)*, pp. 63–75, June 1982.

Latos, T. S., and D. J. Bosak, "A high-efficiency 3-kW switchmode battery charger," *Record of the 1982 IEEE Power Electronics Specialists Conference (PESC '82)*, pp. 341–349, June 1982.

Pelley, B. R., "Thyristor Phase-Controlled Converters and Cycloconverters," Wiley, 1971.

Rashid, M. "Power Electronics: Circuits, Devices, and Applications," 2nd ed., Prentice Hall, 1993.

Rippel, W. E., "Optimizing boost chopper charger design," *Proceedings of the Sixth National Solid-State Power Conversion Conference (POWERCON6)*, pp. D1-1–D1-20, 1979.

Schaeffer, J., "Rectifier Circuits: Theory and Design," Wiley, 1965.