POWER FACTOR CORRECTION

The power a load draws from a utility alternate current (ac) bus can be divided into two components: real or active power P, which is the average rate of electrical energy consumption by the load, and reactive power Q, which is the magnitude of the power circulating between the load and the source. The apparent power S is defined as the product of the root-mean-square (rms) voltage and rms currents and can also be calculated as $S = \sqrt{P^2 + Q^2}$. The power factor (PF) is the ratio of the active power of an electrical system to its apparent power.

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Usually, the utility (mains) voltage can be assumed to be sinuosidal, but the input current that an electrical load draws is distorted and has many harmonic components, which can be calculated from Fourier analysis of the actual current waveform. Only the first harmonic (the fundamental component) of the input current contributes to useful power transfer. The power factor of an electrical load with a distorted current can be expressed as the product of the displacement factor K_θ and the distortion factor K_d:

$$\text{PF} = \frac{P}{S} = K_d K_\theta$$

where $K_\theta = \cos\theta$ and $K_d = I_{\text{rms}}(1)/I_{\text{rms}}$. The angle θ is the displacement angle between the voltage and the fundamental component of the input current, I_{rms} is the rms value of the input current, and $I_{\text{rms}}(1)$ is the rms value of the fundamental component of the input current. When θ is positive (i.e., when the phase of the voltage leads the phase of the current), the load is called an inductive load and has a lagging power factor. When θ is negative, the load is said to be capacitive and has a leading power factor. The displacement factor K_θ indicates how far the voltage and the fundamental current are out of phase, and the distortion factor K_d indicates how distorted the input current is. Another parameter widely used to describe the distortion degree of a current is the total harmonic distortion (THD), which is the distortion current as the percentage of the fundamental current:

$$\begin{aligned} \text{THD} &= \frac{\sqrt{\sum_{n=2}^{\infty} I_{\text{rms}}(n)^2}}{I_{\text{rms}}(1)} * 100 = \frac{\sqrt{I_{\text{rms}}{}^2 - I_{\text{rms}}(1)^2}}{I_{\text{rms}}(1)} * 100 \\ &= \sqrt{\frac{1}{K_d{}^2} - 1} * 100 \end{aligned}$$

where $I_{\text{rms}}(n)$ is the rms value of the nth harmonic component of the input current.

The transfer of active power from the utility mains is required for electrical equipment to function. However, the transfer of reactive power, which does not contribute directly to the output of electrical equipment, causes power loss in the distribution system and reduces the capability of an electrical system to process the active power. The distorted current, which also increases the reactive power, can cause interference for other electrical loads connected to the same utility line and additional distribution loss and may affect the functionality and reduce the reliability and service life of equipment. Therefore, the reactive power in a utility system should be minimized. Unity power factor (i.e., PF = 1), is the ideal condition, which implies that the voltage and the current are in phase, and the current is also a pure sinusoidal waveform, emulating a resistive load. However, the power factor of many electrical loads is less than unity. For example, most ac motors draw input currents with phases lagging to their input voltages, and many electronic systems draw distorted input currents because of the use of diode rectifiers to obtain power from the utility. To optimize the operation of electrical generation and distribution systems, power factor correction techniques are used to increase the power factor toward unity. Utility systems have traditionally implemented power factor correction, at the load side, through the use of fixed or switchable capacitors (because loads are predominantly inductive) or electronically controlled reactors plus fixed capacitors. Recent advances in power electronics topologies and circuit configurations have allowed the development of devices that can provide both real power/frequency control and power factor correction. These new devices can generate both inductive and capacitance reactive power, thus controlling the displacement factor of the system close to unity.

For constant loads with a fixed power factor, the power factor can be effectively improved by shunt capacitors. This minimizes the distribution system power losses for a given level of active power supplied to the load and maintains the right voltage at the load. However, most loads are not constant. For example, many motors stop and restart frequently, and others may run constantly but are loaded only as needed. Power factor for practical loads thus varies greatly with time. Another complicating factor is that transmission lines and distribution underground cables, usually inductive, can show a predominantly capacitive nature under light load conditions. Power factor correction capacitors cannot achieve satisfactory performance for a complex utility system and sometimes even create harmonic resonance, which can produce overcurrents and overvoltages and consequently the deterioration of the quality of the power. In recent years, power electronics systems have been developed to provide reactive power compensation optimally. For example, a static condensor (STATCON) can be controlled to generate the right amount of fundamental frequency reactive power at any time, and active power filters can provide high-order harmonic currents to correct any current distortion caused by nonlinear loads. These systems are intended to improve power factor in the distribution system, but they usually are not applied to individual load.

UTILITY INTERFACE REQUIREMENTS

With the widespread industrial use of power electronics equipment (converters, conditioners, etc.), which usually draw nonsinusoidal input currents and can also react to a utility disturbance very quickly, the interaction between the utility and its industrial users becomes an increasingly important concern. The power electronic systems need to be interface properly with the utility grid to avoid causing interference with the utility system and adjacent sensitive equipment. Significant variations can be found among utilities on what specific functions are required for various sizes and types of power electronics equipment. However, some common basic requirements are usually present in most interfaces. For example, the power electronics systems should be able to operate in certain voltage and frequency ranges (as specified in ANSI/IEEE 929) and should protect themselves when the connected utility is in fault conditions. The most important requirement related to power factor or power quality issues is IEEE-519 (1), which divides the responsibility for limiting harmonic voltage and current contents between the customer (load) and the utility (supplier). This document describes harmonic generation and power factor characteristics of power converters and recommends voltage and current distortion limits. This standard limits the level of harmonic current injection from an individual customer at the point of common coupling (PCC) with other customers. It also limits the voltage distortion from the utility if all customers meet the harmonic current limit.

POWER QUALITY REQUIREMENTS FOR ELECTRICAL EQUIPMENT

IEEE-519 (1) only regulates the current and voltage quality in the PCC. In many applications, it is important to put power quality requirements on individual electronic equipment to eliminate the problem at the source. Many countries have developed regulatory limits to limit the harmonic current components of the current drawn by off-line equipment. The most widely accepted standard is European Standard EN 61000-3-2 (3). For equipment with an input current ≤ 16 A per phase, it classifies equipment into four categories and sets the limits accordingly. Table 1 shows the limits for Class A, which is usually applicable to equipment with power factor correction.

Those limit numbers are, for most applications, far below the harmonic currents created by an off-line diode rectifier, which draws a narrow and high peak current around the peak of the ac voltage. Although passive filters could be used to reduce the current distortion, they are usually bulky and expensive. Additionally, they can introduce a significant displacement between the voltage and the current, causing a large amount of reactive power. Therefore, improving the input current quality using power electronics converters has become one of the hottest topics in the past decade. The basic idea is to use high-frequency switched-mode power conversion techniques to shape the input current to be as close to sinusoidal as possible. Although most people refer to their work as power factor correction (PFC), the main objective is really THD reduction. In this article, the term PFC will be used to comply with the common usage. We also assume that the readers of this article have basic knowledge of switched-mode converters.

An important issue accompanying PFC converters is the electromagnetic interference (EMI) filter. Because of the use of high-frequency switched-mode power conversion technology, the conducted emission of the PFC converter to the main becomes more of a concern. The converter's input current usually has considerable high-frequency components starting from about the converter's switching frequency. The most widely used regulations on EMI are set by the Federal Communications Commission (FCC) in the United States and the International Special Committee on Radio Interference (CISPR, abbreviated from its title in French) in Europe.

Table 1. Limits for Class A Equipment in EN 61000-3-2

Harmonic Order (n)	Maximum Permissible Harmonic Current (A)
Odd harmonics	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
$15 \leq n \leq 39$	$0.15*15/n$
Even harmonics	
2	1.08
4	0.43
6	0.30
$8 \leq n \leq 40$	$0.23*8/n$

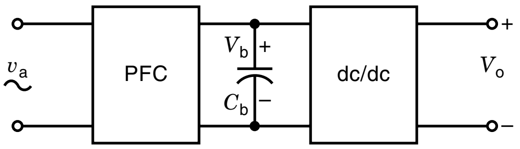

Figure 1. Typical block diagram of an ac-input power system. PFC is a separate function stage.

In most cases, PFC is performed by an independent power converter, called a PFC stage. The input to this PFC stage is an ac outlet of the utility, and the output of this stage is normally a direct current (dc) voltage. The dc voltage can be used to feed dc/dc or dc/ac converters, which are the load to the PFC stage, to further convert the power into forms desired by the end application. Figure 1 shows a block diagram of such a two-stage power conversion system. The PFC converter is a rectifier based on a switching-mode dc/dc converter and accomplishes two major tasks: shape the input current to minimize its harmonic contents and provide a regulated output so that the downstream converter(s) can be designed optimally.

SINGLE-PHASE POWER FACTOR CORRECTION

To adapt the available dc/dc conversion topologies to PFC applications, a full-wave diode rectifier is normally used to rectify the ac input voltage to a dc voltage, which serves as the input to the dc/dc converter. Because the input voltage goes to zero every half line cycle, a proper topology capable of controlling the input current over the entire half cycle must have voltage step-up capability. Among the three basic PWM converter topologies (i.e., buck, boost and buck-boost converters), the boost and buck-boost topologies are capable of stepping up and therefore can be used for PFC. Because the boost topology is more efficient and has a smoother input current than the buck-boost topology, it is used more widely. Figure 2 shows a boost rectifier with its typical control circuit, and Fig. 3 shows its ideal waveforms.

The four diodes (D1–D4) rectify the ac input voltage v_a into a dc voltage v_i as the input to the boost section. When the switch S is closed, the boost inductor L is charged by the input voltage, and the input current increases at a rate determined by the ratio of the voltage and the inductance. When S is open, the boost inductor is discharged and the input current decreases at a rate determined by the ratio of the output-input voltage difference and the inductance. By properly controlling the conduction of the switch, the inductor current i_L averaged at the switching frequency can be controlled to be proportional to v_i, so that the input current i_i after filtering is a pure sinusoidal current in phase with the input voltage, and unity power factor is obtained. In order for the boost topology to function properly, the output voltage V_o needs to be greater than the peak of the input voltage because otherwise the diodes in the bridge will automatically charge the output capacitor, and the input current and input power cannot be controlled. To shape the input current and regulate the output voltage at the same time, two cascaded feedback control loops are normally needed: the outer output voltage loop and the

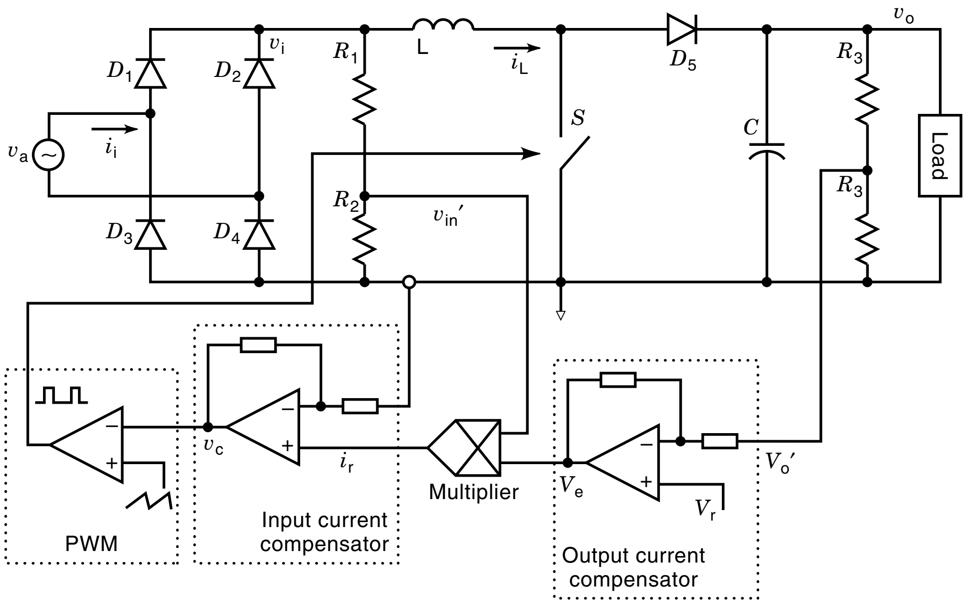

Figure 2. Single-phase boost PFC circuit. This is the basic PFC topology.

inner input current loop as shown in Fig. 2. The voltage compensator output V_e, which is nearly a dc voltage signal, commands the amplitude of the input current, which in turn determines the active power. This signal is multiplied with a signal scaled down from the rectified ac input voltage by R1 and R2 to create a sinusoidal reference for the input current. The distortion of the input voltage is usually not severe enough to affect the goal of controlling the current harmonics.

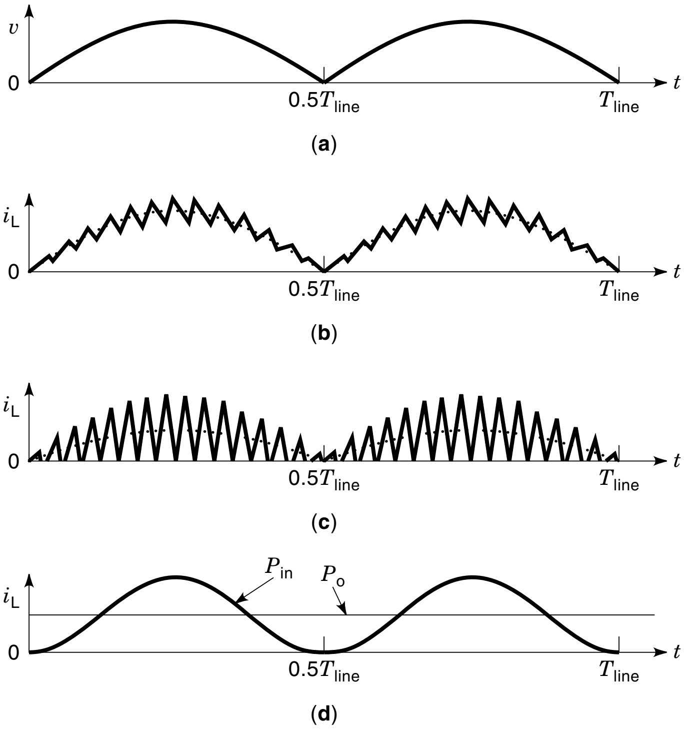

Figure 3. Typical waveforms in PFC converters: (a) input voltage, (b) boost inductor current in CCM, (c) boost inductor current in DCM, and (d) input and output power.

To get a constant voltage loop dc gain, the multiplier usually has a gain inversely proportional to the square of the input rms voltage. The input current controller controls i_L according to the reference signal by changing either the duty-cycle or the switching frequency of the switch S. Variable switching frequency is not a popular choice due to the difficulty in designing the boost inductor and the input filter. Constant switching frequency operation with a controlled duty-cycle, known as the pulse-width modulation (PWM), is almost a standard practice.

The power stage can have two operating modes: continuous conduction mode (CCM) where the inductor current is not discharged to zero every switching cycle and discontinuous conduction mode (DCM) where the inductor current is intentionally discharged to zero in every switching cycle. Figures 3(b, c) show the typical inductor current waveform in CCM and DCM, respectively. The dotted lines are the high-frequency averaged inductor currents. The advantages of CCM operation compared to DCM operation include that the input current ripple is smaller and thus requires less filtering, and the rms current in all the switching devices are smaller, which means less power loss. These advantages make the CCM rectifier more suitable for relatively high power applications. For power levels lower than a few hundred watts, DCM operation is more popular, because in DCM operation the boost diode has no reverse recovery, and therefore a snubber is usually not needed. The current control is also very simple in DCM operation. Because a fixed switch duty cycle can achieve a reasonably low THD, and some simple modifications such as second-order harmonic injection can improve the current quality further.

When the input current is properly shaped (i.e., under unity power factor), both the input voltage and input current is sinusoidal and in phase. Therefore, the input power is in the form of a sinewave squared, which has a fundamental frequency of twice the ac voltage frequency, as shown in Fig. 3(d). The output power is the input power averaged over a line cycle and is constant in steady state operation. The low-

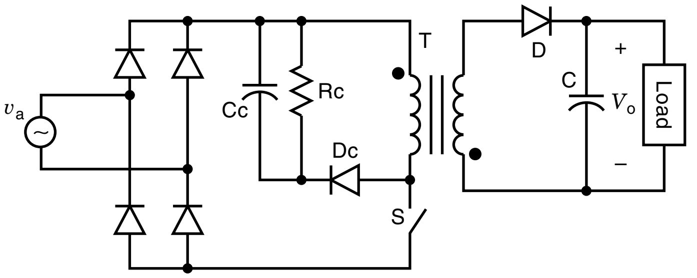

Figure 4. Single-stage flyback PFC converter. The output voltage is regulated but has low-frequency ripples.

frequency variation of the input power requires a bulk capacitor at the output of the PFC stage to absorb the energy difference between the input and the output. In Fig. 1, the bulk capacitor C, which is the output capacitor of the PFC stage and is intentionally drawn outside the PFC stage to emphasize its importance, will have some second-order harmonic voltage due to the input-output power difference. The bandwidth of the output voltage loop should be low enough, usually in a 10–20 Hz range, to avoid responding to the second-order harmonic voltage ripple.

There are a few options for the current control schemes for CCM boost rectifiers. The averaged current mode scheme controls the average of the input current over a switching cycle to follow the current reference. In this mode, the average of the input current will follow the sinusoidal current reference to minimize THD. Other schemes include peak current mode control and constant on-time control. In peak current mode control, the peak of the input current is forced to follow the sinusoidal reference; therefore, the average input current has a certain distortion, which is acceptable for relatively low-power applications. In constant on-time control, the switch on-time is set to a fixed value, which is determined by the load level, and the boost inductor is operated at the boundary of CCM and DCM to reduce the current distortion. The penalty is that the switching frequency must vary as a function of the load and the ac line conditions.

For some low-power applications, the two-stage approach might be replaced with a single-stage approach, in which the downstream dc/dc converter is used also to shape the input current. The flyback rectifier, shown in Fig. 4, is a simple example of single-stage PFC without tight output voltage regulation. With only one active switch, it can achieve unity power factor, provide input-output isolation necessary for most off-line equipment, and regulate the outut voltage to the desired value. The energy storage capacitor in this case is at the output; therefore, the output voltage contains a certain amount of low-frequency ripple (second harmonic of the line frequency), and the dynamic response of the output voltage is also quite slow. Single-stage PFC techniques with tight output voltage regulation have also been developed recently. They combine the two cascaded stages into one as a tradeoff between performance and cost, taking advantage of the fact that the input current does not need to be very close to sinusoidal to meet the input harmonic current requirements. The technique details are disussed in the section entitled “Single-Stage Power Factor Correction.”

THREE-PHASE POWER FACTOR CORRECTION

Because the maximum power from a single-phase input is limited, a three-phase input is usually required when the power rating of an application is higher than a few kilowatts. Although three single-phase PFC converters can still be used to form a three-phase system, a three-phase converter is usually preferred because it can have better performance. First, fewer semiconductor devices are required to conduct current simultaneously in a three-phase converter, which usually means less cost and power loss. Second, the input power of each phase pulsates at twice the line frequency, but the total input power of three phases under ideal conditions is constant in steady state, because the pulsating components of the three-phase powers sum to zero. This means that the output capacitor can be sized independently of the low-frequency output voltage ripple requirement, and very fast output voltage control can be used to achieve tight output voltage regulation without distorting the input current references. Third, because only two sets of phase variables (voltages and currents) are independent in a balanced three-phase system, there is design freedom to optimize the performances of a three-phase converter, usually the switching losses and conduction losses of the power switches. More importantly, because not all three-phase voltages reach zero at the same time, it is possible to use the two voltages of higher magnitudes to control a three-phase converter, so the capability of boosting up the phase voltage is no longer required in a three-phase PFC converter, and buck and buck-derived topologies can also be used.

Three-Phase Single-Switch DCM Rectifiers

When a dc/dc converter with an input inductor, such as boost, buck-boost, flyback, Sepic, and Cúk converters, are operated in DCM with a constant duty cycle, its input current peak will be proportional to its input voltage. Similar to a single-phase PFC, this phenomenon can be used to achieve a high power factor in three-phase applications. Figure 5 shows a three-phase DCM boost rectifier as an example. Before the active switch S is turned on, the three inductor currents are all zero. After S is turned on, the three phases are shorted through the diode bridge (D1–D6) and the switch, so the volt-

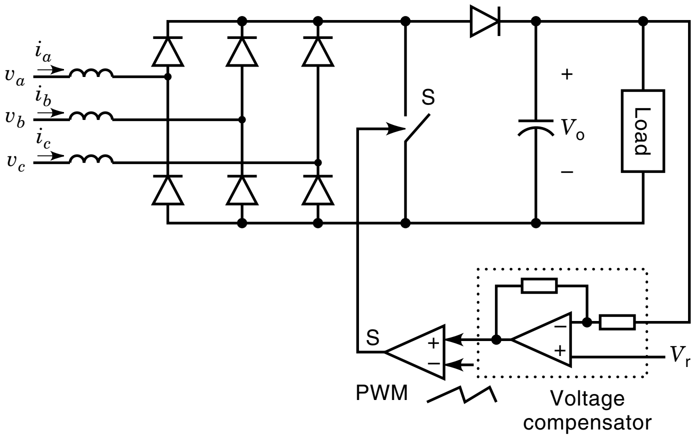

Figure 5. Three-phase single-switch DCM boost rectifier. Three phase currents are shaped by one switch.

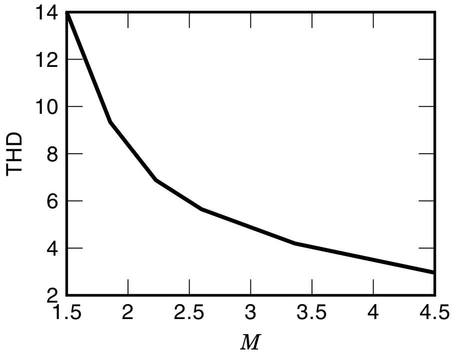

Figure 6. Theoretical current distortion in three-phase DCM boost rectifiers. Low current THD requires high output voltage.

age across each of the three input inductors is the same as the input voltage in that phase. The current in each input inductor is charged up by its corresponding phase voltage in this stage, which is called the charging mode. After S is turned off, the input currents are forced to flow through the output diode (D). Positive currents will flow into the positive node of the output capacitor, and negative current will flow out of the negative node of the output capacitor, so energy is delivered to the output, and the input inductors are discharged because the polarities of the voltages across them are reversed compared to in the charging mode. This is the discharging mode. When an inductor current is discharged to zero, the corresponding conducting diode in the diode bridge is turned off naturally, so the current in that phase will remain at zero. In this way, all three inductor currents are discharged to zero before the switch is turned on in the next switching cycle. Because of the DCM operation, only one active switch is required to control the three-phase rectifier. This topology is a low-cost solution to three-phase PFC and is quite popular because of its simplicity and relatively good performance.

Usually, the converter is controlled by a slow voltage loop that keeps the switch duty cycle practically constant over a line cycle, so each input current has an envelope proportional to its corresponding phase voltage. The typical control scheme, shown also in Fig. 5, is usually implemented with a voltage control PWM controller chip, which directly controls the switch duty cycle. The duty cycle determines the magnitude of the input currents, and thus the input power, which provides a means to regulate the output voltage. The filtered input currents, though generally having waveforms similar to the phase voltages, are distorted by the inductor current during the discharging state, whose duration is determined by the difference between the output and input voltages. To reduce the distortion, the output voltage must be sufficiently higher than the input line to line voltage peak to reduce the duration of the discharging stage. Figure 6 shows the dependence of input current THD on the voltage gain $M = V_o/\sqrt{3}V_i$ in which V_i is the amplitude of input phase voltage. The input current THD can be reduced to a certain degree by modified control, such as variable duty cycle/switching frequency or harmonic injection. With these enhanced control techniques, the optimum THD of input currents is around 10% with $M = 1.5$, which can meet the requirements of EN 61000-3-2 up to around 10 kW.

CCM Boost Rectifiers

For high-power applications, especially when high performance is required, the CCM three-phase boost rectifier is usually used because of its high efficiency, good current quality, and low EMI emissions. Figure 7 shows the basic topology, which is identical to a voltage source inverter. The boost inductance is designed to be large enough so that the currents in the three input inductors do not decrease to zero in every switching cycle, but the inductor voltage drop at the line frequency is still a small fraction of the input voltage. The output voltage must be higher than the line-to-line input voltage peak (i.e., $\sqrt{3}V_i$) to ensure good current control. The six switches and their antiparallel diodes comprise a fully controlled bridge with three legs, each consisting of a top switch and a bottom switch. The operational principle of a CCM boost rectifier is very similar to that of a current-regulated voltage source inverter. The gate signals will determine which switch in a leg can conduct. For example, if the gate signal for Sap is ON, than i_a is conducted either by Sap if $i_a > 0$ or by its antiparallel diode Dap if $i_a < 0$. San and Dan can never conduct if the gate signal for Sap is ON. The gate signals for Sap and San cannot be simultaneously ON; otherwise, the output capacitor, which can be considered a voltage source because of its large capacitance, is shorted, and the switches will be damaged because of the excessive current. The three bridge voltages, v_{as}, v_{bs}, and v_{cs}, which are completely determined by the gate signals for the six switches, can be controlled to provide any desired currents i_a, i_b, and i_c, and thus any required active and reactive power. In a PFC application, the converter is usually controlled to achieve unity input power factor and a regulated output voltage. Figure 8 shows a typical control scheme. The voltage loop compensator regulates the output voltage and generates a power reference. The three multipliers produce three current references proportional to the power reference and in shape with the corresponding phase voltages. The three current compensators control the phase currents to follow their references.

Because the sum of i_a, i_b, and i_c is zero, only two of the phase currents can be controlled independently, and the other one does not need active control. The switches in the uncontrolled phase can be turned off. In practice, the uncontrolled phase is usually chosen to be the phase having the highest voltage and current, called the dominating phase, to reduce the switching loss and conduction loss of the active switches. Notice that in a balanced three-phase system, the dominating

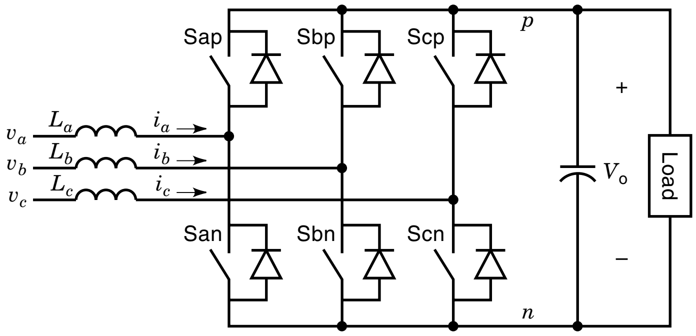

Figure 7. A three-phase CCM boost rectifier. Six switches are used to actively control the input currents.

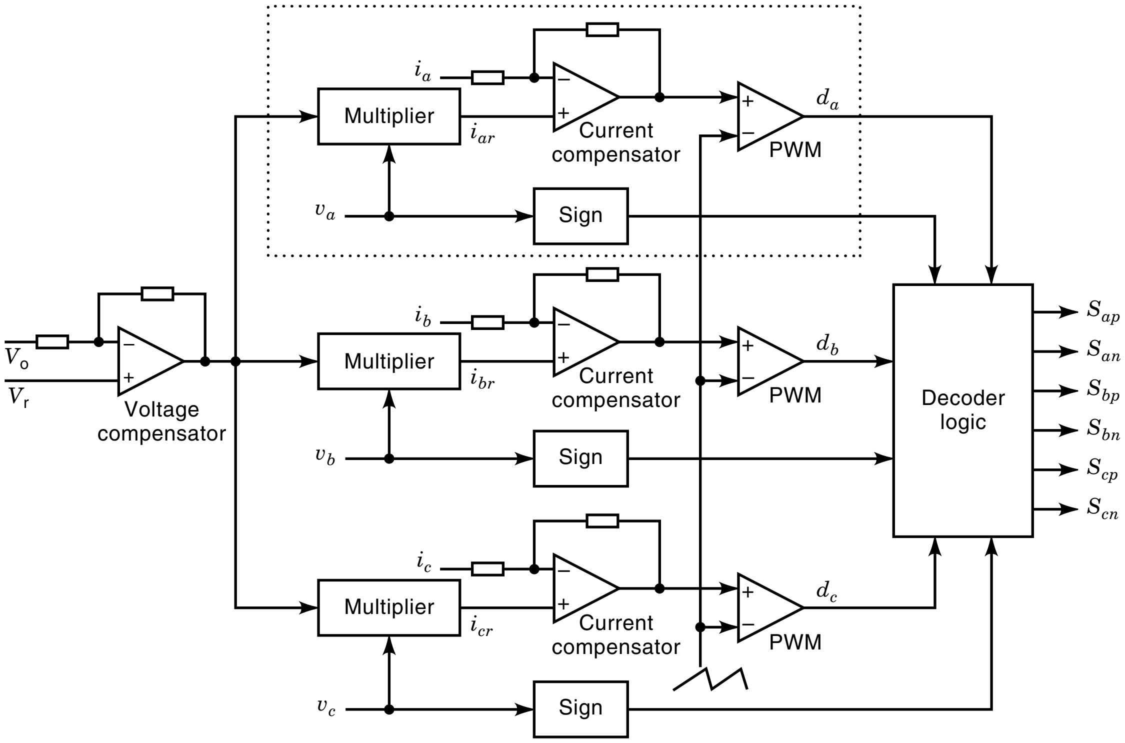

Figure 8. A typical control scheme for three-phase CCM boost rectifier. Separate current loops are used to control the input currents.

phase is changed every 1/6 line cycle according to the relative magnitude of the three-phase voltages. For example, in the three-phase voltages shown in Fig. 9 Phase A is the dominating phase in the intervals of ωt = [−30°, 30°] and ωt = [−150°, 210°], Phase B is the dominating phase in the intervals of ωt = [−30°, 90°] and ωt = [−210°, 270°], and Phase C is the dominating phase in the intervals of ωt = [−90°, 150°] and ωt = [−270°, 330°]. Because the active switches never conduct the highest current, their current rating is much lower than the diodes'.

Three-Phase Buck Rectifier

Figure 10 shows the basic topology of a three-phase buck rectifier. The diodes in series with active switches are used to block the negative voltage imposed to the bridge arms because most high-frequency power semiconductor devices, such as IGBTs, MOSFETs and BJTs, are not designed to withstand negative voltage. If bidirectional voltage devices, such as SCRs and symmetrical GTOs are used as the switches, the series diodes can be removed. The dc-link inductor is usually large enough that its current I_o is almost constant in the steady state, so it can be considered a current source. Because of the symmetry of a three-phase converter, the operation of the buck rectifier can be explained with the example of $v_a > 0 > v_b > v_c$ (i.e., the input voltages are in the 30 ° of ωt = [0°, 30°]) shown in Fig. 9. Because of the requirement of the unity power factor, the averaged input currents in this period should satisfy the following relationship: $i_a > 0 > i_b > i_c$. Because phase A has a positive voltage, Sap should be used to control its current, so that i_a will be positive. Similarly, Sbn and Scn should be used to control the currents in phase B and phase C so that i_b and i_c will be negative. Because i_a has the highest magnitude, Sap can be turned on during the whole 30° period whereas Sbn and Scn will be switched on and off alternately in a PWM manner. When Sbn is turned on, i_a is the same as the dc-link current I_o, whereas i_b equals $-I_o$.

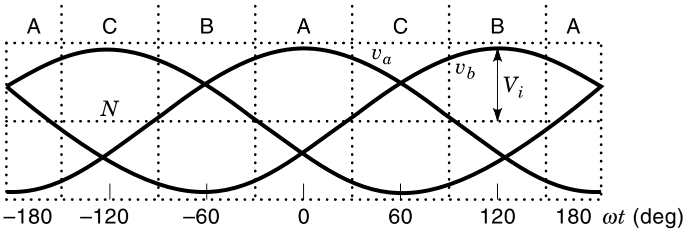

Figure 9. Phase voltages and dominating phases in a line cycle.

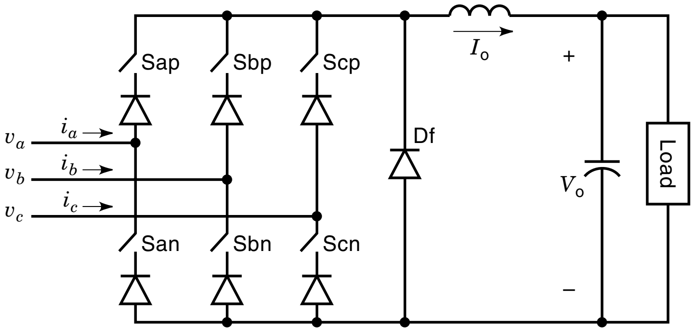

Figure 10. Three-phase buck rectifiers. All switches are voltage-unidirectional devices.

When Scn is turned on, i_a still equals I_o, whereas i_c equals $-I_o$. During these two operation modes, energy is absorbed from the input and delivered into the output at the same time. When both Sbn and Scn are turned off, the dc-link current freewheels through Df, and no power is transferred from the input. The freewheeling diode Df provides an alternative path for the dc-link current in the freewheeling mode and can reduce the conduction loss in the freewheeling mode of the bridge. Otherwise, the dc-link current must freewheel through the bridge with higher power loss, but the energy flow can then be reversed. Notice that with this control strategy, the two switches in one phase can be turned on simultaneously when a nonzero input current is required in that phase, and the voltage polarity of that phase can automatically select the right switch to conduct the current. For example, when Sbn is to conduct a current, Sbp can be gated on at the same time, but it cannot conduct current because its series diode is reversely biased. Because the two switches in a phase can be turned on and off simultaneously, they can also be combined into one to reduce the number of active switches. The shortcoming is that more diodes are required, and the rectifier may suffer from lower efficiency.

From this description, we can seen that each input phase current can have three values: I_o if the top switch is ON, $-I_o$ if the bottom switch is ON, and zero is both switches are ON or OFF simultaneously. The averaged input currents in a switching cycle are controlled directly by the duty cycles of the switches. If the duty cycle of the switches in a phase are controlled to be proportional to the phase voltage, then the averaged input current has the same waveform as the input voltage, and unity power factor is achieved. However, the dc-link current must be able to remain constant in a line cycle to ensure a good input current waveform. To avoid the use of very high dc-link inductance, the highest input line-line voltage in the charging mode, v_{ac} in the previous example, should be higher than the output voltage to guarantee that there is enough voltage to charge the dc-link inductor when needed. Considering that the lowest value of v_{ac} during this period is 1.5 V_i, the maximum output voltage of a three-phase buck rectifier is less than 1.5 V_i.

The buck rectifier is topologically similar to the phase-controlled bridge rectifier. However, the switches in a buck rectifier are controlled with high-frequency PWM, so that the averaged input currents follow the sinusoidal waveforms of the input voltages. Because the fundamental-frequency components of the input currents are directly controlled by the switch duty cycles, the control circuit for a three-phase buck rectifier is simpler than the CCM boost rectifier, and dedicated input current controllers are not required. Also, the inrush current during the start-up can be easily controlled in a buck rectifier by the switch duty cycles, which is another advantage over the boost rectifier. However, because diodes and switches are in series in the bridge, the buck rectifier requires higher switch and diode current ratings and has higher conduction loss than a boost rectifier for the same application. Generally, a buck rectifier has lower efficiency than a comparable boost rectifier, but its simplier control and protection, as well as its lower output voltage, make it attractive for certain applications.

Control of Three-Phase PFC Converters

Control of power converters usually can be divided into three functions: modulation, current control, and regulation of an output variable (the output voltage in rectifiers). Among the many control strategies, hysteresis control is the simplest control for boost rectifiers because it combines the modulation and current control into a single function. It also provides the widest current loop bandwidth of all control schemes. The major problems with hysteresis control are its load dependence on the switching frequency, and the interference among phases in three-phase converters, resulting in irregular converter operation and uneven current waveforms, which deteriorate the control and EMI performances. These problems can be remedied to a certain degree by changing the hysteresis band in a line cycle and controlling two line-to-line currents of three-phase converters (differences between the phase currents). Still, hysteresis control is used mainly in low-power converters as a result of its relatively low performance. Average current control is the most widely used scheme in boost rectifiers, whereby the voltage compensator sets references for the input currents, while dedicated current compensators control the currents to follow their references. The modulator then converts the control duty cycles generated by the current compensators to switch gate pulses. The typical average-mode current control block diagrams of three-phase boost rectifiers are shown in Fig. 8. If the current compensators are changed into comparators, then they become hysteresis or peak-mode current controllers, depending on whether a clock signal is used. For buck rectifiers, the modulator alone can achieve a good input current control, and closed-loop current compensators are unnecessary because the input currents are algebraic functions of the dc-link current and switch duty cycles.

Modulation schemes are of special importance to three-phase converters. Because the sum of the three input currents in a three-phase rectifier is zero, only two input currents need to be controlled. Generally, any set of voltages or currents in a balanced three-phase system has only two independent variables and can be converted into an orthogonal two-dimensional space (α-β plane) through a basis transformation. The transformation from three-phase variables x_a, x_b, x_c to α-β system x_α, x_β is defined as

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = T \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}, \qquad T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$$

where T is the transformation matrix.

Therefore, voltages and currents in a three-phase converter can be represented as vectors in the α–β plane. These vectors are called space vectors, and modulation schemes based on space vectors are called space vector modulations (SVM). A three-phase boost rectifier can have eight valid switch states under the constraint that the two switches in any phase leg do not conduct simultaneously. These switch states are represented by combinations such as PNN and PPN. The sequence of the combinations is Phase A-Phase B-Phase C. P means that the phase is connected to the positive dc rail p of the dc link through the top switch in that phase leg, whereas N means that the phase is connected to the negative dc rail n of the dc link through the bottom switch in that phase leg. For the eight states, the phase voltages in the bridge at each state can be represented as a space vector, denoted as V1–V8 in Fig. 11(a). V1–V6 are nonzero vectors with a length proportional to the output voltage, whereas V7(PPP) and V8(NNN) are zero vectors because their lengths equal zero. Similarly, the input currents in a three-phase buck rectifier can be represented by current space vectors, as is shown in Fig. 11(b), in which O in the switch combination means that the input current in the corresponding phase is zero (both switches closed or open).

The trajectory of a vector representing any balanced set of three-phase sinusoidal variables (such as phase or line voltages/currents) is a circle, with its radius proportional to the amplitude and rotational speed proportional to the frequency of the sinusoidal variables. At any given time, a reference vector V_r or I_r can be synthesized by the two adjacent nonzero vectors and one or two zero vectors with proper duty cycles. The switching sequence and selection of zero vectors are not unique and can be optimized in a specific application. For example, in boost rectifiers, if V_r is in the 30° period of ωt = [0°, 30°], the active space vectors in the modulation should be V1 (PNN), V2 (PPN), V7 (PPP), or V8 (NNN). If V8 is not used, then Sap and San do not need to be switches, and i_a is conducted by D1. This SVM scheme is the same as the dominating phase disabling control discussed previously. Generally, SVM is a simple way to coordinate three-phase control, and any three-phase modulation scheme can be explained with SVM theory. More information on SVM can be found in (18–20).

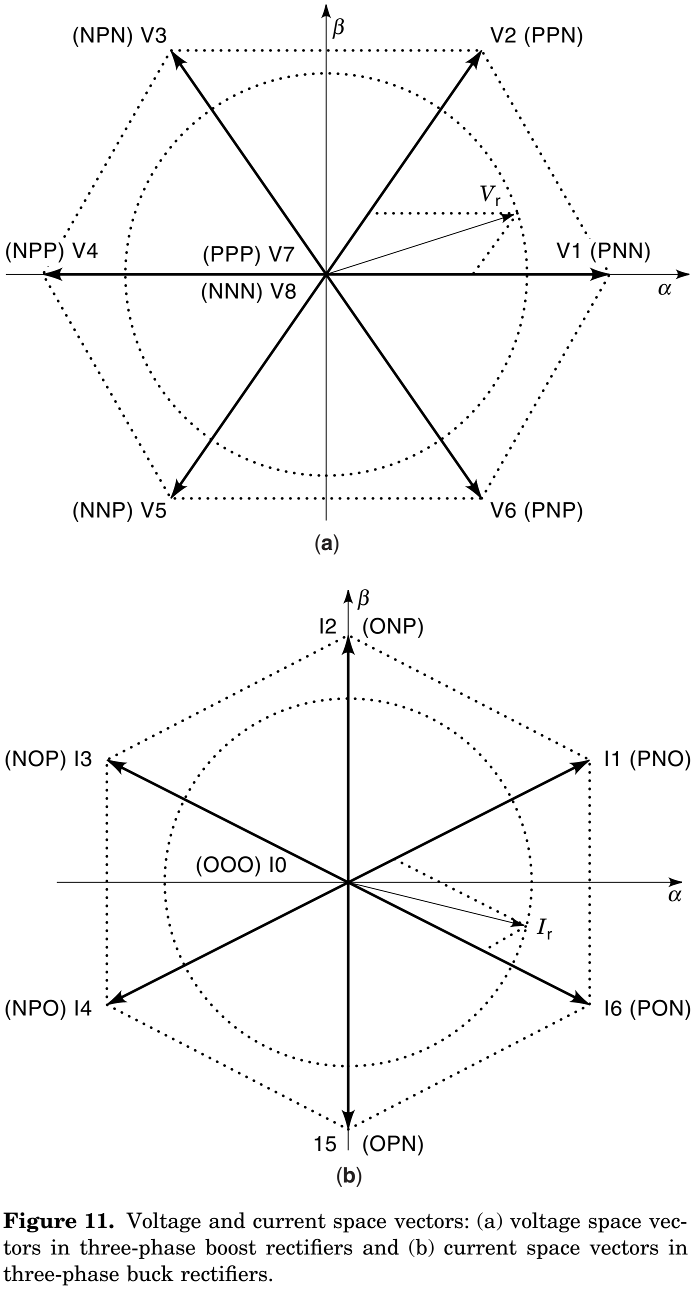

Figure 11. Voltage and current space vectors: (a) voltage space vectors in three-phase boost rectifiers and (b) current space vectors in three-phase buck rectifiers.

The current compensator design in three-phase PFC converters should achieve good current control, unlike in inverter applications where the system dynamics are usually dominated by the slow electromechanical and/or large reactive components, so that the inverter dynamic performance is not critical, and accurate ac current control is not very important (except for field-oriented drives). In PFC applications, high performance and very wide bandwidth control must be designed without the use of large reactive components. The control system can be implemented with either analog or digital hardware. In analog implementations, the current compensators are usually set up in *a*, *b*, *c* coordinates as shown in Fig. 8, and the control variables are piecewise sinusoidal. In digital implementations, two current compensators are usually set up in the rotating *d*–*q* coordinates, which are obtained through a time-variant transformation matrix. The advantage of the digital implementation is that all control variables are constant in steady state for a balanced system, and good steady state current quality can be easily obtained. Conversely, in the analog current control, the control variables are time-varying, and the ideal control voltages may be even discontinuous at the current zero-crossing. Therefore, very fast analog controllers must be used to achieve good current control, and the current distortion is usually higher than with the digital controllers because of finite controller gains at line frequency. For digital control implementations, however, the control bandwidth is limited more by the computational and sampling delays.

INPUT FILTER DESIGN

With the PWM control of a PFC converter, the input current usually has low low-order harmonic components but significant high-frequency harmonics starting around the switching frequency. The high-frequency current components cause nearby electronic equipment to malfunction and thus are subject to EMI regulations. The starting frequency of EMI regulations is 150 kHz for CISPR, 450 kHz for FCC, and might be as low as 10 kHz for military equipment. The management of EMI involves many tasks, such as switching-frequency selection/modulation, snubbering, and careful circuit layout, but an input filter is imperative for most practical applications to reduce the EMI emission to an acceptable level. The input filter should be designed to achieve enough attenuation at the switching frequency or the lowest starting frequency of the applicable conducted EMI regulations, and its effect on input current THD and system stability should also be minimized.

Because the conducted EMI can be divided into differential mode (DM, the noise current between the phase line and the

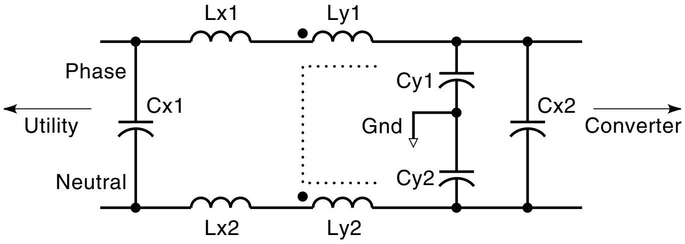

Figure 12. A typical EMI filter.

neutral and is calculated as half the difference between the phase current and the neutral current) and common mode (CM, the noise current that flows from the phase and neutral to the ground and is calculated as half the sum of the phase current and the neutral current), an input filter usually consists of a DM filter and a CM filter. Figure 12 shows the most widely used filter topology in its single-phase version. *L*y1 and *L*y2, a common mode choke, form a CM filter with *C*y1 and *C*y2, whereas *L*x1 and *L*x2, which also include the leakage inductance of the CM choke, and *C*x1 and *C*x2 form a DM filter. The capacitances of *C*y1 and *C*y2 are usually limited by safety regulations because they produce ground currents, and *C*x1 and *C*x2 are usually limited by the power factor requirement because they introduce a phase shift between the phase voltage and current. Therefore, in practice the filter attenuation is determined by the filter inductors. If a very high attenuation is required, several filters of the type shown in Fig. 12 can be cascaded to form a multistage filter.

An important consideration in input filter design is the interaction between the filter and the PFC converter. Because the input filter imposes a finite impedance to the converter, it might interfere with the control of the PFC converter and cause subharmonic oscillation of the input currents or even system instability. This interaction issue should be studied carefully in the design process, and if necessary a damping circuit should be added to damp the filter oscillation and reduce the peak of the filter output impedance. Another method to reduce the filter output impedance is to increase the filter capacitance (and to reduce the filter inductance for the same attenuation), if input displacement control is used in the PFC converter to compenate the reactive current of the filter capacitors.

RECENT RESEARCH RESULTS

Soft-Switching Techniques

Because of undesired parasitics in a practical circuit, such as stray inductance in the circuit layout, and nonideal switching characteristics of power devices, such as finite switching times of switches and reverse recovery of diodes, the switching action in a practical PFC circuit usually causes switching power losses and voltage/current stresses to the power devices. Soft-switching techniques try to solve these problems by shaping the switch voltage or current waveforms in the switching transients to create a favorable switching condition to reduce the switching losses and *di*/*dt* and *dv*/*dt* during the switching transients (44–49). This allows soft-switching converters to be operated at higher switching frequencies than conventional PWM power converters. The lower *di*/*dt* and *dv*/*dt* in soft-switching converters also have a favorable impact on device voltage spike, converter reliability, and EMI noise emissions. The reduced reactive component requirements, resulting from high switching frequencies, and lower switch voltage-ampere rating, resulting from less voltage ringing in soft-switching converters, also imply a higher power density and possible cost reduction. Therefore, soft switching is an important aspect of PFC circuits and needs to be studied carefully.

Soft-switching techniques can be classified into two categories: zero-voltage switching (ZVS) and zero-current switching (ZCS). ZVS reduces or even eliminates the switch turn-on losses by shaping the switch voltage to zero prior to its turn-on, whereas ZCS reduces the turn-off loss by shaping the current of a switch to zero prior to its turn-off. Soft-switching techniques have evolved from resonant converters (RC), quasi-resonant converters (QRC), multiresonant converters (MRC), quasi square-wave PWM converters (QSW), and soft-transition PWM techniques, which include zero-voltage transition (ZVT) and zero-current transition (ZCT). RCs, QRCs, and MRCs use reactive components, including parasitic elements in a practical circuit, to achieve soft-switching power conversion in a resonant fashion and usually do not require extra active switches. On the other hand, ZVT and ZCT use additional auxiliary switches to control the resonance between the reactive components and affect the converter operation only during the turn-on or turn-off switching transition. Although RCs, QRCs, and MRCs seem simple topologically, they suffer from variable switching frequency, high voltage/current stresses, and high circulating energy, compared to their PWM counterparts, and are used mainly in low-voltage and low-power applications. For PFC circuits, which usually require high voltages and significant power transfer, ZVT and ZCT are preferable because they achieve soft switching with minimum switch voltage/current stresses and minimum converter circulating energy, and incorporate the widely accepted PWM control. ZVT is more widely accepted because it solves the diode reverse recovery associated with switch turn-on, which is one of the major concerns in CCM PFC applications.

The basic ZVT circuit is shown in the dotted frame in Fig. 13(a) with a boost converter as an example. Figure 13(b) shows the key waveforms of the ZVT operation. Before the main switch S is turned on, the inductor current *I* is conducted by the main diode D. Prior to the turn-on instant of S, which is determined from the PWM control, the auxiliary switch Sx is turned on, and the inductor current is gradually diverted into the auxiliary circuit. When the current in D is reduced to zero, D is turned off naturally, and the resonant inductor *L*x resonates with the paralleling capacitor *C*s, which includes the switch junction capacitance and any snubber capacitor used to reduce the switch turn-off loss and *dv*/*dt*. This resonance finally brings the main switch voltage to zero, so S can be turned on with zero voltage and thus no power loss. The zero-current turn-off of D and the controlled *dv*/*dt* in the resonance also eliminate diode reverse recovery loss. After S is turned on, Sx can be turned off so that commutation energy in *L*x is delivered to the output through Dx. In this way, the commutation energy is fed into the output, so the converter efficiency can be improved. Because Sx conducts current only with a small duty cycle, its power loss is much lower than the main switches and thus can be implemented with lower-current-rated devices. The efficiency improvement

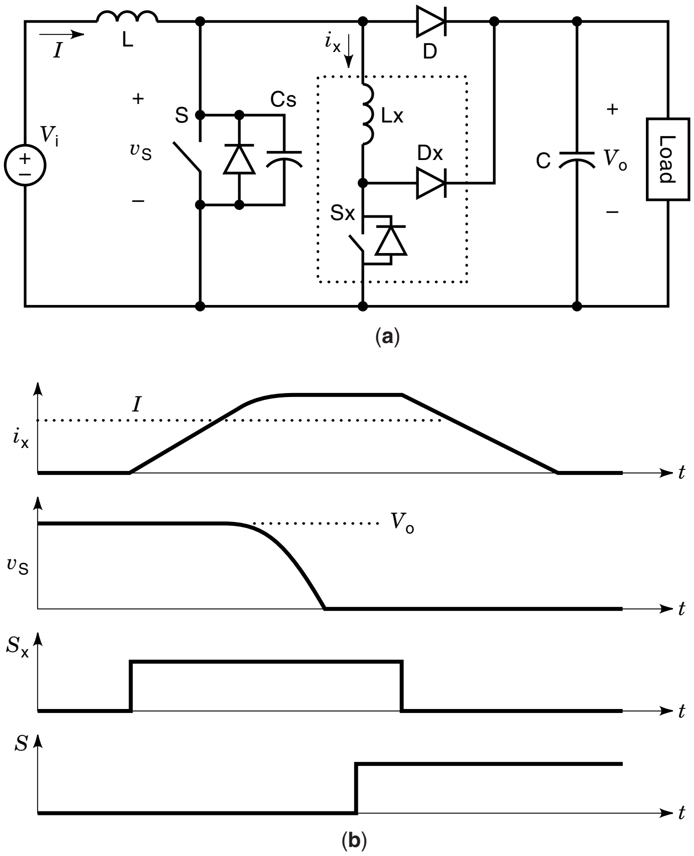

Figure 13. A ZVT topology and its operation: (a) topology and (b) key operational waveforms. The main switch is turned on with zero voltage.

with the ZVT circuit is usually more than 1% at a switching frequency of 100 kHz.

When the ZVT technique is applied to three-phase PFC converters, the control of the converter can be carefully arranged to synchronize the switch turn-on instants in the three phases, so a simple auxiliary circuit with one or two auxiliary switches can be used to achieve soft-switching function for all main switches. The synchronization of switch turn-on may require more main switch turn-off actions in some soft-switching topologies or major control modification. When choosing a soft-switching scheme, special attention should be paid to the effects of the soft-switching operation on the converter control resolution, circulating energy, device voltage/current stresses, and extra switching action of the main power switches.

Single-Stage Power Factor Correction

For low-power applications, it is possible to use a single power stage to achieve high power factor and low THD at the input and to provide tight regulation at the output (37–43). The fundamental idea is to combine the two dc/dc converters in the PFC rectifier and the load converter into one by letting them share some components, such as the active switches. Component sharing almost always reduces the control freedom and conversion efficiency in practical applications. Therefore, the resulting solution usually cannot achieve the same performance as a two-stage system. The basic single-stage PFC topologies usually integrate a boost rectifier at the input side into a forward or flyback converter at the output side and use only one active switch. An intermediate energy storage bulk capacitor is also included to absorb the input-output power difference and to provide an input voltage to the equivalent output dc/dc stage. The bulk capacitor voltage is nearly constant in an ac line cycle, so the switch duty cycle, which is controlled to regulate the output voltage, is also nearly constant in the steady state. Therefore, if the input boost inductor is operated at DCM mode, high power factor and low THD are achieved without additional switch and control. The output stage can work in either DCM or CCM mode, but a DCM output stage will result in lower intermediate voltage and thus lower circuit power loss and cost. The most significant shortcoming of such an approach is the high bulk capacitor voltage at light load. Frequency modulation of the active switch could reduce the bulk voltage to a certain degree, but it is still not practical for a wide input voltage range beyond a few tens of watts power level. In recent years, people have been trying to use a CCM input stage to increase the power range, or a DCM flyback to further improve the input current quality. Many of these techniques also reduce the bulk capacitor voltage requirement. However, the intermediate voltage then usually changes roughly in proportion to the input rms voltage, and the input current THD is usually much higher, so the electrical performance of the input stages in these single-stage PFC converters is similar to a diode bridge rectifier with a well-designed input filter. However, a single-stage PFC rectifier might require a smaller input filter, and thus have higher power density. The application of these techniques is generally limited to a power range below a few hundred watts.

In three-phase applications, single-stage PFC can be implemented as a bidirectional buck rectifier with a transformer isolation. However, the complex power stage and relatively high switch stresses (since all components are subjected to the input disturbances) decrease its cost-effectiveness for general applications.

Simplified PFC Controllers

For a power level above a few hundred watts, the single-phase CCM boost rectifier is the most popular PFC topology. Even though many control strategies are available, the average current control with a multiplier to generate the input current reference is almost an industry standard, and many PFC chips implementing this control strategy (e.g., the UC3854 series) are widely used. The average current control can achieve an input current THD as low as 5% at full load over the universal input voltage range of 85–265 V, but the reference multiplier causes the PFC controller to have a much higher cost than a comparable PWM controller. Because the power factor regulations can tolerate a THD higher than 10% up to a few kilowatts power level, simple PFC controllers without a reference multiplier have been developed to achieve a good performance-cost trade-off (28–32). Most of these controllers use the steady state relationship between the input current and other circuit parameters to develop current control laws, and the resulting control schemes are implemented without a specific current reference or current compensator to save cost.

Three-Level PFC Converters

In the previous topologies, each phase in the bridge can be controlled either to the positive dc rail or the negative dc rail

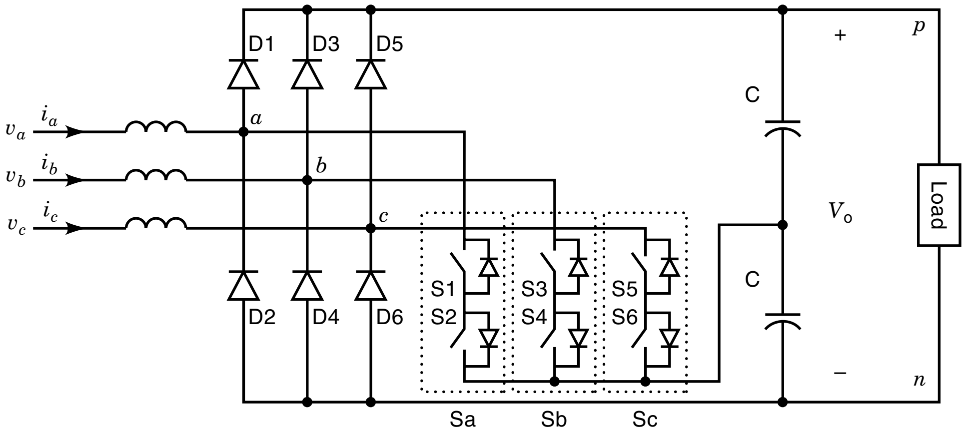

Figure 14. A three-level boost rectifier. Switches block half the output voltage.

(i.e., it can have two voltage levels). In the three-level three-phase boost rectifier shown in Fig. 14, each phase can also be connected to the middle point of the output voltage (16). Because the active switches withstand half the output voltage, they can be implemented with faster, cheaper, and more efficient devices. The availability of more voltage levels also improves the control resolution of the converter, so the boost inductance can be reduced for the same input current ripple. Compared to other three-phase PFC topologies, the three-level boost rectifier has significantly better performance/cost characteristics in high power applications. Three-level boost rectifiers can also be used in single-phase PFC applications. However, they are not as popular as in three-phase applications because of the relatively low power requirement of single-phase systems.

CONCLUSION

Compared with traditional diode or phase-controlled rectifiers, PFC converters can actively control the input currents to have a desired sinuosidal waveform and increase the power capability of utility equipment. The filtering requirement of PFC converters to meet power quality regulations is also much smaller than that of other rectifiers because the corner frequency of its input filter is much higher. Therefore, a PFC converter usually has high power density due to its small inductor and capacitor size. Another important advantage of PFC techniques is that their actively controlled output voltage is largely independent of the input voltage variation, so their downstream load converters can be optimized with a fixed input voltage. Because of these technical benefits, PFC techniques are increasingly accepted in industry. However, before a PFC rectifier is designed into a system, it is still important to weigh its advantages over the increase of cost and power loss.

Power factor correction is a relatively new and thus fast growing field in power electronics. With the wide acceptance of this technology in industry, many research efforts are underway to further simplify the control schemes, increase converter efficiency, improve EMI management, and reduce cost. Although the basic principles of PFC will not change significantly, it can be expected that many results of practical importance will be achieved in the near future.

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POWER FACTOR CORRECTION. See POWER SYSTEM HARMONIC CONTROL.