

Power Factor Correction (PFC) Circuits

Outline

A power factor correction (PFC) circuit is added to a power supply circuit to bring its power factor close to 1.0 or reduce harmonics. This application note discusses the basic topologies of the PFC circuits and their operations.

There are three PFC techniques: 1) passive (static) PFC using a reactor; 2) switching (active) PFC that controls a current at high frequency using a switching device; and 3) partial-switching PFC that switches on and off a switching device to control the current a few times per mains cycle and whose applications are restricted. To reduce the size and improve the efficiency of power supplies, switching PFC circuits in various topologies have appeared, including interleaved and bridgeless PFC.

Table of Contents

Outline	1
Table of Contents	2
1. What are a power factor and power factor correction?	4
1.1. Power factors for different types of loads	4
1.2. Causes of a decrease in the power factor of electrical circuits with a smoothing capacitor	5
2. Power factor correction (PFC) circuits	6
2.1. Passive PFC	6
2.2. Partial-switching PFC	7
2.3. Active PFC	8
2.4. Switching conduction modes	8
2.4.1. Continuous conduction mode (CCM)	8
2.4.2. Critical conduction mode (CRM)	9
2.4.3. Discontinuous conduction mode (DCM)	10
2.5. Comparison of different active PFC modes	11
2.6. MOSFET switching losses	11
3. PFC application circuits	12
3.1. PFC using parallel MOSFETs	12
3.2. Interleaved PFC	12
3.3. Bridgeless PFC	14
3.4. Other circuit examples	15
3.5. Improvement of a bridgeless PFC circuit	15
4. Supplemental information	17
RESTRICTIONS ON PRODUCT USE	20

List of Figures

Figure 1.1 Supply voltage and load current in the case of a purely resistive load.....	5
Figure 1.2 Supply voltage and load current in the case of a capacitive load.....	5
Figure 1.3 Example of a power supply circuit with a capacitor	5
Figure 2.1 Example of a passive PFC circuit	6
Figure 2.2 Example of an input current waveform for passive PFC.....	6
Figure 2.3 Partial-switching PFC circuit	7
Figure 2.4 Current waveform of a partial-switching PFC circuit.....	7
Figure 2.5 Basic active PFC circuit and its current paths.....	8
Figure 2.6 Typical waveforms in CCM mode.....	8
Figure 2.7 Waveforms of a CCM PFC circuit.....	9
Figure 2.8 Waveforms of a CRM PFC circuit	9
Figure 2.9 Waveforms of a DCM PFC circuit	10
Figure 2.10 Basic PFC circuit	12
Figure 2.11 CCM PFC circuit and its operating waveforms.....	12
Figure 3.1 Example of a PFC circuit using parallel MOSFETs	12
Figure 3.2 Interleaved PFC circuit and its operation	13
Figure 3.3 Interleaved PFC waveform.....	13
Figure 3.4 Bridgeless PFC circuit and its operation	14
Figure 3.5 Example of a totem-pole PFC circuit and its operation.....	15
Figure 3.6 Bridgeless PFC circuit with reduced noise.....	16
Figure 3.7 Improved bridgeless PFC circuit	16
Figure 4.1 Active power and reactive power	17
Figure 4.2 CCM waveform.....	18
Figure 4.3 DCM waveform.....	19

List of Tables

Table 2.1 Comparison of three current conduction modes.....	11
Table 3.1 Comparison of conducting devices every half cycle.....	14

1. What are a power factor and power factor correction?

Many electronic circuits have a capacitor at the input of the power supply so as to operate with DC voltage. This capacitor might causes a phase shift between the sinusoidal AC power supply voltage and current and the power factor (PF) will drop. A power factor correction (PFC) circuit reduces the harmonic distortion in the supply current and creates a current waveform close to a fundamental sine wave in order to increase the power factor to unity (1). See Supplement 1 for the details of the power factor.

The power factor is defined as the ratio of the active power used by a load (P_{act}) to the apparent power supplied to a circuit (P_{apr}). Depending on whether the load is inductive or capacitive, the phase of the load current lags or leads the phase of the voltage, possibly causing reactive power (P_{rea}) to increase. Many electronic devices, if used under such conditions, might generate harmonic current components or cause damage to power transmission and distribution facilities. See Supplement 2 for harmonic current components.

Power factor (PF) is defined as active power divided by apparent power. When the phase difference between AC voltage and current is ϕ , then $PF = \cos\phi$. If the current waveform has considerable distortion relative to a sine wave and therefore the power factor drop well below 1.0. To bring the power factor close to 1, it is necessary to reduce harmonic current.

1.1. Power factors for different types of loads

1) Resistive loads

In the case of purely resistive loads, the supply voltage and the load current are in phase with each other ($\phi=0$) as shown in Figure 1.1. Hence, $\cos\phi = 1$. Therefore, electrical circuits with a purely resistive load have a power factor of 1.0.

In this case, active power (P_{act}) is:

$$\begin{aligned} P_{act} &= \frac{1}{2\pi} \int_0^{2\pi} I_M \sin\theta \times V_M \sin\theta d\theta \\ &= \frac{1}{2} I_M \times V_M = \frac{I_M}{\sqrt{2}} \times \frac{V_M}{\sqrt{2}} = I_{rms} \times V_{rms} \end{aligned}$$

Apparent power (P_{apr}) is:

$$P_{apr} = I_{rms} \times V_{rms}$$

Hence, the power factor (PF) is calculated as $P_{act}/P_{apr} = 1.0$.

2) Capacitive and inductive loads

In the case of capacitive and inductive loads, there is a phase difference of ϕ degrees between the current and voltage waveforms as shown in Figure 1.2. In this case, active power (P_{act}) is:

$$\begin{aligned} P_{act} &= \frac{1}{2\pi} \int_0^{2\pi} I_M \sin(\theta + \phi) \times V_M \sin\theta d\theta \\ &= I_{rms} \times V_{rms} \times \cos\phi \end{aligned}$$

Apparent power (P_{apr}) is:

$$P_{apr} = I_{rms} \times V_{rms}$$

Hence, the power factor (PF) is calculated as $P_{act}/P_{apr} = \cos\phi$.

3) Purely capacitive and reactive loads

Because ϕ is equal to either $(\pi/2)$ or $(-\pi/2)$, $PF=0$.

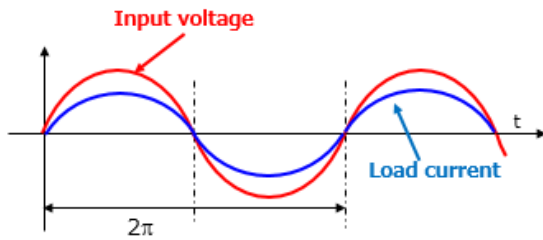


Figure 1.1 Supply voltage and load current in the case of a purely resistive load

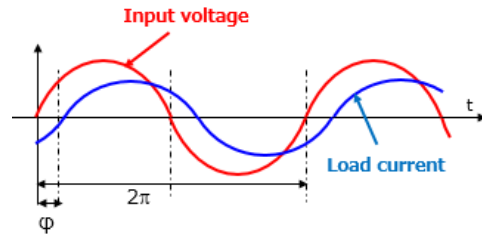


Figure 1.2 Supply voltage and load current in the case of a capacitive load

1.2. Causes of a decrease in the power factor of electrical circuits with a smoothing capacitor

In a circuit using a smoothing capacitor, harmonic current is generated as the charging current for the capacitor distort from the input sine wave current. In the circuit of Figure 1.3, the input AC voltage is applied to an input smoothing capacitor (C) via a diode bridge rectifier. Consequently, current (I) flows only during periods when the input AC voltage is higher than the charging voltage of C. Figure 1.3 shows an example of an input current (I) waveform, which has considerable distortion relative to a sine wave because of many harmonic components and therefore causes the power factor (PF) to drop well below 1.0. The power factor correction (PFC) circuit is reducing the harmonic content of the input current and thereby bringing the waveform close to a sine wave. As a result, the power factor increases to close to 1.0.

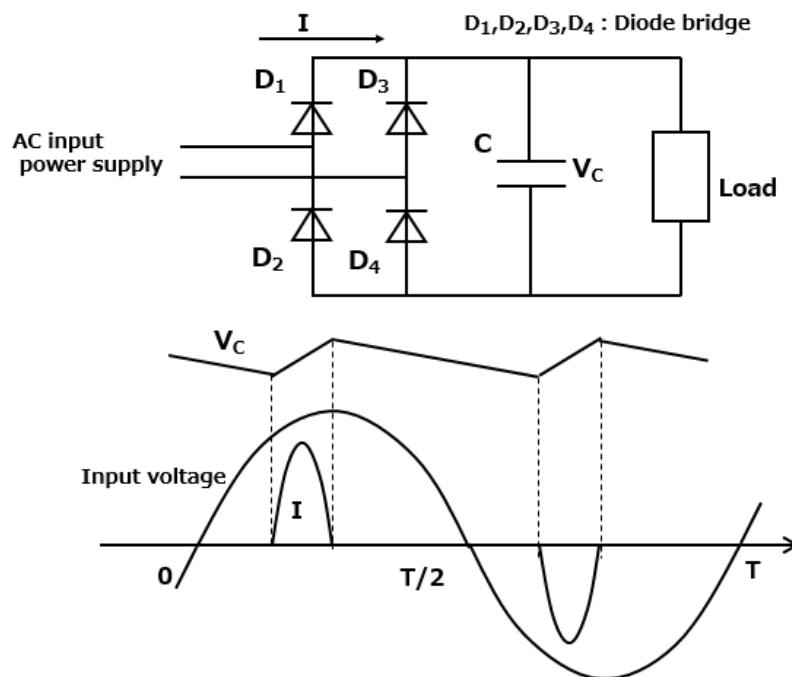


Figure 1.3 Example of a power supply circuit with a capacitor

2. Power factor correction (PFC) circuits

PFC techniques are broadly divided into passive (static) PFC, partial-switching PFC, and active (switching) PFC. Passive (static) PFC inserts a reactor in series with a power supply. Depending on the capacity of the power supply, a large reactor is required. Therefore, passive PFC is commonly used for low-capacity power supplies. Partial-switching PFC is widely used in combination with a voltage doubler rectifier for the power supplies of 100-VAC inverter air conditioners and other home appliances. Switching (active) PFC using MOSFETs as switching devices is commonly used for switched-mode power supplies requiring high efficiency and small size. A boost chopper is a basic topology of a switching PFC circuit. Depending on the power supply capacity, various circuit topologies are used such as PFC using parallel switching devices, interleaved PFC, and bridgeless PFC that provides even higher efficiency. In addition, there are three current conduction modes: 1) continuous conduction mode (CCM) that continuously passes current to a switching reactor; 2) critical conduction mode (CRM) that turns on switching devices at zero current; and 3) discontinuous conduction mode (DCM) that passes current with an interval. Different conduction modes require different control methods.

2.1. Passive PFC

Figure 2.1 shows an example of a passive PFC circuit having a voltage doubler rectifier. Figure 2.2 shows an example of an input current waveform for this circuit. The reactor (L) helps improve the power factor and the diodes and smoothing capacitors convert AC to DC. Because the passive PFC circuit operates at a mains frequency (50 or 60 Hz), a large reactor and capacitors are necessary. Therefore, passive PFC tends to be used for low-capacity power supplies.

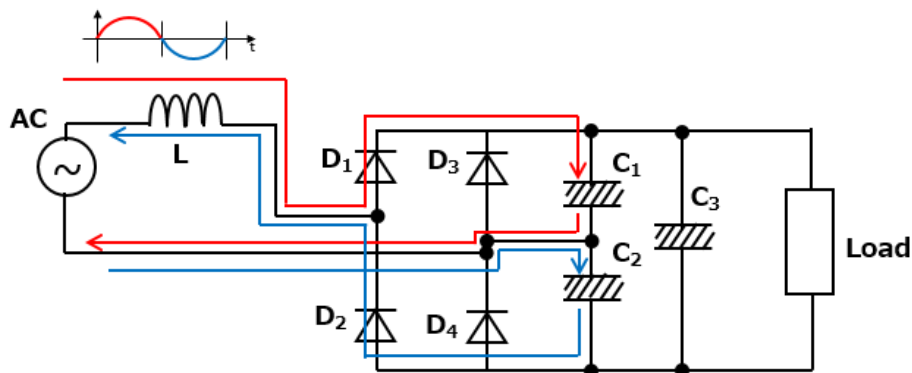


Figure 2.1 Example of a passive PFC circuit

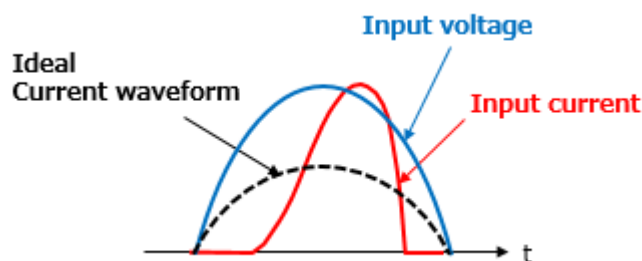


Figure 2.2 Example of an input current waveform for passive PFC

Side note:

The circuit shown in Figure 2.1 is a full-wave voltage doubler rectifier, which is widely used in 100-VAC inverter air conditioners and other home appliances. An AC power source supplies an AC current to the voltage-doubling rectifier via a PFC reactor (L) and charges voltage-doubling capacitors C_1 and C_2 . In addition, diodes D_3 and D_4 are connected in parallel with capacitors C_1 and C_2 , respectively. These diodes protect capacitors C_1 and C_2 from destruction.

2.2. Partial-switching PFC

This PFC circuit consists of a switching device and performs switching operations a few times per half cycle. This PFC partially turns on the switching element and passes current to the reactor when no current is flowing in the case of passive PFC. This PFC increases the period during which the input current flows and improves the power factor. Because energy can be stored in the reactor, a partial-switching PFC circuit can boost the output voltage to a level higher than the supply voltage. In addition, a partial-switching PFC circuit can be designed to exhibit very low switching losses because it performs switching operations only a few times per half mains cycle. Figure 2.3 shows the schematic of a partial-switching PFC circuit. Figure 2.4 gives an example of an input current waveform for this circuit.

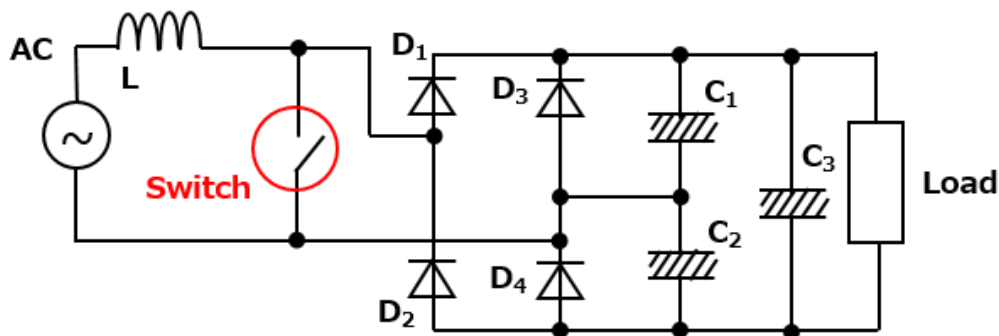


Figure 2.3 Partial-switching PFC circuit

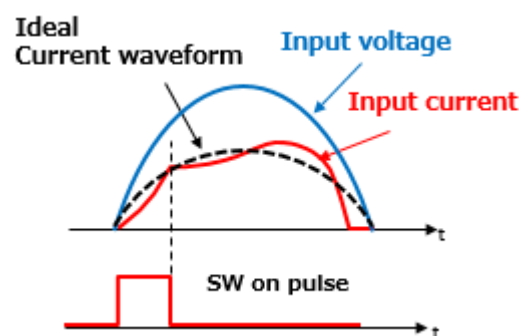


Figure 2.4 Current waveform of a partial-switching PFC circuit

2.3. Active PFC

Since the boost chopper (boost converter) shown in Figure 2.5 is commonly used for active PFC, this section describes the boost chopper. Active PFC circuits are divided into three types according to the current conduction mode used: CCM, CRM, and DCM. The active PFC circuit controls the current by turning the MOSFET on and off, synchronizes the power supply voltage and phase, and brings the input current waveform closer to a sine wave. In Figure 2.5, the current path for MOSFET turn-on is indicated by arrow #1 whereas the one for MOSFET turn-off is highlighted by arrow #2. Figure 2.6 shows the typical the current waveforms of a MOSFET Q_1 and output diode D_5 of a CCM PFC circuit. The current flowing through the MOSFET and the forward current through the output diode combine to provide an input current for inductor L .

Side note:

The input AC voltage range for many switched-mode power supply is commonly specified as 85 to 265 VAC to support the WW range. In this case, the maximum peak input AC voltage (V_{in}) is 372 V ($265 \text{ VAC} \cdot \sqrt{2}$), and the output voltage (V_{out}) is specified as 380 to 400 V, a little higher than the maximum peak value of V_{in} . A CCM PFC circuit uses PWM control to generate a sinusoidal input current. The CCM PFC circuit increases the on-duty cycle (D) of the switching MOSFET when the difference between V_{out} and V_{in} is large. In CCM mode, V_{in} (input AC voltage) and V_{out} have the following relationship. See Supplement 3 for more details.

$$V_{out} (\text{setpoint value}) = V_{in} (T_{on} + T_{off}) / T_{off}$$

$$= V_{in} \cdot T / T_{off} = V_{in} / (1 - D) \text{--- Equation 2-1}$$

(where, T (cycle) = $T_{on} + T_{off}$, and D is the duty cycle of the switching device.)

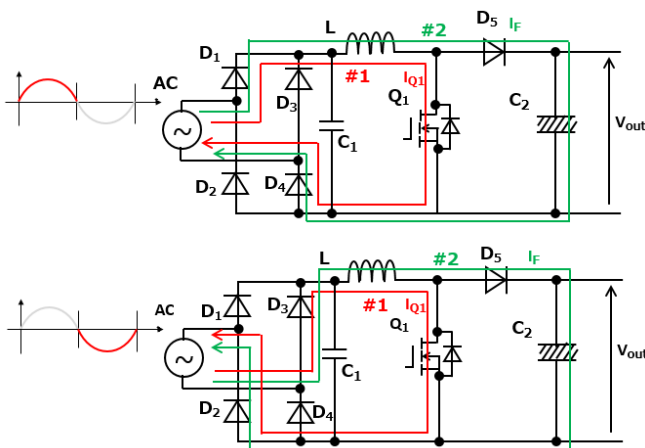


Figure 2.5 Basic active PFC circuit and its current paths

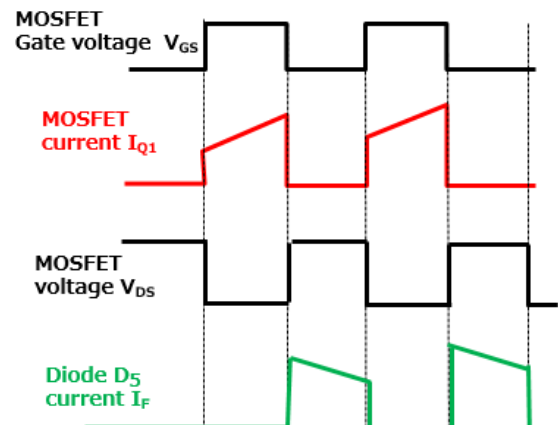


Figure 2.6 Typical waveforms in CCM mode

2.4. Switching conduction modes

2.4.1. Continuous conduction mode (CCM)

Figure 2.7 shows an example of the waveforms of an active PFC circuit in CCM mode. In CCM mode, the PFC circuit continuously passes current through reactor (L). Therefore, the MOSFET turns on

before the reactor (L) current drops to zero. Generally, the CCM PFC mode operates at a fixed frequency to generate a sinusoidal input current. Compared to CRM and DCM PFC modes, the CCM PFC mode can be designed to reduce ripples in the current flowing to the MOSFET. However, a drawback of the CCM PFC mode is that because current is flowing through an output diode when the MOSFET turns on, the diode's reverse recovery current combines with the reactor (L) load current, increasing the MOSFET turn-on loss. To reduce the turn-on loss and thereby increase efficiency, it is necessary to use a high-speed diode with short reverse recovery time. For this purpose, an SiC Schottky barrier diode (SBD) is widely used for power supplies requiring high efficiency.

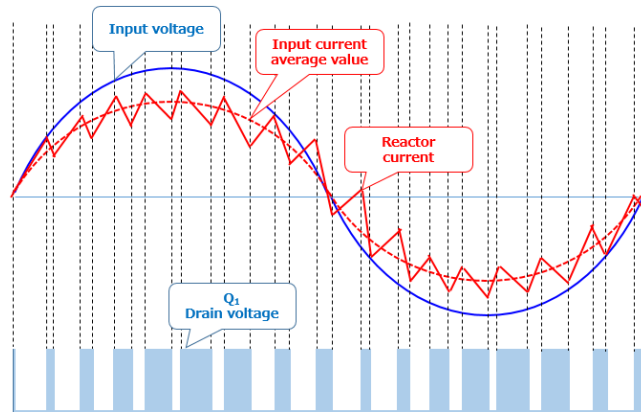


Figure 2.7 Waveforms of a CCM PFC circuit

2.4.2. Critical conduction mode (CRM)

Figure 2.8 shows the waveforms of a CRM PFC circuit. The MOSFET turns on when the reactor (L) current drops to zero. Assume that the instantaneous input voltage during operation is V_{AC} . The peak current (i_p) is $V_{AC} \cdot t/L$. Because the input voltage (V_{in}) is $\sqrt{2} \cdot V_{AC} \cdot \sin \omega t$, i_p changes sinusoidally with V_{in} . And because the average input current (i_{ave}) is $i_p/2$, the average current value also changes sinusoidally with V_{in} . The CRM PFC circuit senses the output voltage and accordingly controls the MOSFET pulse width. The CRM PFC circuit reduces the MOSFET pulse width when the output voltage is too high and increases the pulse width when it is too low. The operating frequency is not fixed because it varies depending on the output voltage and input voltage values. The operating frequency decreases as the load increases.

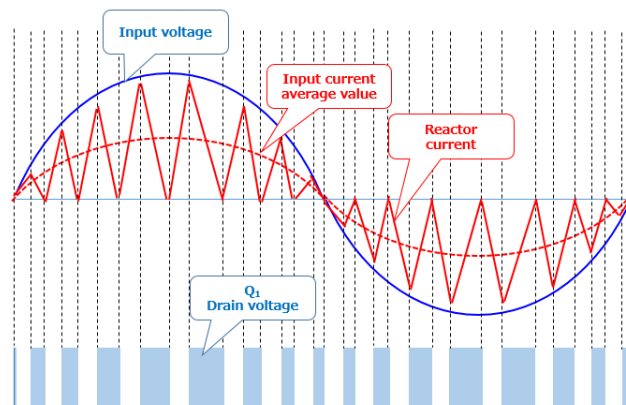


Figure 2.8 Waveforms of a CRM PFC circuit

2.4.3. Discontinuous conduction mode (DCM)

The DCM PFC mode has the period of zero current every cycle. Figure 2.9 shows an example of the current waveform of the DCM PFC circuit. In this example, since both the frequency and the MOSFET "on" width are constant, the control circuit for DCM PFC is simple. The DCM PFC circuit exhibits a higher peak current than CCM and CRM circuits, therefore tends to have lower efficiency. However, there is no influences of the reverse recovery characteristics of the diode because the MOSFET is turned on when no current flows through the output diode, resulting in low noise.

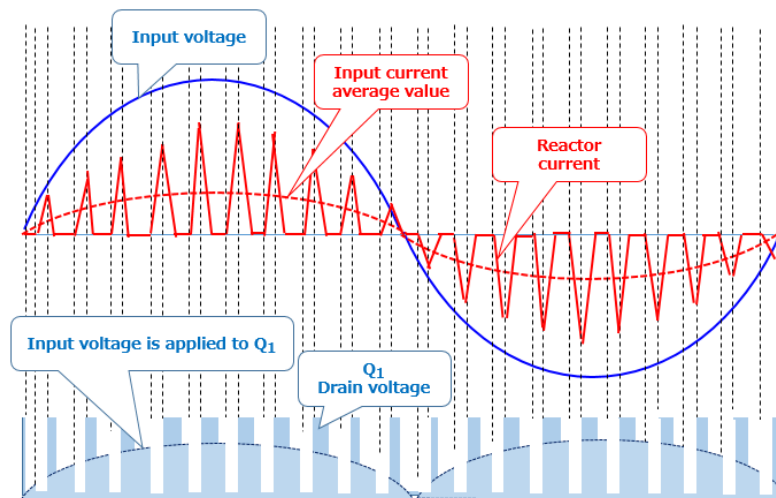
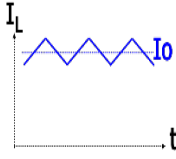
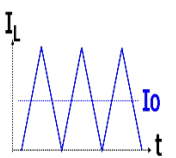
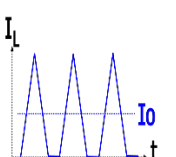


Figure 2.9 Waveforms of a DCM PFC circuit

2.5. Comparison of different active PFC modes

As described in the preceding sections, the active PFC circuits are divided into three types according to the current conduction mode. They have different characteristics. CCM is used for power supplies with a relatively large capacity whereas CRM and DCM are primarily used for low-capacity commercial power supplies. Table 2.1 summarizes their characteristics.

Table 2.1 Comparison of three current conduction modes

Conduction Mode	Control Method	Output Capacity and Applications	Advantages and Disadvantages	Reactor Current Waveform
Continuous conduction mode CCM	PWM control (Pulse Width Modulation)	> 300 W Industrial power supplies	- Has small ripples in input current - Small peak current - Decreases a circuit's overall efficiency and causes a noise problem if the PFC diode has a long reverse recovery time (t_{rr})	
Critical conduction mode CRM	PFM control (Pulse Frequency Modulation)	75 to 300 W LCD TVs, PCs, commercial power supplies	- Has small ripples in reactor current - High peak current - Zero-current switching, and low switching loss	
Discontinuous conduction mode DCM	PWM control PFM and valley control	25 to 100 W Power supplies for LED lighting, small-capacity power supplies	- Has large ripples in reactor current - Zero-current switching, and low switching loss - High peak current - Exhibits valley oscillation during zero-current periods	

2.6. MOSFET switching losses

At high switching frequency, a switching PFC circuit can be designed with a small reactor (L) and a small charging capacitor. Therefore, a high-speed MOSFET is required. $R_{ON} \cdot Q_{gd}$ is a figure of merit for the high-speed switching MOSFET. A MOSFET with a small $R_{ON} \cdot Q_{gd}$ value is necessary. Toshiba's latest DT MOSVI super-junction MOSFET series has outstanding $R_{ON} \cdot Q_{gd}$ characteristics and has been well received in the market as it is suitable for improving the efficiency of a PFC circuit. (Note: Care should be exercised in design because high speed switching tends to cause an increase in switching noise.) Because the reverse recovery characteristics of an output diode greatly affect the MOSFET turn-on loss in CCM mode, an SiC SBD is generally used as an output diode to reduce the loss.

Figure 2.10 shows a basic PFC circuit. Figure 2.11 shows the current and voltage waveforms of the MOSFET Q_1 and the output diode D_5 in CCM mode. This indicates that when the MOSFET is turned on, reverse recovery current (I_{rr}) of the diode D_5 flows, which greatly affects the MOSFET turn-on loss.

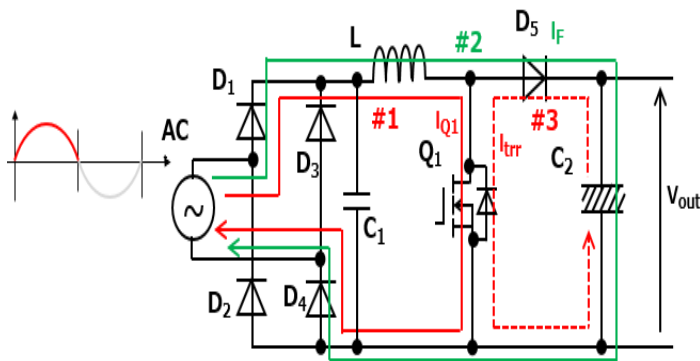


Figure 2.10 Basic PFC circuit

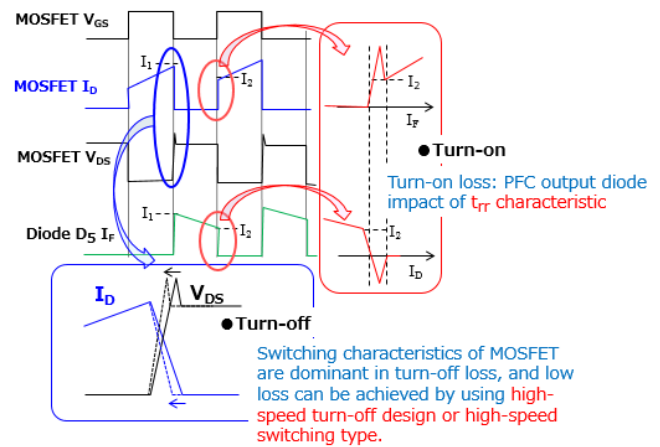


Figure 2.11 CCM PFC circuit and its operating waveforms

3. PFC application circuits

Figure 2.10 shows a basic active PFC circuit. In addition, many variants of active PFC circuit systems have been proposed in order to increase the efficiency and capacity of power supplies. Most commonly used active PFC circuits include 1) PFC using parallel MOSFETs, 2) interleaved PFC, 3) and bridgeless PFC, each of which is discussed in the following sections.

3.1. PFC using parallel MOSFETs

Connecting multiple MOSFETs in parallel makes it possible to support high-capacity power supplies. Because parallel MOSFETs perform switching operations simultaneously, current flowing in one MOSFET is halved when two MOSFETs are connected in parallel. Paralleling multiple MOSFETs helps improve heat dissipation because current flows and circuit losses are more widely dispersed.

Parallel MOSFETs must have the same electrical characteristics and drive conditions as well as equal and low stray inductance.

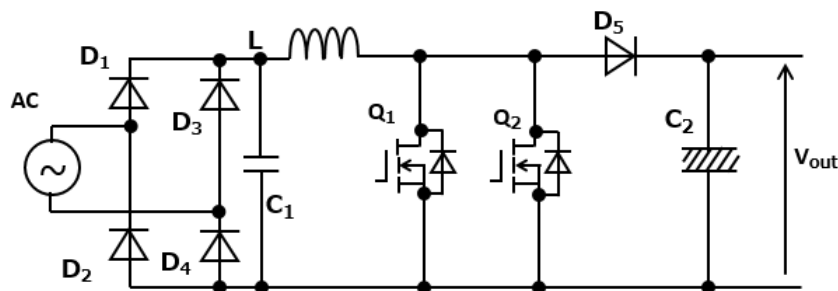


Figure 3.1 Example of a PFC circuit using parallel MOSFETs

3.2. Interleaved PFC

Medium and large power supplies with a capacity greater than 500 W are now widely used. In principle, a multi-phase interleaved PFC may be used for such power supplies, but a large majority of them use a two-phase interleaved PFC circuit like the one shown in Figure 3.2. With two-phase interleaved PFC, two switching devices switch alternately so that two PFC circuits operate in reverse polarity (with a 180° phase difference). Therefore, the switching frequency of each switching device is half the circuit frequency. Figure 3.2(a) and Figure 3.2(b) show the current paths in an interleaved

PFC circuit while the input AC voltage is in the positive half cycle whereas Figure 3.2(c) and Figure 3.2(d) show the current paths while it is in the negative half cycle. Figure 3.3 shows the current waveforms of this circuit. The input current is always equal to the sum of the currents flowing through two reactors (L_1 and L_2). Since the ripple currents of the reactors in reverse phase cancel each other out, the input ripple current due to the reactors becomes small. Since power losses are dispersed across two devices as is the case with a PFC circuit using parallel MOSFETs, an interleaved PFC circuit also simplifies thermal design.

Since each MOSFET switches independently, delicate consideration is unnecessary for the selection of MOSFETs. Since the switching frequency of one MOSFET is half that of the circuit, the switching loss is half. On the other hand, the disadvantage of interleaved PFC circuits is that they have higher conduction losses, because they have a peak current that is twice that of a PFC circuit using parallel MOSFETs.

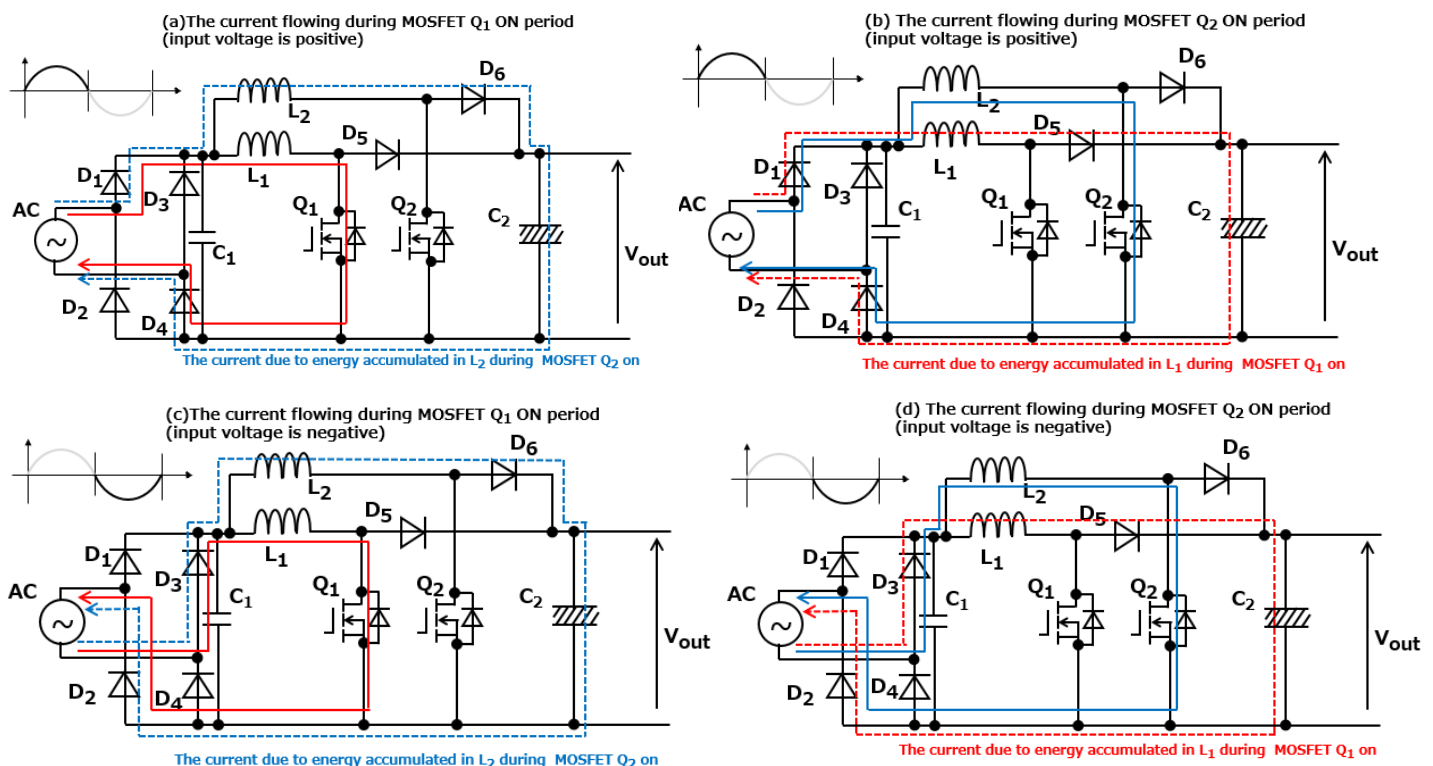


Figure 3.2 Interleaved PFC circuit and its operation

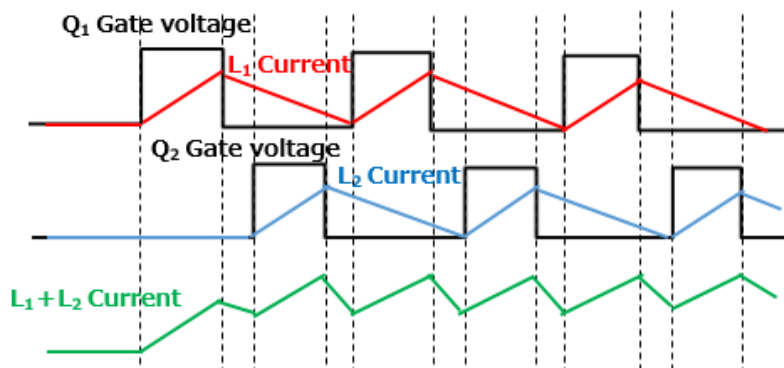


Figure 3.3 Interleaved PFC waveform

3.3. Bridgeless PFC

The bridgeless PFC circuit helps further improve efficiency. To reduce the loss of the input diode bridge, the bridgeless PFC circuit integrates its functionality into PFC. Figure 3.4 shows the basic circuit configuration of the bridgeless PFC circuit and its current paths in positive and negative half cycles of the AC input. While the L_1 side of the AC source is positive, Q_1 acts as a switching device whereas D_1 acts as an output diode. During this half-cycle period, Q_2 operates in synchronous rectification mode to rectify the AC mains input. In contrast, while the L_2 side of the AC source is positive, Q_2 and D_3 perform a switching operation, and Q_1 operates as a synchronous rectifier. The difference in the losses of the basic PFC circuit shown in Figure 2.10 and the bridgeless PFC circuit shown in Figure 3.4 occurs because of the differences in the forward voltage drop of the two diodes ($2V_F$) and the voltage drop ($V_{DS(on)}$) caused by the R_{ON} of one MOSFET. Table 3.1 shows a comparison of conducting devices every half cycle.

Table 3.1 Comparison of conducting devices every half cycle

		Input Diode	Switching MOSFET	Off MOSFET (Rectification)	Output Diode	Voltage drop of conducting devices
Basic Active PFC circuit (Figure 2.5/2.10)	MOSFET Q_1 on	D_1, D_4	Q_1			$2 \times V_F$ (Diode voltage drop) $V_{DS(on)}$ (MOSFET on voltage)
	MOSFET Q_1 off	D_1, D_4			D_5	$3 \times V_F$ (Diode voltage drop)
Bridgeless PFC circuit (Figure 3.4)	MOSFET Q_1 on		Q_1	$Q_2(D_4)$		$2 \times V_{DS(on)}$ (MOSFET on voltage)
	MOSFET Q_1 off			$Q_2(D_4)$	D_1	V_F (Diode voltage drop) $V_{DS(on)}$ (MOSFET on voltage)

Whether Q_1 is on or off, the voltage drop difference between the basic active PFC circuit and bridgeless PFC is the difference of $2 \times V_F$ and $V_{DS(on)}$.

Normally, a MOSFET's $V_{DS(ON)}$ is lower than its V_F . Thus, bridgeless PFC circuits can help reduce circuit losses. A single input inductor can be used instead of two input inductors (L_1 and L_2). However, using two inductors prevents high dv/dt transients from being applied directly to the input pins

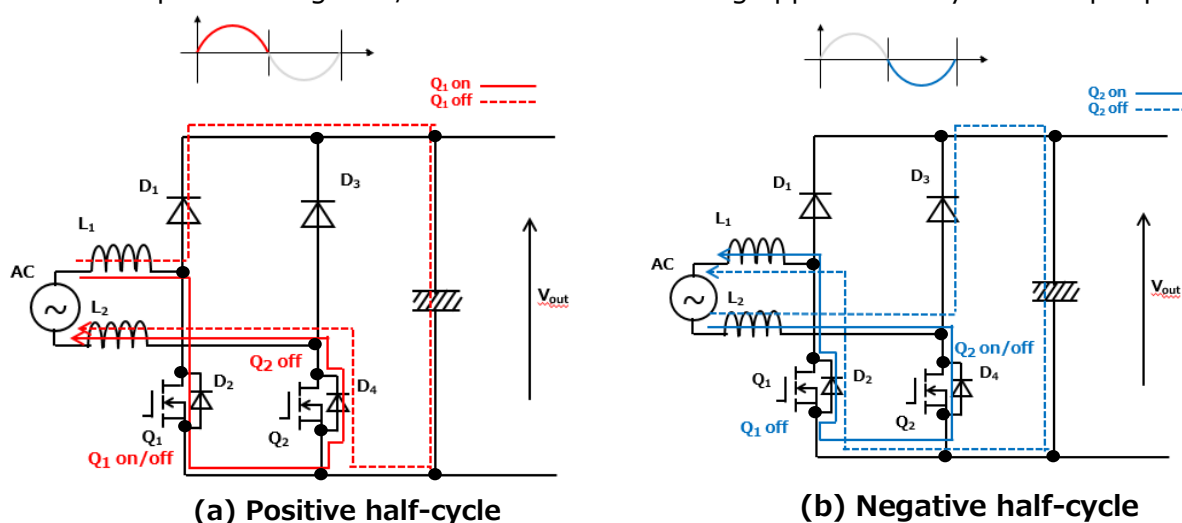


Figure 3.4 Bridgeless PFC circuit and its operation

3.4. Other circuit examples

Figure 3.5 shows a bridgeless PFC circuit in which Q_1 and Q_2 are connected in a totem-pole configuration.

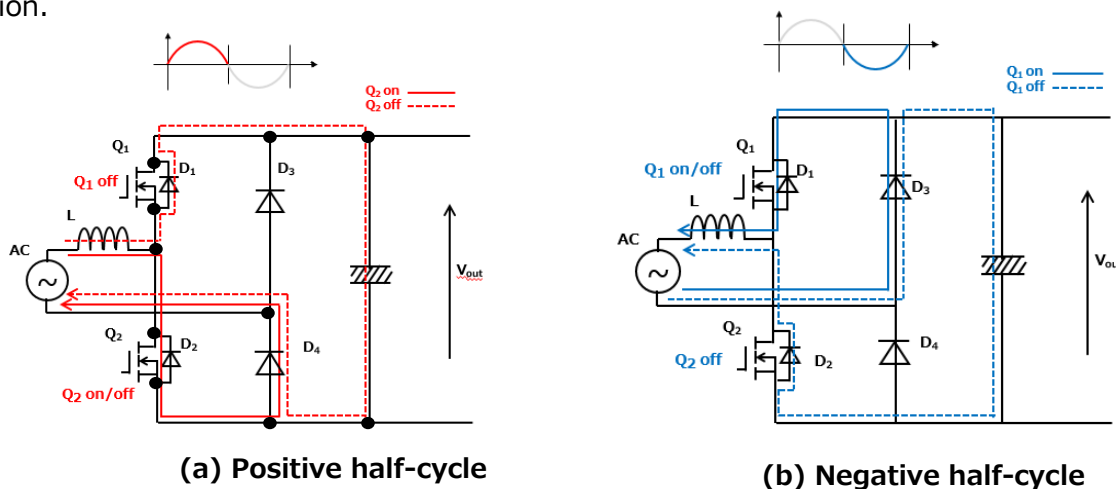


Figure 3.5 Example of a totem-pole PFC circuit and its operation

Figure 3.5 shows a circuit that performs synchronous rectification with MOSFETs for the operation functions of D_1 and D_3 in the circuit of Figure 3.4.

SiC SBDs are widely used in the bridgeless PFC circuit of Figure 3.4 so as to reduce the reverse recovery current of D_1 or D_3 that flows when Q_1 or Q_2 turns on. Unlike the circuit in Figure 3.4, the one shown in Figure 3.5 uses MOSFETs instead of SiC SBDs to reduce reverse recovery current. Therefore, Q_1 is on during the positive half cycle, and Q_2 is on during the negative half. Consequently, the MOSFET on-state voltage $V_{DS(ON)}$, during synchronous rectification is lower than the forward voltage drop (V_F) of the SiC SBD. Therefore, this circuit helps improve efficiency. However, a dead time is inserted to prevent cross-conduction of Q_1 and Q_2 . Since the body diode conducts during the dead-time period, a reverse recovery current can be a problem. It is therefore necessary to add a countermeasure to the circuit or use devices with excellent reverse recovery characteristics such as SiC MOSFETs and GaN HEMTs.

3.5. Improvement of a bridgeless PFC circuit

Figure 3.6 shows a bridgeless PFC circuit with diodes added on the input AC mains side. The ground of the PFC output is connected to the input lines via two diodes (D_a and D_b). As a result, the input line voltage is no longer floating with the output line. Therefore, this eliminates the need for a transformer or a photocoupler for the sensing of input voltage and makes it possible to sense it with a simple resistor divider. In addition, D_a and D_b help reduce noise.

D_c and D_d act as diodes that charge capacitor C_0 to peak voltage during the initial startup. After the PFC circuit starts operation at the peak voltage of C_0 , D_c and D_d to C_0 are not charged. As shown in the schematic of the bridgeless PFC circuit of Figure 3.6, current flows through the body diode of an inactive MOSFET (or a MOSFET in the case of synchronous rectification) in addition to the paths via D_a and D_b . While the sinusoidal input voltage is positive (i.e., the L line is high), most current flows

through MOSFET Q_2 or its body diode regardless of whether MOSFET Q_1 is on or off, but a little current flows through diode D_b . (The same is true when the sinusoidal input voltage is negative (i.e., the N line is high).)

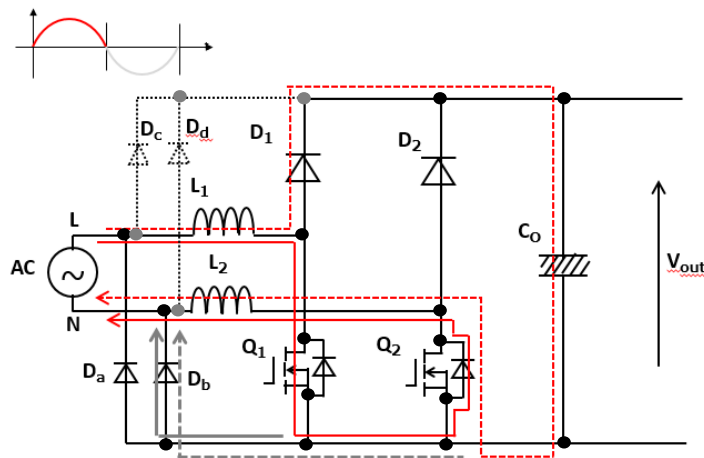


Figure 3.6 Bridgeless PFC circuit with reduced noise

In the circuit shown in Figure 3.7, MOSFETs Q_{D3} and Q_{D4} are used in synchronous rectification mode in order to reduce the forward voltage drop (V_F) of diodes D_3 and D_4 in the circuit of Figure 3.5. Because Q_{D3} and Q_{D4} alternately perform synchronous rectification when the input AC voltage crosses the zero point every half cycle, MOSFETs with a body diode having short reverse recovery time are not needed for Q_{D3} and Q_{D4} . It suffices to select low-on-resistance MOSFETs for Q_{D3} and Q_{D4} . (Note: As is the case with the circuit shown in Section 3.4, MOSFETs with short reverse recovery time must be selected for Q_1 and Q_2 .)

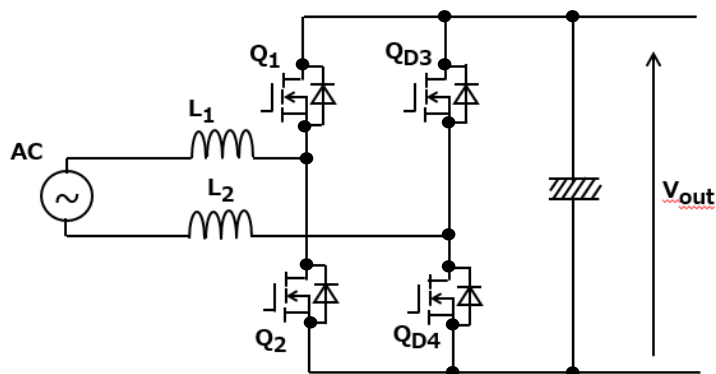


Figure 3.7 Improved bridgeless PFC circuit

4. Supplemental information

Supplement 1. Power factor

The power factor is defined as the ratio of active power (P_{act}), i.e., the power consumed by a load, to apparent power (P_{apr}):

$$\text{Power factor (PF)} = \frac{\text{active_power}}{\text{apparent_power}} = \frac{P_{act}}{P_{apr}} \text{ --- Equation 4-1}$$

Active power (P_{act}) is the amount of power consumed by a load whereas apparent power (P_{apr}) is the amount of power transferred from a power supply.

Apparent power (P_{apr}) can be expressed as follows:

$$P_{apr} = \sqrt{\text{active_power}^2 + \text{reactive_power}^2} = \sqrt{P_{act}^2 + P_{rea}^2} \text{ --- Equation 4-2}$$

where reactive power (P_{rea}) is the amount of power that is not consumed by a load. Therefore, the power factor can be expressed as follows:

$$\text{Power factor } PF = \frac{P_{act}}{\sqrt{P_{act}^2 + P_{rea}^2}} \text{ --- Equation 4-3}$$

The power factor is equal to the cosine of the phase difference between voltage and current (i.e., the phase angle between apparent power and active power) as shown in Figure 4.1. Therefore, the product of voltage and current (i.e., power) is converted into energy. When AC voltage is applied to an inductive or capacitive load results in a phase difference between voltage and current. This phase difference changes the rate of conversion to energy. The power factor is the ratio of the power converted into energy to apparent power.

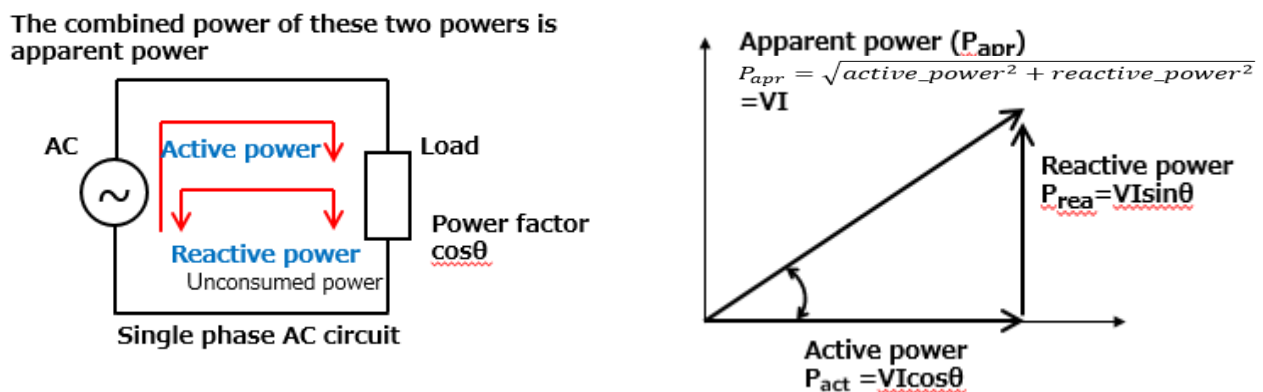


Figure 4.1 Active power and reactive power

Supplement 2. Harmonics

A harmonic is a distortion contained in the sinusoidal AC current waveform and is defined as a component having a frequency that is an integer multiple of its fundamental frequency. The n th-order harmonic is the n th multiple of the fundamental frequency. A harmonic is a sine waveform with a frequency that is an integer multiple of the fundamental frequency. A sine waveform without distortion consists of only the fundamental frequency and no harmonics. All waveforms with distortion contain harmonics.

The waveform of the mains power supply with harmonics is distorted. Distortion is caused by the

rectification and smoothing circuits at the input of electronic systems. Harmonics generated by an electrical or electronic system might adversely affect electrical facilities and other systems (e.g., the heating of phase-advancing capacitors and reactors).

Noise is a phenomenon similar to harmonics. In a broad sense, harmonics are also noise. However, noise is not associated with the power supply frequency. Harmonics are always a function of the power supply frequency.

Supplement 3. Relationship of the input and output voltages of a boost converter

1) Boost converters in continuous conduction mode (CCM)

In the CCM waveform shown in Figure 4.2, a voltage of V_{in} is applied across inductor L during the turn-on period of a switching device (see Figure 3.5).

Current changes with V_{in} (which is equal to $L \cdot (di_L/dt)$).

Changes in current (Δi_L) during the "on" period (T_{on}) of a MOSFET are expressed as:

$$\Delta i_L = (V_{in}/L) \cdot T_{on}$$

A voltage of $(V_{in} - V_{out})$ is applied across inductor L during the "off" period of a MOSFET.

Therefore, changes in current ($\Delta i_L'$) during the "off" period (T_{off}) of a MOSFET are expressed as:

$$\Delta i_L' = ((V_{in} - V_{out})/L) \cdot T_{off}$$

Because $\Delta i_L = -\Delta i_L'$ in the steady state,

$$\begin{aligned} V_{out} &= V_{in} \cdot (T_{on} + T_{off})/T_{off} \\ &= V_{in}/(1-D) \quad \text{--- Equation 4-1} \end{aligned}$$

(where D is the on-duty cycle, which is defined as $T_{on}/(T_{on} + T_{off})$.)

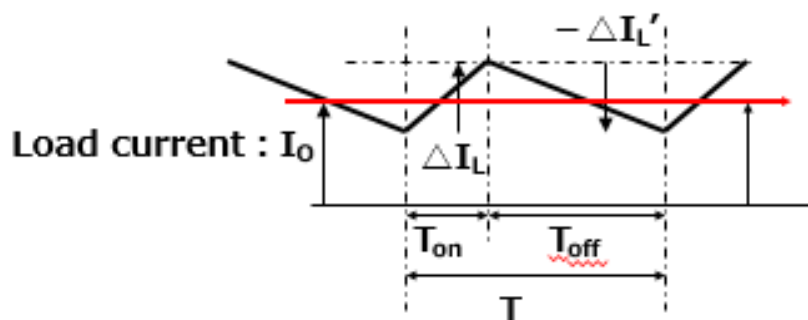


Figure 4.2 CCM waveform

2) Boost converters in discontinuous conduction mode (DCM)

In the DCM waveform shown in Figure 4.3, the peak currents that flow during the “on” and “off” periods of a switching device are equal because of the continuity of the current flowing through an inductor.

$$(V_{in}/L) \cdot T_{on} = [(V_{out} - V_{in})/L] \cdot T_d \quad \text{--- Equation 4-2(1)}$$

The total amount of charge (i.e., current) supplied to a load during a cycle (T) is equal to the total amount of charge supplied to a capacitor from the inductor.

$$(V_{out}/R)T = [(V_{out} - V_{in})/L] \cdot T_d^2/2 \quad \text{--- Equation 4-2(2)}$$

The following equation is obtained when T_d is eliminated from Equation 4-2(1) and Equation 4-2(2):

$$(V_{out}/R) [(V_{out} - V_{in})/L]T = (V_{in}/L)^2 \cdot T_{on}^2/2 \Rightarrow V_{out}^2 - V_{in} \cdot V_{out} - V_{in}^2 \cdot T_{on}^2 \cdot R/2 \cdot T \cdot L = 0$$

Hence, V_{out} is calculated as follows (where D is the on-duty cycle of the switching device):

$$\begin{aligned} \blacksquare V_{out} &= V_{in}/2 \pm (V_{in}^2/4 + V_{in}^2 \cdot T_{on}^2 \cdot R/2 \cdot T \cdot L)^{1/2} \\ &= (V_{in}/2) [1 \pm (1 + 2T_{on}^2 \cdot R/T \cdot L)^{1/2}] \\ &= (V_{in}/2) [1 \pm (1 + 2D^2 \cdot R \cdot T/L)^{1/2}] \quad \text{--- Equation 4-3} \end{aligned}$$

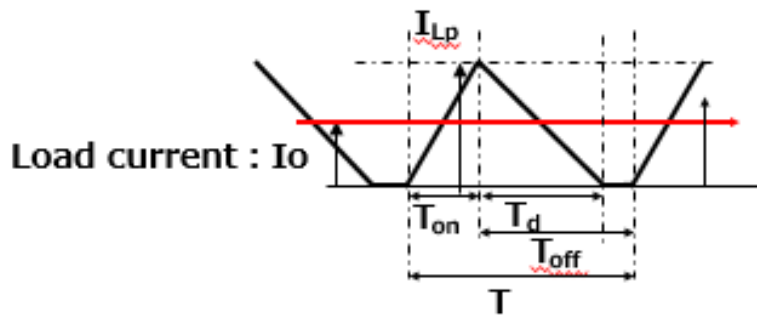


Figure 4.3 DCM waveform

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