Chapter 4: *Power Factor Correction*

Electronic equipment connected to the mains interacts with the supply grid to varying extents. Passive loads such as heaters sink current in a steady manner and do not affect the operation of other equipment connected to the mains. Other equipment, however, switch the current supply on and off rapidly and this causes disturbances in the mains network in the form of additional current harmonics. These harmonics are generated by the switching activity in the equipment and may interfere with sensitive electronics connected to the same network. Legislation (EN61000-3-2) has been introduced that specifies acceptable levels of reflected harmonics from electronic equipment into the mains supply. Utility companies do not like this switching behaviour because it means they must supply extra power to the equipment and install extra thick cabeling to account for circulating currents that are created by the switching action.

This chapter discusses how these reflected harmonic currents may be reduced and the supply from the mains made more efficient by additional circuits at the input of the converter.

4.1 Introduction

Modern electronic equipment does not represent a completely passive load to the AC mains or powerline. Historically, loads have been fairly benign, having either resistive characteristics (light bulbs) or input currents that are sinusoidal but phase-shifted (AC motors). Most electronic systems now use one or more switchmode power converters that will tend to draw current from the powerline in a non-sinusoidal fashion. This input current characteristic results in current and possibly voltage distortions that can create problems with other equipment connected to the powerline and degrade the capability of the mains. These problems have led to the creation of design standards for the purpose of limiting the allowable harmonic distortion on the powerline. Fortunately, solutions are available for meeting these standards. These solutions are referred to as Power Factor Correction (PFC) techniques.

In this chapter we will first define the various terms used in the field of PFC. We will then examine the characteristics of the off-line rectifier, which is the most common front-end for conventional switchmode power supplies. The possible effects of high harmonic distortion and low power factor will be discussed along with the tradeoffs involved in correcting them. Examples will be provided of both passive and active correction techniques. The status of the latest international standards for harmonic distortion and power factor will be discussed along with general design strategies for achieving compliance with them.

4.2 Fundamental Principles

Power factor is a measure of the relationship between the input voltage and current waveforms to an electrical load that is powered from an AC source. This source is most often the AC utility mains, but could also be the output of an electronic inverter, motor drive or other localized AC source. Before specifying how power factor is defined and measured, it is useful to be aware of the generalized types of AC current waveforms that we will be considering, as shown in Figure 4.1.

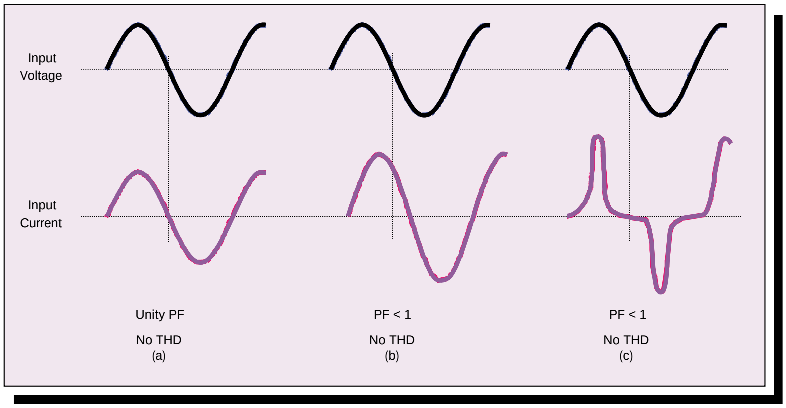


Figure 4.1 - AC Input Voltage vs. Current Relationships

Figure 4.1a shows the most basic situation, which is a purely resistive linear load. Examples would be incandescent lamps or heating elements. In this case, the current waveform is sinusoidal and is in-phase with the input voltage. As we will see later, the power factor in this case is unity and the Total Harmonic Distortion (THD) is zero. Figure 4.1b depicts the situation with a linear reactive load. Note that the current waveform is still a pure sinusoid, but that it is phase-shifted from the voltage waveform. This phase shift will result in a power factor that is less than unity. Because the input current waveform remains sinusoidal, the THD is still zero. Examples of this situation would be inductive loads such as lighting ballasts, transformers or AC motors. Figure 4.1c shows the behaviour of a nonlinear load. In this case, the current waveform is non-sinusoidal, resulting in a power factor less than unity and a non-zero THD. The most common example of this situation would be would be an off-line rectifier with capacitive energy storage. If the source impedance of the powerline is very low, the non-sinusoidal current will not significantly distort the line voltage waveform. For purposes of simplicity in analysis, we will make this assumption unless noted otherwise.

We will next see how the definitions of power factor and THD will encompass all of these situations.

To understand the definition of power factor, we must first look at the power relationships that correspond to a reactive load such as that shown in Figure 4.1b. Such a load will have a real power component (dissipated power) and a reactive power component (voltage and current into a pure reactance). The vector sum of these two power components is the apparent power to the load. Figure 4.2a shows this vector relationship. The phase angle ϕ between the real power P and reactive power Q is called the power factor angle. Consequently, if the current leads or lags the voltage by 90º ($\phi = 90°$) the load is purely reactive and the real power is zero. With a resistive load, the reactive power will be zero (since $\phi = 0°$) and the apparent power is equal to the real power. If the load has a net inductive reactance, the current will lag the voltage. The current will lead the voltage in the case of a linear load with a net capacitive reactance. The greater the reactive power, the greater the phase shift angle will be and the lower the power factor.

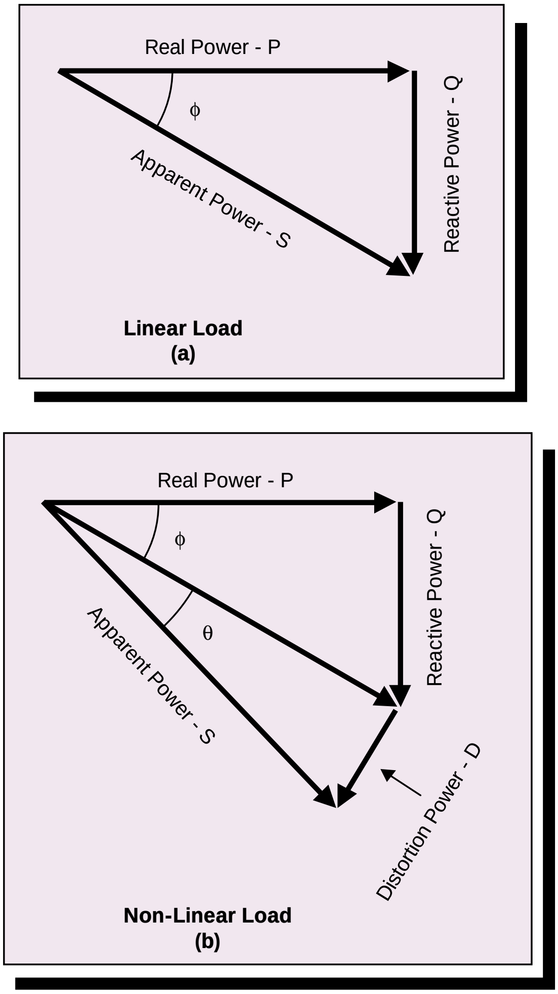


Figure 4.2 - Vector Relationships

We are now able to define power factor for a linear load - actually in two ways:

$$\text{Power Factor} = \frac{\text{RealPower(P)}}{\text{ApparentPower(S)}} = \cos\phi$$

Equation 1

Consequently, once the apparent power (S) is measured as Vrms x Irms, the real power (P) and the reactive power (Q) can be determined by:

$$\text{Real Power} = P = S\cos\phi$$

Equation 2

$$\text{Reactive Power} = Q = S\sin\phi$$

Equation 3

For the linear load case, the power factor can be determined by either measuring the real and apparent powers and doing the division or, alternatively, by measuring the phase shift between the voltage and current waveforms and taking the cosine of this angle. For the nonlinear load case, things get more complex. The phase shift cannot easily be measured due to the non-sinusoidal nature of the current waveform. Consequently, for the nonlinear case, the power factor is best defined as follows:

$$\text{Power Factor} = \frac{\text{RealPower(P)}}{\text{ApparentPower(S)}}$$

Equation 4

For the nonlinear load with distortion on the current waveform, all of the current will not be at the fundamental line frequency, but rather be composed of the fundamental summed with various harmonic currents. This adds yet another type of power to the mix, which we will refer to as distortion power. Distortion power is similar to the reactive power in that it does not contribute directly to the useful power dissipated in the load, but rather adds to the reactive power to create a higher value of apparent power. This is shown in Figure 4.2b. The additional angle between the real and apparent powers due to a non-sinusoidal current waveform is defined as the distortion angle, θ. This allows another form of the definition for power factor:

$$\text{Power Factor} = \frac{\text{RealPower(P)}}{\text{ApparentPower(S)}} = k_d k_\phi$$

Equation 5

where k_d and k_ϕ are both factors between 0 and 1 and

$$k_d = \text{distortion factor} = \frac{I_1\text{rms}}{\text{Irms}}$$

Equation 6

$$k_\phi = \text{displacement factor} = \cos\phi_1$$

Equation 7

where, I_1rms = fundamental current

Irms = total current

ϕ_1 = phase shift of fundamental current

Consequently, for the non-distorted case, Irms = I_1rms, k_d = 1, and Equation 5 reverts to Equation 1.

THD is a very common way of specifying and measuring the amount of distortion present on a waveform. For the case of distortion on the input current waveform, THD is defined as:

$$\text{THD} = \sqrt{\frac{I^2\text{rms} - I_1^2\text{rms}}{I_1^2\text{rms}}}$$

Equation 8

Equation 8 will result in a positive number. It is common practice to express THD as a percentage. For example, if I = 5A and I_1 = 4A, then Equation 8 gives a value of 0.75 which is referred to as 75% THD. Note that THD can be higher than 100%.

We next turn our attention to defining some terminology used in power factor correction (PFC) design. If the inherent power factor of the selected design is not compatible with either the desired power factor or the power factor required by the appropriate regulatory agencies, then some sort of PFC circuit is used to bring the power factor to within the desired limits. The PFC circuit can also be used to ensure that the input current harmonics comply with legislation such as EN61000-3-2. We will discuss this in more detail in Section 4.7.

The location of this circuit relative the other circuits on the assembly determines whether the PFC circuit is considered as ***input*** PFC or ***output*** PFC. Input PFC incorporates the PFC circuit ahead of the other electronics on the assembly. An example would be the PFC correction circuitry on the front-end of an off-line AC/DC power converter. Output PFC places the PFC circuit at the output of the assembly. For example, a drive electronics assembly for an external motor (with an inductive input impedance) might include correction components on its output rather than installing them on the input of the motor assembly. The remainder of this chapter will focus on input PFC, which is the most commonly used technique for power system electronics.

There are two basic types of PFC circuits - ***passive*** and ***active***. Passive PFC circuits incorporate passive components (typically capacitors and inductors) to compensate for the inherent power factor of the circuit to be corrected. Active approaches utilize feedback circuitry along with switchmode converters to synthesise input current waveforms consistent with high power factor. While we will provide one example of passive

PFC, the main focus will be on the more commonly used active approaches.

4.3 The Off-Line Rectifier

With the widespread use of switchmode power converters, there are now literally millions of off-line rectifiers connected to the utility mains. These circuits have capacitive energy storage on their input and present a power factor to the utility that is far from unity. We will explore this configuration in more detail because it is so widespread and offers a good opportunity for understanding power factor and harmonics in a more quantitative fashion. Understanding the behaviour of the off-line rectifier without power factor correction will be a valuable baseline for assessing the improvements arising out of utilisation of the PFC techniques to be discussed later.

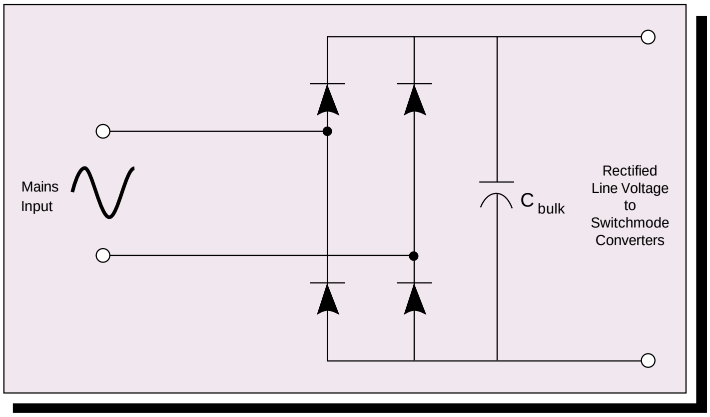


Figure 4.3 - Typical Input Stage for a Mains Supplied Converter

A mains supplied power supply usually consists of a bridge rectifier followed by a bulk capacitor and the power stage as shown in Figure 4.4 The bulk capacitor reduces the ripple on the voltage waveform into the dc converter stage. The diode network and the capacitor only draw current from the mains when the instantaneous mains voltage is greater than the capacitor voltage. Since the capacitor is chosen for a certain hold-up time, should the mains miss a number of cycles, its time constant is much greater than the frequency of the mains. This implies that the instantaneous mains voltage is greater than the capacitor voltage only for very short periods of time, t_{charge}. During these short periods the capacitor must be charged fully. Therefore large pulses of current of duration t_{charge} are drawn from the line over very short periods of time. This is true of all rectified AC sinusoidal signals with capacitive filtering: they draw high amplitude current pulses, see Figure 4.4, from their source. This system has many disadvantages:

- Creation of harmonics and EMI
- High losses
- Requires over-dimensioning of parts
- Reduced maximum power capability from the line

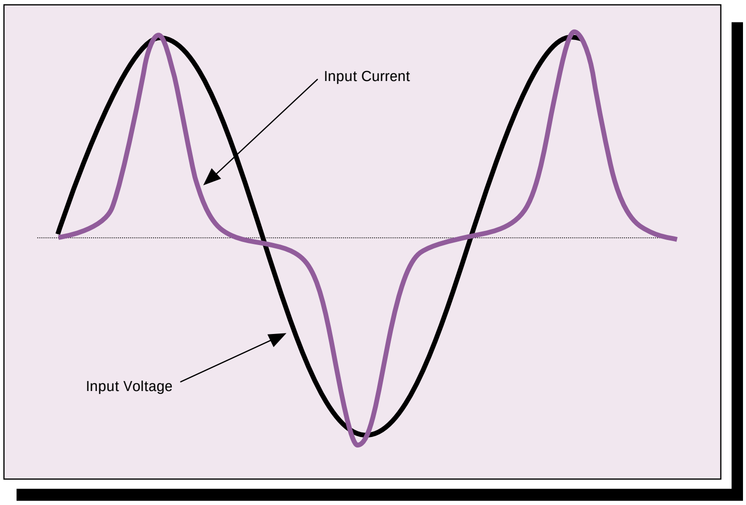
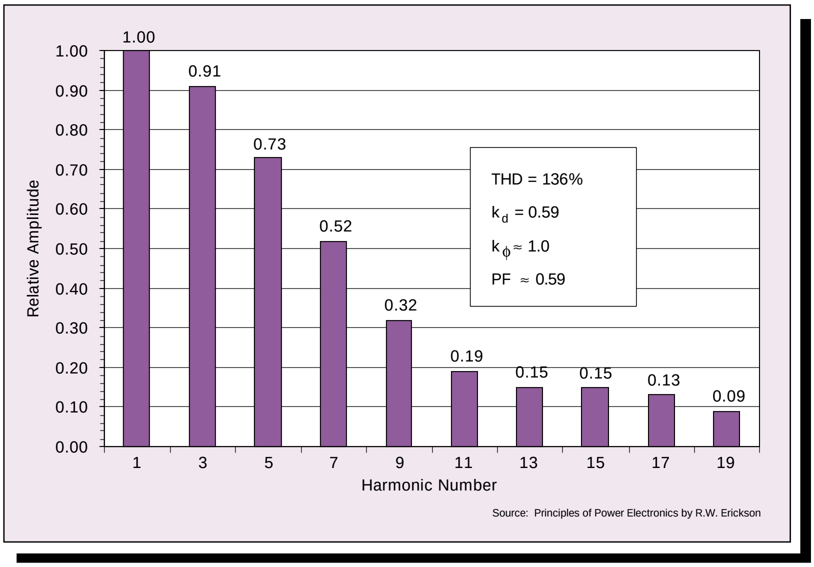


Figure 4.4 - Input Current and Voltage Waveforms for the Off-Line Rectifier

Conventional AC rectification is thus a very inefficient process, resulting in high electricity costs for the utility company and waveform distortion of the current drawn from the powerline. It produces a large spectrum of harmonic signals that may interfere with other equipment. A circuit similar to that shown in Figure 4.3 is used in most mains-powered conventional and switchmode power supplies. At higher power levels (200 to 500 Watts and higher) severe interference with other electronic equipment may become apparent due to these extra harmonics reflected back into the powerline. Another problem is that the powerline cabling, the installation, and the transformers must all be designed to withstand these peak current values.

The typical spectral content of such an off-line rectifier is shown in Figure 4.5 and contains only odd harmonics. The sum of the relative harmonic currents from n = 1 to n = 19, Irms, is 2.838. The fundamental current, I_1rms is 1.0. Therefore we can use Equation 8 to obtain the THD, which is 136%.



Source: Principles of Power Electronics by R.W. Erickson

Figure 4.5 - Typical Harmonic Content for an Off-Line Bridge Rectifier

4.4 The Ramifications of Power Factor and Harmonic Distortion

Situations in which the power factor is less than unity and/or the input current waveform is distorted can create havoc with the product in question, with other equipment attached to the same power source and with the AC utility itself. We have briefly alluded to some of the possible problems, but it will be useful to examine some of them in more detail.

Less Useful Power Available - The powerline circuit is designed, rated, and fused predicated on the amount of current that it can safely deliver. Since low power factor increases the apparent current from the source, the amount of useful power that can be drawn from the circuit is lowered. We will use the 120V 15A outlet circuit commonly found in offices and homes in the United States as an example. If we assume that the overall efficiency of the power conversion system inside the equipment is 80% and that the line current is derated by 20% to avoid nuisance tripping, then the useful power available from such a circuit assuming a unity power factor (best possible case) can be calculated as:

Max. Power = 120V x (15A x 0.80) x 0.80 = 1152 Watts

Repeating the calculation using the uncorrected power factor of 0.59 that we calculated in Section 4.3, we obtain the maximum available useful power to be:

Max Power = 120V x (15A x 0.80) x 0.59 x 0.80 = 680 Watts

Note the huge decrease in available load power. The low power factor could have been caused by either phase-shift (displacement) or harmonic distortion with equally devastating impact on the useful power capability.

AC Distribution Cost - Low power factor increases the apparent line current, and additional current capacity costs money. This starts within the equipment itself, and extends all the way back to the generation and distribution system of the electric utility. Wire sizes within the equipment and the building must be increased to carry the additional current. When there is an abundance of loads with poor power factor, this need for increased capacity will require that additional power generation and distribution capability will be needed. This cost increase will, to a first approximation, be directly proportional to the inverse of the power factor:

$$\text{Cost of Additional Power Capability} = \frac{1}{\text{Power Factor}}$$

Thus, if all connected loads had a power factor of 0.59 rather than 1.00, the increase in the hardware cost for supplying the additional current would be approximately 69%. The power losses in any dissipative circuit elements (such as wire, connections and transformer windings) will be proportional to the apparent current. Therefore, costs associated with providing this dissipated power will also scale inversely with power factor. Utility meters in residential and office environments will actually only register the real power drawn from the powerline, so that the user is not directly penalized in terms of utility costs for the reactive component of the power.

Voltage Waveform Distortion - For purposes of simplicity, most of our calculations have assumed that the AC source impedance is zero and that the AC voltage waveform is not distorted by nonlinear current waveforms. In actuality, the source impedance, while low, is not zero. For fault protection purposes, the conductor sizes get smaller as the AC power gets closer to the final load electronics. The smallest conductors are within the equipment itself, and high levels of distortion on the current waveform will start to affect the quality of the voltage waveform, making it non-sinusoidal. If this voltage distortion becomes severe, it can cause operational problems with the product and with other equipment connected nearby to the same power source.

EMC - The higher line currents associated with poor power factor, especially if distortion and higher frequency harmonics are present, can make for a much more difficult EMC environment. Passive PFC solutions often entail adding a capacitor, which often also acts as an EMC filter to reduce noise imposed onto the powerline. Active PFC approaches can be a source of additional switching activity and associated EMC. However, this noise is high frequency in nature and can be controlled by filters utilizing physically small components, often at only one location in the power system.

Three Phase Systems - While we are focusing our attention on single-phase systems, the ramifications of harmonic distortion on some three-phase systems should be mentioned. Specifically, a four wire three-phase system containing a neutral conductor can be severely compromised by harmonic current content on its loads. Loads that are not balanced phase to phase will result in undesired neutral current content. But even in the best case of completely balanced loads, harmonic content in the loads will appear in the neutral conductor. The good news is that most of the harmonics (including the fundamental) will cancel out and not result in a net current in the neutral conductor. The bad news is that the so-called 'triple' harmonics (3rd, 6th, 9th, ….) will appear and be directly additive in the neutral conductor. For example, if the three loads each only contained a 3rd harmonic that was 15% of the fundamental, the neutral would experience a 3rd harmonic current equal to 45% of the fundamental current. Since the neutral conductors are sized assuming that they will conduct minimal current, this will create a significant problem for the power system.

Regulatory Non-compliance - Because of the types of problems cited above, all industrialized countries have established regulations and standards that address power factor and harmonic distortion on their power utilities, which we will examine in Section 4.7. Without compliance to the appropriate standard(s), the product will have a difficult time gaining acceptance in the marketplace. In fact, it may be illegal to attempt to sell it. These legal and profit related issues make it mandatory that power system designers understand the power factor and current distortion potential of their designs and also appropriate methods of making them compliant.

Increasingly, PFC techniques are being used in new off-line power converter designs. This is motivated both by the concerns listed above and by regulatory requirements, and is overall a positive development for equipment users and the power utilities. Most PFC circuits are now active rather than passive and this results in exceptional PFC performance but requires that additional circuitry be added. The added circuitry can have the following negative impacts on the system:

- Additional cost and complexity for the power converter
- Lower power converter reliability
- Slightly lower efficiency (additional conversion stage sometimes needed)

In spite of these potential limitations, including active PFC is most often a very good design tradeoff for the power system. The above concerns are usually more than offset by the reduced input current, undistorted current waveforms and additional useful power capability of converters that utilize PFC.

4.5 Passive PFC

Although most switchmode power converters now use active PFC techniques, we will give a couple of examples of using the simpler passive approach.

Example 1 - Consider an AC motor with an inductive input operating from a 208V single phase 60 Hz powerline. The real power delivered by the motor (including efficiency losses) is 350W. The input power factor is 0.6 lagging (inductive), and there is no distortion of the input current waveform (linear load). The equivalent circuit of the input to the motor, as seen by the powerline, is shown in Figure 4.6. It is desired to compensate the power factor by adding a capacitor across the input as shown. What value capacitor is needed?

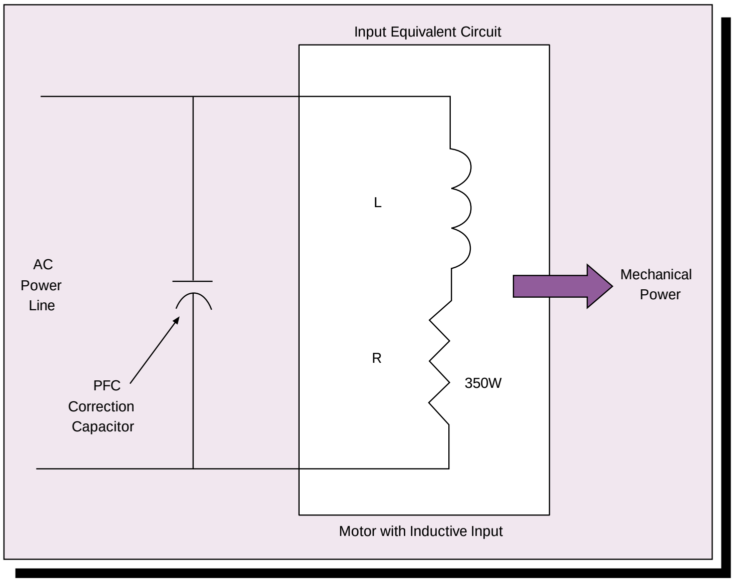


Figure 4.6 - Example of Passive PFC for Linear Load

From Equation 1,

$$\text{Power Factor Angle} = \phi = \text{Cos}^{-1}(0.6) = 53.13^{\circ}$$

We can now use the triangle in Figure 4.2a to calculate the reactive power (Q) and apparent power (S) of the uncompensated motor:

$$\text{Tan}\,(53.13) = \frac{Q}{P}$$

$$Q = \text{Reactive Power} = 350\ \text{Tan}\,(53.13) = 466.66\ \text{VAR}$$

$$S = \text{Apparent Power} = \sqrt{P^2 + Q^2} = 583.33\text{VA}$$

Of course, S could also be determined by dividing the real power P by the power factor (0.6).

For unity power factor, we must add a capacitive reactive power, QC, that is equal to the previously calculated inductive reactive power of the motor. Using the relationship,

$$Q_C = \frac{V^2}{X_c}, \text{ where } X_C \text{ is the capacitive reactance,}$$

$$X_C = \frac{(208)^2}{466.66} = 92.71\Omega$$

$$\text{Finally, from } C = \frac{1}{\omega X_C}$$

$$C = \frac{1}{(2)(\text{Pi})(60)(92.71)} = 28.6\mu\text{F}$$

The addition of the 28.6 µF capacitor will correct the power factor to unity, make the load appear as completely resistive, and reduce the line current from 2.80 A to 1.68 A, a 40% reduction. This is an ideal application for the passive approach, since only phase shift is needed (no distortion present) and the correction can be done with a single capacitor.

Example 2 - Passive PFC techniques can be used to improve the power factor of nonlinear loads, such as power converters with off-line rectifiers. In Figure 4.8 we show an input waveshaping circuit consisting of an inductor and a capacitor. This type of circuit will help the input current waveform become more sinusoidal, but not completely so. Some distortion will remain, and the power factor can be improved to a maximum of perhaps 0.9. Active techniques can do much better, achieving power factors of up to 0.99. The other major shortcoming of the passive approach in this application is the need for an inductor that operates at the line frequency. The low frequency inductor is physically large and heavy. The advantages and disadvantages of passive PFC are summarized in Figure 4.8.

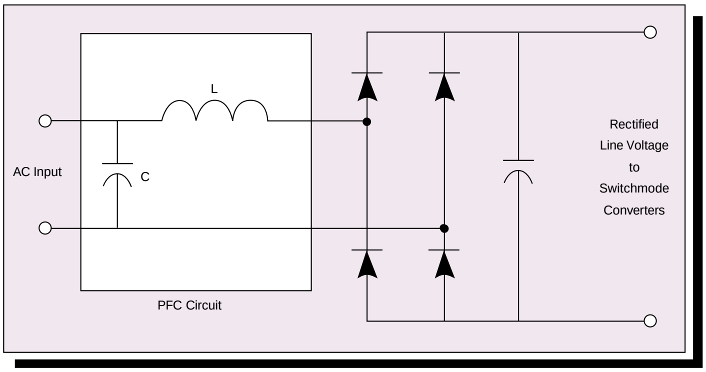


Figure 4.7 - Example of Passive PFC for Non-Linear Load

Advantages
Simple
Cost Effective at Low Power
Reliable and Rugged
Not a Source of EMC
Can Assist with EMC Filtering
Unity Power Factor for Linear Loads

Disadvantages
Line Frequency Components are Large and Heavy
Cannot Completely Correct Nonlinear Loads
AC Range Switching Required
Needs to be Re-Designed as Load Characteristics Change
Magnetics needed if Load is Capacitive

Figure 4.8 - Advantages and Disadvantages of Passive PFC

4.6 Active PFC

Active PFC circuits are based on switchmode converter techniques and are designed to compensate for distortion as well as displacement on the input current waveform. They tend to be significantly more complex than passive approaches, but this complexity is becoming more manageable with the availability of specialized control ICs for implementing active PFC. Active PFC operates at frequencies higher than the line frequency so that compensation of both distortion and displacement can occur within the timeframe of each line frequency cycle, resulting in corrected power factors of up to 0.99. Active approaches can be divided into two classes:

- Slow switching topologies
- High frequency topologies

Slow switching topologies - The slow switching approach can be thought of as a mix of passive and active techniques, both in complexity and performance. The most common implementation is shown in Figure 4.9, and includes the line frequency inductor L. The inductor is switched during the operating cycle, so this is considered an active approach, even though it operates at a relatively low frequency - typically twice the line frequency. This is a boost circuit in the sense that the AC zero crossing is sensed and used to close the switch that places the inductor across the AC input. Consequently, the inductor current ramps up during the initial portion of the AC cycle. At time T1, the switch is opened so that the energy stored in the inductor can freewheel through the diodes to charge the capacitor. This energy transfer occurs from T1 to T2 and the input current drops as a result. From T2 to T3 the input current rises again because the line voltage is larger than the bulk capacitor voltage. From T3 to T4, the current reduces to zero. Consequently, the conduction angle as seen at the input is much longer than that of a non-compensated off-line rectifier, resulting in lower distortion and a power factor of up to 0.95.

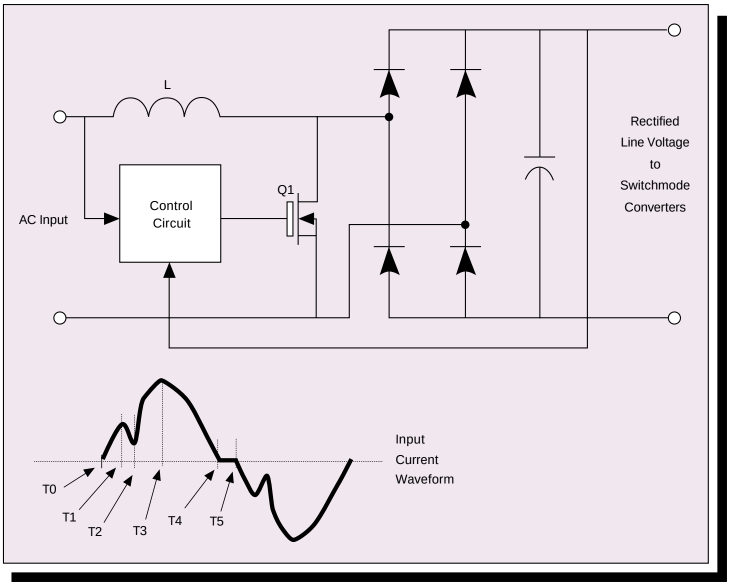


Figure 4.9 - Slow Switching Active PFC Circuit

This circuit is much simpler than the high frequency circuit to be discussed next, but has a few shortcomings in addition to its limited maximum power factor. Since the switching activity is usually in the 100Hz to 500Hz range, there can be audible noise associated with its operation. Also, a large and heavy line frequency inductor is required. The advantages and disadvantages of the slow switching approach are summarized in Figure 4.10.

Advantages	Disadvantages
Simple	Line Frequency Components are Large and Heavy
Cost Effective at Low Power	Cannot Completely Correct Nonlinear Loads - 95% Maximum Power Factor
High Efficiency - 98% Typical	Audible Noise
Low EMC due to Inductor	

Figure 4.10 - Advantages and Disadvantages of Slow Switching Active PFC

High frequency topologies - Conceptually, any of the popular basic converter topologies, including the flyback and buck, could be used as a PFC stage. We will focus, however, on the boost topology since it is the most popular implementation. There are several possible control techniques that can be used to implement a boost PFC converter, but the version shown in Figure 4.11 is a good general representation of the concept and will be used here for illustration.

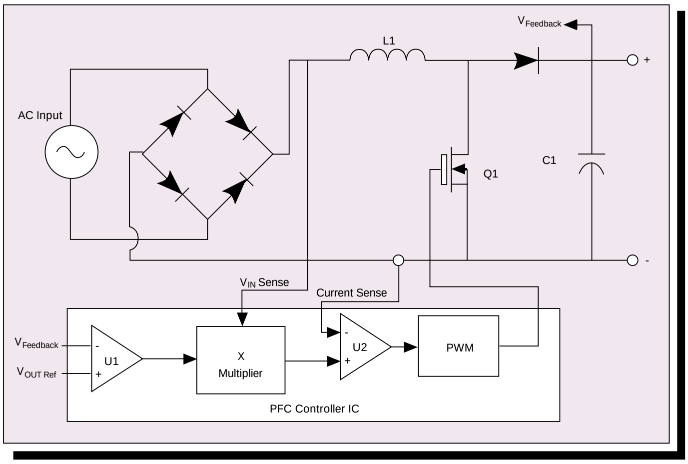


Figure 4.11 - High Frequency Active PFC Circuit

Almost all present day boost PFC converters utilize a standard controller chip for the purposes of ease of design, reduced circuit complexity and cost savings. These ICs are available from many of the analog IC suppliers and greatly simplify the process of achieving a reliable high-performance circuit. In order for the converter to achieve power factor correction over the entire range of input line voltages, the converter (in the PFC circuit) must be designed so that the output voltage, V_{OUT} is greater than the peak of the input line voltage*. Assuming a maximum line voltage of 240Vrms and allowing for at least a 10% margin results in a nominal V_{OUT} in the vicinity of 380 Vdc. V_{OUT} is regulated via feedback to the operational amplifier U1. The sensed VIN will be in the form of a rectified sine wave, which accurately reflects the instantaneous value of the input AC voltage. This signal is used as in input to the multiplier along with the V_{OUT} error voltage to formulate a voltage that is proportional to the desired current. This signal is then compared with the sensed actual converter current to form the error signal that drives the converter switch Q1. The result is that the input current waveform will track the AC input voltage waveform almost perfectly. By definition, this constitutes a power factor approaching

---

* Because of the boost topology - the opposite is the case for a buck converter.

unity. The active boost circuit will correct for deficiencies in both displacement and distortion.

During operation of the converter, the duty cycle will vary greatly during each half cycle of the input AC waveform. The duty cycle will be the longest when the instantaneous value of the AC is near zero and will be very short during the peaks of each half cycle. The voltage stress on the switch Q1 is equal to only V_{OUT} and the current levels are reasonable, resulting in an economical device selection. Since Q1 is referenced to ground, its control and driver circuits are relatively straightforward and easy to implement. The inductor L1 assists in reducing EMC from the converter and in suppressing some input transients from the powerline. It is not large enough in value, however, to be considered as protection from start-up inrush current, which must be provided by other methods.

This circuit, of course, is much more complex than the other PFC techniques we have considered. However, there are some additional benefits to be derived from its use. The topology allows for inclusion of automatic range switching on the AC input at essentially no extra cost. Since this universal input function is now a requirement on the majority of power converters to allow for operation in all countries without any manual settings, this feature helps offset the cost of the additional componentry for the PFC function. Because the circuit operates at high frequencies, typically over 100kHz, the components, including the inductor L1, tend to be small and light and much more conducive to automated manufacturing. The relatively high output voltage is actually an advantage for the down-converter following the boost stage. The current levels in the silicon and transformer of the down-converter are modest, resulting in lower cost devices. The efficiency of the active boost circuit is very high, approaching 95%. However, it will constitute a second conversion stage in some applications and can somewhat degrade the overall power conversion efficiency compared to a solution without PFC.

Considering all the tradeoffs, the active boost is a very good solution for many applications, especially where the power level is high enough so that the cost of the extra components is not a big percentage of the total cost. Its advantages and disadvantages are summarized in Figure 4.12.

Advantages	Disadvantages
High Power Factor ≈ 0.99	Complexity
Corrects both Distortion and Displacement Autoranging	V_{OUT} has to be > Peak V_{IN} ≈ 380 Vdc
Circuit includes Input Voltage	Cost for Low Power Applications
Regulated V_{OUT}	Adds 2nd Conversion Stage in some cases and Decreases Efficiency
Small and Light Components	No Inrush Current Limiting
Good EMC Characteristics	
Absorbs Some Line Transients	
Design Supported by Standard Controller ICs	
Low Stresses on Switching Devices	

Figure 4.12 - Advantages and Disadvantages of High Frequency Active PFC

4.7 Harmonic Current Emission Standards

As we have seen, PFC techniques are used to reduce the harmonic current content on the powerline as well as to correct the power factor and, in this context, they are often required in order to meet the appropriate international conducted emission EMC requirements. In this section we will summarize the present standards that relate to conducted harmonic emissions as well as mention proposals that are presently being formulated that will change the requirements for the future. We will also discuss which of the PFC techniques and strategies are useful for meeting these standards.

European standards tend to be the most severe due to the high density of both people and electronic equipment and the desire to have a common design base for equipment sold anywhere within the European Community. When designing for an international market, therefore, a common strategy is to design to the latest European standards. Such designs tend to be marketable in most developed countries. Except for stand-alone power supply units, the harmonic current standards technically need to be met only at the end equipment level and would not apply to power converters inside the equipment. As a practical matter, however, the appropriate harmonic correction is often most easily done within the power supply unit. Because of this, harmonic current standards are demanded and specified as part of the power supply by the OEM in the case of custom designs, and included as a part of many of Artesyn's standard AC/DC converters intended for application in systems that require adherence to the harmonic standards.

It will be useful to define some of the acronyms and agency names that are associated with harmonic current standards before proceeding. The majority of electronic standards are first drafted and developed by the International Electrotechnical Commission (IEC). These standards are then free to be adopted by any countries that desire to use them. In the case of the European Community, adopted IEC standards are referred to as European Norms (EN). It is commonplace to see the same suffix numbers on both documents. For example, EN61000-3-2 would be the equivalent European Community standard to IEC 61000-3-2. The European standards agency that develops ENs is the European Committee for Electrotechnical Standardization (CENELEC).

The standard that forms the foundation for both present and proposed future harmonic current standards is IEC 555 (now IEC 61000-3-2). IEC 555 was first released in draft form in 1982, has since received a number of revisions, and is presently considered the de-facto worldwide harmonic current emission standard for commercial equipment. The latest version, EN61000-3-2, is discussed in this section. Artesyn power supplies intended for use in high power factor applications are completely compliant with this new standard.

EN61000-3-2 applies to equipment with input power in the range 75W and 1000W and divides equipment into four classes, only two of which will apply to power conversion applications. The four classes are summarized below along with some general information about the harmonic current limits for each. Note that some classes contain exceptions and other sub-divisions and that the information here is only a broad-brush characterization of their content and requirements. Please refer to the standard for additional detail.

Class A - Contains equipment with balanced three phase power and also all equipment that does not fall into Class B, C or D. There are restrictions on both odd and even order harmonics, and these restrictions are expressed in terms of absolute maximum values of current for each harmonic. For off-line rectifier applications, only the odd order harmonics will be a consideration, and they are summarized in Figure 4.13.

Harmonic Number	**Class A Limits (A)**	**Class D Limits (mA / W)**	**Class D Limits for 100 W Input (A)**
3	2.30	3.4	0.34
5	1.14	1.9	0.19
7	0.77	1.0	0.10
9	0.40	0.5	0.05
11	0.33	0.35	0.035
13 ≤ n ≤ 39	0.15 x 15 / n	3.85 / n	0.385 / n

Figure 4.13 - Class A vs. Class D Odd Harmonic Current Limits

Class B - Contains portable tools and similar equipment. Harmonic current limits are absolute maximum values and are approximately 50% higher than the limits for Class A.

Class C - Contains lighting equipment including dimmers and gas discharge lamps. There are limits on the second harmonic and also all odd harmonics. The limits are expressed in terms of a percentage of the fundamental current.

Class D - The situation regarding Class D compliance is complicated by having dual standards. These standards will co-exist until 1st January 2004, at which the older EN61000-3-2 will be replaced by EN61000-3-2 with prA14. This is explained in more detail in a seperate bulletin on the Artesyn website (www.artesyn.com).

4.7.1 Class D limits according to EN61000-3-2

According to this version of the legislation Class D contains all equipment whose input current waveform conforms to the requirements shown in Figure 4.14. The requirements are defined such that equipment using an uncompensated off-line rectifier with a capacitive filter will be considered as Class D. The current limits for Class D are expressed in terms of mA per Watt of power consumed. Consequently, low power equipment has very low absolute limits of harmonic current. The limits for odd order harmonics are shown in Figure 4.13.

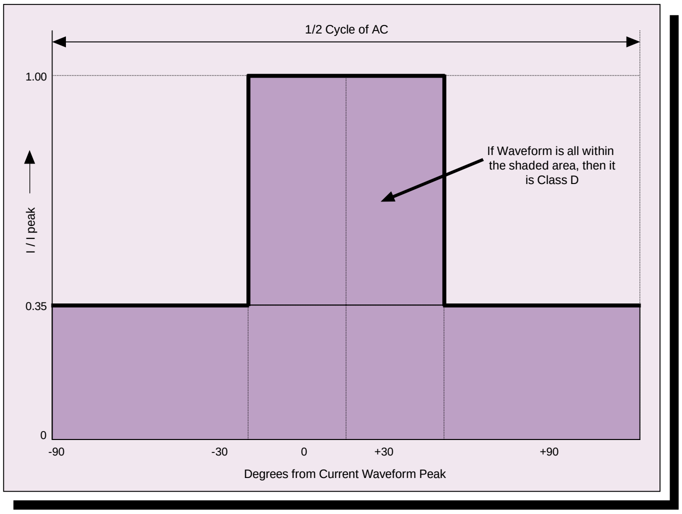


Figure 4.14 - Input Current Waveform Criterion for Class D

Power converters will thus be either Class D or Class A depending upon the shape of the input current waveform. High distortion factors will fall into Class D, while lesser distortion will allow for inclusion into Class A. There is an advantage to be in Class A, since, at power levels less than approximately 600W, the absolute limit for each odd harmonic will be higher than that based on the mA per Watt limit calculated for Class D. The lower the power level, the greater this advantage will be. For example, the absolute limits for Class D at a power level of 100W are shown in the rightmost column of Figure 4.13. Note the much higher limits for Class A. For the third harmonic, for example, the Class A limit is 2.3 A vs. a value of 0.34 A for Class D, a 6.7 times increase.

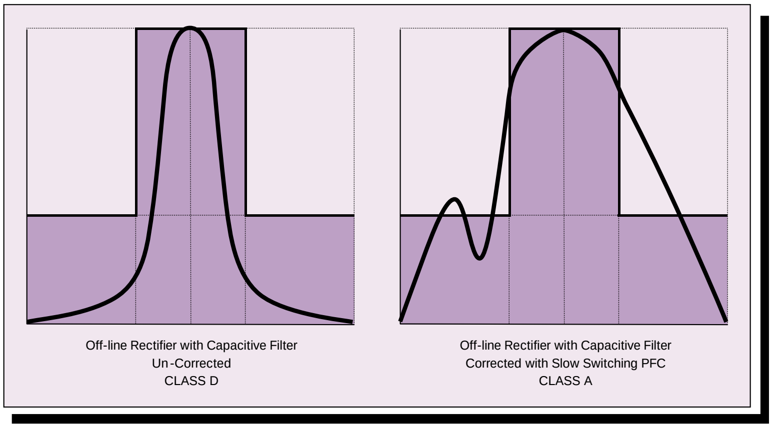
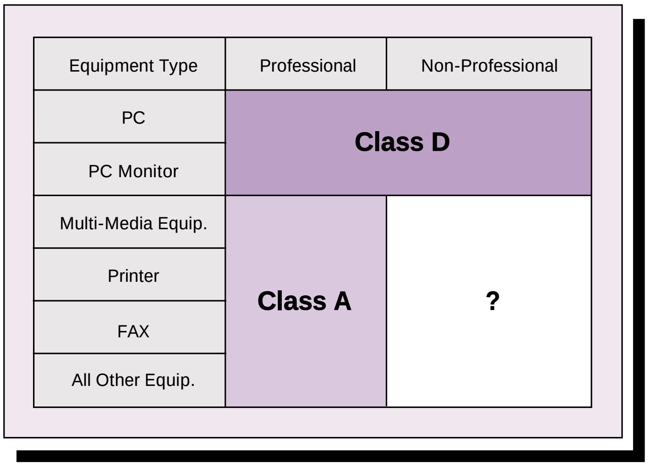


Figure 4.15 - Moving From Class D to Class A by Modifying Current Waveform

This advantage for being in Class A rather than Class D has lead to another approach to meeting the harmonic current standards. If the input current waveform on a Class D power converter can be modified, sometimes only slightly, so that it no longer falls into the Class D criteria, the converter can be considered to be Class A. This can be accomplished with either passive or slow-switching active techniques. Figure 4.15 shows an example of using this approach. This technique can be used as a low cost way to make a system compliant to harmonic standards, but note that it will not result in unity power factor and there will still be a fair amount of remaining distortion to the waveform. Consequently, most high performance systems still tend to use high frequency active techniques in order to maximize the power factor, minimize distortion and draw the maximum available useful power from the powerline.

4.7.2 Class D limits according to EN61000-3-2 prA14

This amendment to the EN legislation modifies EN61000-3-2 to allow for the removal of some types of equipment from the more severe Class D limits. Note, however, that any equipment shown to have a significiant effect on the supply system may be reclassified in a future revision of the legislation. In fact, the local authority can refuse connection even for eqipment meeting the legislation if mains supply is already over loaded. Refer to the bulletin on the Artesyn website (www.artesyn.com) for more details. This interim solution is being referred to as 'the Common Modification to EN 61000-3-2'. Figure 4.16 illustrates how this legislation affects various equipment types. Therefore, according to prA14, only PCs and PC monitors remain in class D (assuming that the power level is less than 600W). However, it could be that some types of equipment in the questionable area could end up as Class D. In the meantime, many manufacturers of systems and power supplies are hedging their bets by designing to the more conservative limits. Artesyn will attempt to keep you informed as to the latest status by publishing bulletins and updates on their website (www.artesyn.com). The information on the website should be considered more current than what is published here.



<table>
<tr><th>Equipment Type</th><th>Professional</th><th>Non-Professional</th></tr>
<tr><td>PC</td><td colspan="2" rowspan="2">Class D</td></tr>
<tr><td>PC Monitor</td></tr>
<tr><td>Multi-Media Equip.</td><td rowspan="4">Class A</td><td rowspan="4">?</td></tr>
<tr><td>Printer</td></tr>
<tr><td>FAX</td></tr>
<tr><td>All Other Equip.</td></tr>
</table>

Figure 4.16 - Status of Common Modification to EN 61000-3-2