Power Factor Correction

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Introduction

The conventional power factor correction circuit has a fixed output voltage. However, insome applications, a PFC circuit with a wide output voltage range is needed. A singlephase power factor correction circuit with wide output voltage range is developed in this work.After a comparison of two main power stage candidates (Buck+Boost and Sepic) in terms of efficiency, complexity, cost and device rating, the buck+boost converter is employed as the variable output PFC power stage. From the loss analysis, this topology has a high efficiency from light load to heavy load.The control system of the variable output PFC circuit is analyzed and designed. Charge average current sensing scheme has been adopted to sense the input current. The problem of high input harmonic currents at low output voltage is discussed. It is found that the current loop gain and cross over frequency will change greatly when the output voltage changes. To solve this problem, an automatic gain control scheme is proposed and a detailed circuit is designed and added to the current loop. A modified input current sensing scheme is presented to overcome the problem of an insufficient phase margin of the PFC circuit near the maximum output voltage. The charge average current sensing circuit will be bypassed automatically by a logical circuit
when the output voltage is higher than the peak line voltage. Instead, a resistor is used to sense the input current at that condition. Therefore, the phase delay caused by the charge average current sensing circuit is avoided.
The design and analysis are based on a novel air conditioner motor system application.Some detailed design issues are discussed. The experimental results show that the variable output PFC circuit has good performance in the wide output voltage range, under both the Boost mode when the output voltage is high and the Buck+Boost mode when the output voltage is low.

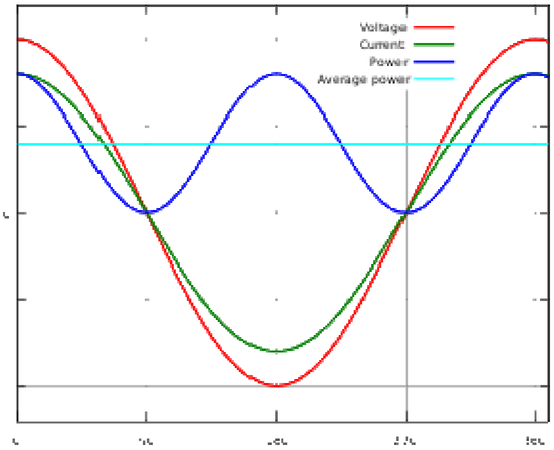
The **power factor** of an AC electric power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit, and is a dimensionless number between 0 and 1. Real power is the capacity of the circuit for performing work in a particular time. Apparent power is the product of the current and voltage of the circuit. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power will be greater than the real power.

In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, electrical utilities will usually charge a higher cost to industrial or commercial customers where there is a low power factor.

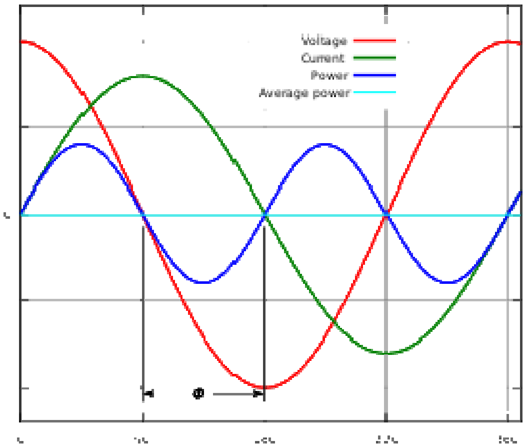
Linear loads with low power factor (such as induction motors) can be corrected with a passive network of capacitors or inductors. Non-linear loads, such as rectifiers, distort the current drawn from the system. In such cases, active or passive power factor correction may be used to counteract the distortion and raise the power factor. The devices for correction of the power factor may be at a central substation, spread out over a distribution system, or built into power-consuming equipment.

Contents

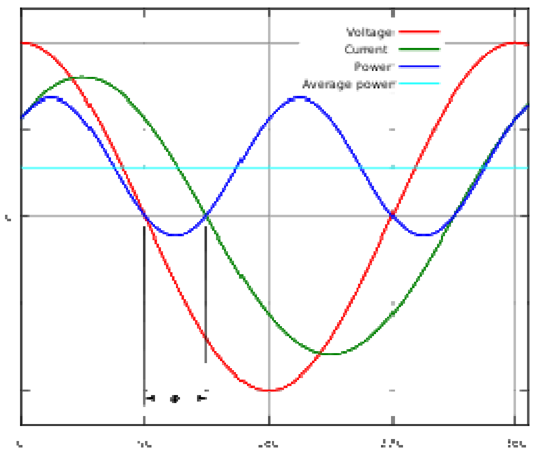
Linear circuits



Instantaneous and average power calculated from AC voltage and current with a unity power factor ($\varphi = 0$, $\cos\varphi = 1$). Since the blue line is above the axis, all power is real power consumed by the load.



Instantaneous and average power calculated from AC voltage and current with a zero power factor ($\varphi = 90$, $\cos\varphi = 0$). The blue line shows all the power is stored temporarily in the load during the first quarter cycle and returned to the grid during the second quarter cycle, so no real power is consumed.



Instantaneous and average power calculated from AC voltage and current with a lagging power factor ($\varphi = 45$, $\cos\varphi = 0.71$). The blue line shows some of the power is returned to the grid during the part of the cycle labelled φ

In a purely resistive AC circuit, voltage and current waveforms are in step (or in phase), changing polarity at the same instant in each cycle. All the power entering the load is consumed. Where reactive loads are present, such as with capacitors or inductors, energy storage in the loads result in a time difference between the current and voltage waveforms. During each cycle of the AC voltage, extra energy, in addition to any energy consumed in the load, is temporarily stored in the load in electric or magnetic fields, and then returned to the power grid a fraction of a second later in the cycle. The "ebb and flow" of this nonproductive power increases the current in the line. Thus, a circuit with a low power factor will use higher currents to transfer a given quantity of real power than a circuit with a high power factor. A linear load does not change the shape of the waveform of the current, but may change the relative timing (phase) between voltage and current.

Circuits containing purely resistive heating elements (filament lamps, cooking stoves, etc.) have a power factor of 1.0. Circuits containing inductive or capacitive elements (electric motors, solenoid valves, lamp ballasts, and others) often have a power factor below 1.0.

Definition and calculation

AC power flow has the three components: real power (also known as active power) (P), measured in watts (W); apparent power (S), measured in volt-amperes (VA); and reactive power (Q), measured in reactive volt-amperes (var).

The power factor is defined as:

$$\frac{P}{S}.$$

In the case of a perfectly sinusoidal waveform, P, Q and S can be expressed as vectors that form a vector triangle such that:

$$S^2 = P^2 + Q^2.$$

If φ is the phase angle between the current and voltage, then the power factor is equal to the cosine of the angle, $|\cos\varphi|$, and:

$$|P| = |S|\,|\cos\varphi|\,.$$

Since the units are consistent, the power factor is by definition a dimensionless number between 0 and 1. When power factor is equal to 0, the energy flow is entirely reactive, and stored energy in the load returns to the source on each cycle. When the power factor is 1, all the energy supplied by the source is consumed by the load. Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle.

If a purely resistive load is connected to a power supply, current and voltage will change polarity in step, the power factor will be unity (1), and the electrical energy flows in a single direction across the network in each cycle. Inductive loads such as transformers and motors (any type of wound coil) consume reactive power with current waveform lagging the voltage. Capacitive loads such as capacitor banks or buried cable generate reactive power with current phase leading the voltage. Both types of loads will absorb energy during part of the AC cycle, which is stored in the device's magnetic or electric field, only to return this energy back to the source during the rest of the cycle.

For example, to get 1 kW of real power, if the power factor is unity, 1 kVA of apparent power needs to be transferred (1 kW ÷ 1 = 1 kVA). At low values of power factor, more apparent power needs to be transferred to get the same real power. To get 1 kW of real power at 0.2 power factor, 5 kVA of apparent power needs to be transferred (1 kW ÷ 0.2 = 5 kVA). This apparent power must be produced and transmitted to the load in the conventional fashion, and is subject to the usual distributed losses in the production and transmission processes.

Electrical loads consuming alternating current power consume both real power and reactive power. The vector sum of real and reactive power is the apparent power. The presence of reactive power causes the real power to be less than the apparent power, and so, the electric load has a power factor of less than 1.

Power factor correction of linear loads

A high power factor is generally desirable in a transmission system to reduce transmission losses and improve voltage regulation at the load. It is often desirable to adjust the power factor of a system to near 1.0. When reactive elements supply or absorb reactive power near the load, the apparent power is reduced. Power factor correction may be applied by an electrical power transmission utility to improve the stability and efficiency of the transmission network. Individual electrical customers who are charged by their utility for low power factor may install correction equipment to reduce those costs.

Power factor correction brings the power factor of an AC power circuit closer to 1 by supplying reactive power of opposite sign, adding capacitors or inductors that act to cancel the inductive or capacitive effects of the load, respectively. For example, the inductive effect of motor loads may be offset by locally connected capacitors. If a load had a capacitive value, inductors (also known as *reactors* in this context) are connected to correct the power factor. In the electricity industry, inductors are said to *consume* reactive power and capacitors are said to *supply* it, even though the energy is just moving back and forth on each AC cycle.

The reactive elements can create voltage fluctuations and harmonic noise when switched on or off. They will supply or sink reactive power regardless of whether there is a corresponding load operating nearby, increasing the system's no-load losses. In the worst case, reactive elements can interact with the system and with each other to create resonant conditions, resulting in system instability and severe overvoltage fluctuations. As such, reactive elements cannot simply be applied without engineering analysis.

1. Reactive Power Control Relay;
2. Network connection points;
3. Slow-blow Fuses;
4. Inrush Limiting Contactors;
5. Capacitors (single-phase or three-phase units, delta-connection);
6. Transformer for controls and ventilation fans)

An **automatic power factor correction unit** consists of a number of capacitors that are switched by means of contactors. These contactors are controlled by a regulator that measures power factor in an electrical network. Depending on the load and power factor of the network, the power factor controller will switch the necessary blocks of capacitors in steps to make sure the power factor stays above a selected value.

Instead of using a set of switched capacitors, an unloaded synchronous motor can supply reactive power. The reactive power drawn by the synchronous motor is a function of its field excitation. This is referred to as a *synchronous condenser*. It is started and connected to the electrical network. It operates at a leading power factor and puts vars onto the network as required to support a system's voltage or to maintain the system power factor at a specified level.

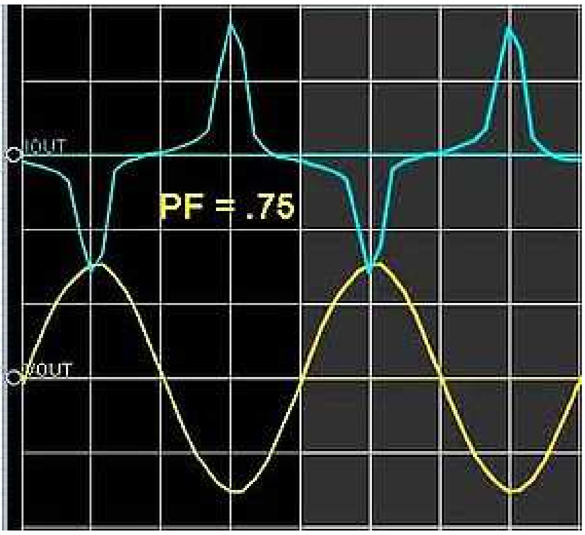
The condenser's installation and operation are identical to large electric motors. Its principal advantage is the ease with which the amount of correction can be adjusted; it behaves like an electrically variable capacitor. Unlike capacitors, the amount of reactive power supplied is proportional to voltage, not the square of voltage; this improves voltage stability on large networks. Synchronous condensors are often used in connection with high-voltage direct-current transmission projects or in large industrial plants such as steel mills.

For power factor correction of high-voltage power systems or large, fluctuating industrial loads, power electronic devices such as the Static

VAR compensator or STATCOM are increasingly used. These systems are able to compensate sudden changes of power factor much more rapidly than contactor-switched capacitor banks, and being solid-state require less maintenance than synchronous condensers.

Non-linear loads

A non-linear load on a power system is typically a rectifier (such as used in a power supply), or some kind of arc discharge device such as a fluorescent lamp, electric welding machine, or arc furnace. Because current in these systems is interrupted by a switching action, the current contains frequency components that are multiples of the power system frequency. Distortion power factor is a measure of how much the harmonic distortion of a load current decreases the average power transferred to the load.



Sinusoidal voltage and non-sinusoidal current give a distortion power factor of 0.75 for this computer power supply load.

Non-sinusoidal components

Non-linear loads change the shape of the current waveform from a sine wave to some other form. Non-linear loads create harmonic currents in addition to the original (fundamental frequency) AC current. Filters consisting of linear capacitors and inductors can prevent harmonic currents from entering the supplying system.

In linear circuits having only sinusoidal currents and voltages of one frequency, the power factor arises only from the difference in phase between the current and voltage. This is "displacement power factor". The concept can be generalized to a total, distortion, or true power factor where the apparent power includes all harmonic components. This is of importance in practical power systems that contain non-linear loads such as rectifiers, some forms of electric lighting, electric arc furnaces, welding equipment, switched-mode power supplies and other devices.

A typical multimeter will give incorrect results when attempting to measure the AC current drawn by a non-sinusoidal load; the instruments sense the average value of a rectified waveform. The average response is then calibrated to the effective, RMS value. An RMS sensing multimeter must be used to measure the actual RMS currents and voltages (and therefore apparent power). To measure the real power or reactive power, a watt meter designed to work properly with non-sinusoidal currents must be used.

Distortion power factor

The *distortion power factor* describes how the harmonic distortion of a load current decreases the average power transferred to the load.

$$\text{distortion power factor} = \frac{1}{\sqrt{1+\mathrm{THD}_i^2}} = \frac{I_{1,\,\mathrm{rms}}}{I_{\mathrm{rms}}}$$

$\mathrm{THD}_i$is the total harmonic distortion of the load current. This definition assumes that the voltage stays undistorted (sinusoidal, without harmonics). This simplification is often a good approximation in practice. $I_{1,\mathrm{rms}}$is the fundamental component of the current and $I_{\mathrm{rms}}$is the total current - both are root mean square-values.

The result when multiplied with the displacement power factor (DPF) is the overall, true power factor or just power factor (PF):

$$\mathrm{PF} = \mathrm{DPF}\frac{I_{1,\,\mathrm{rms}}}{I_{\mathrm{rms}}}$$

Switched-mode power supplies

A particularly important class of non-linear loads is the millions of personal computers that typically incorporate switched-mode power supplies (SMPS) with rated output power ranging from a few watts to more than 1 kW. Historically, these very-low-cost power supplies incorporated a simple full-wave rectifier that conducted only when the mains instantaneous voltage exceeded the voltage on the input capacitors. This leads to very high ratios of peak-to-average input current, which also lead to a low distortion power factor and potentially serious phase and neutral loading concerns.

A typical switched-mode power supply first makes a DC bus, using a bridge rectifier or similar circuit. The output voltage is then derived from this DC bus. The problem with this is that the rectifier is a non-linear device, so the input current is highly non-linear. That means that the input current has energy at harmonics of the frequency of the voltage.

This presents a particular problem for the power companies, because they cannot compensate for the harmonic current by adding simple capacitors or inductors, as they could for the reactive power drawn by a linear load. Many jurisdictions are beginning to legally require power factor correction for all power supplies above a certain power level.

Regulatory agencies such as the EU have set harmonic limits as a method of improving power factor. Declining component cost has hastened implementation of two different methods. To comply with current EU standard EN61000-3-2, all switched-mode power supplies with output power more than 75 W must include passive PFC, at least. 80 PLUS power supply certification requires a power factor of 0.9 or more.

Power factor correction in non-linear loads

Passive PFC

The simplest way to control the harmonic current is to use a filter: it is possible to design a filter that passes current only at line frequency (50 or 60 Hz). This filter reduces the harmonic current, which means that the non-linear device now looks like a linear load. At this point the power factor can be brought to near unity, using capacitors or inductors as required. This filter requires large-value high-current inductors, however, which are bulky and expensive.

A passive PFC requires an inductor larger than the inductor in an active PFC, but costs less.

This is a simple way of correcting the nonlinearity of a load by using capacitor banks. It is not as effective as active PFC

Passive PFCs are typically more power efficient than active PFCs. *Efficiency* is not to be confused with the PFC, though many computer hardware reviews conflate them. A passive PFC on a switching computer PSU has a typical power efficiency of around 96%, while an active PFC has a typical efficiency of about 94%.

Active PFC

An "active power factor corrector" (active PFC) is a power electronic system that changes the waveshape of current drawn by a load to improve the power factor. The purpose is to make the load circuitry that is power factor corrected appear purely resistive (apparent power equal to real power). In this case, the voltage and current are in phase and the reactive power consumption is zero. This enables the most efficient delivery of electrical power from the power company to the consumer.

Specifications taken from the packaging of a 610W PC power supply showing Active PFC rating

Some types of active PFC are:

- Boost
- Buck
- Buck-boost

Active power factor correctors can be single-stage or multi-stage.

In the case of a switched-mode power supply, a boost converter is inserted between the bridge rectifier and the main input capacitors. The boost converter attempts to maintain a constant DC bus voltage on its output while drawing a current that is always in phase with and at the same frequency as the line voltage. Another switchmode converter inside the power supply produces the desired output voltage from the DC bus. This approach requires additional semiconductor switches and control electronics, but permits cheaper and smaller passive components. It is frequently used in practice. For example, SMPS with passive PFC can achieve power factor of about 0.7–0.75, SMPS with active PFC, up to 0.99 power factor, while a SMPS without any power factor correction has a power factor of only about 0.55–0.65.

Due to their very wide input voltage range, many power supplies with active PFC can automatically adjust to operate on AC power from about 100 V (Japan) to 230 V (Europe). That feature is particularly welcome in power supplies for laptops.

Importance of power factor in distribution systems

Power factors below 1.0 require a utility to generate more than the minimum volt-amperes necessary to supply the real power (watts). This increases generation and transmission costs. For example, if the load power factor were as low as 0.7, the apparent power would be 1.4 times the real power used by the load. Line current in the circuit would also be 1.4 times the current required at 1.0 power factor, so the losses in the circuit would be doubled (since they are proportional to the square of the current). Alternatively all components of the system such as generators, conductors, transformers, and switchgear would be increased in size (and cost) to carry the extra current.

Utilities typically charge additional costs to customers who have a power factor below some limit, which is typically 0.9 to 0.95. Engineers are often interested in the power factor of a load as one of the factors that affect the efficiency of power transmission.

With the rising cost of energy and concerns over the efficient delivery of power, active PFC has become more common in consumer electronics. Current Energy Star guidelines for computers (ENERGY STAR Program Requirements for Computers Version 5.0) call for a power factor of ≥ 0.9 at 100% of rated output in the PC's power supply. According to a white paper authored by Intel and the U.S. Environmental Protection Agency, PCs with internal power supplies will require the use of active power factor correction to meet the ENERGY STAR 5.0 Program Requirements for Computers.

In Europe, IEC 555-2 requires power factor correction be incorporated into consumer products.

Measuring power factor

Power factor in a single-phase circuit (or balanced three-phase circuit) can be measured with the wattmeter-ammeter-voltmeter method, where the power in watts is divided by the product of measured voltage and current. The power factor of a balanced polyphase circuit is the same as that of any phase. The power factor of an unbalanced polyphase circuit is not uniquely defined.

A direct reading power factor meter can be made with a moving coil meter of the electrodynamic type, carrying two perpendicular coils on the moving part of the instrument. The field of the instrument is energized by the circuit current flow. The two moving coils, A and B, are connected in parallel with the circuit load. One coil, A, will be connected through a resistor and the second coil, B, through an inductor, so that the current in coil B is delayed with respect to current in A. At unity power factor, the current in A is in phase with the circuit current, and coil A provides maximum torque, driving the instrument pointer toward the 1.0 mark on the scale. At zero power factor, the current in coil B is in phase with circuit current, and coil B provides torque to drive the pointer towards 0. At intermediate values of power factor, the torques provided by the two coils add and the pointer takes up intermediate positions.

Another electromechanical instrument is the polarized-vane type. In this instrument a stationary field coil produces a rotating magnetic field, just like a polyphase motor. The field coils are connected either directly to polyphase voltage sources or to a phase-shifting reactor if a single-phase application. A second stationary field coil, perpendicular to the voltage coils, carries a current proportional to current in one phase of the circuit. The moving system of the instrument consists of two vanes that are magnetized by the current coil. In operation the moving vanes take up a physical angle equivalent to the electrical angle between the voltage source and the current source. This type of instrument can be made to register for currents in both directions, giving a four-quadrant display of power factor or phase angle.

Digital instruments can be made that either directly measure the time lag between voltage and current waveforms and so calculate the power factor, or by measuring both true and apparent power in the circuit and calculating the quotient. The first method is only accurate if voltage and current are sinusoidal; loads such as rectifiers distort the waveforms from the sinusoidal shape.

Mnemonics

English-language power engineering students are advised to remember: "ELI the ICE man" or "ELI on ICE" – the voltage E leads the current I in an inductor L, the current leads the voltage in a capacitor C.

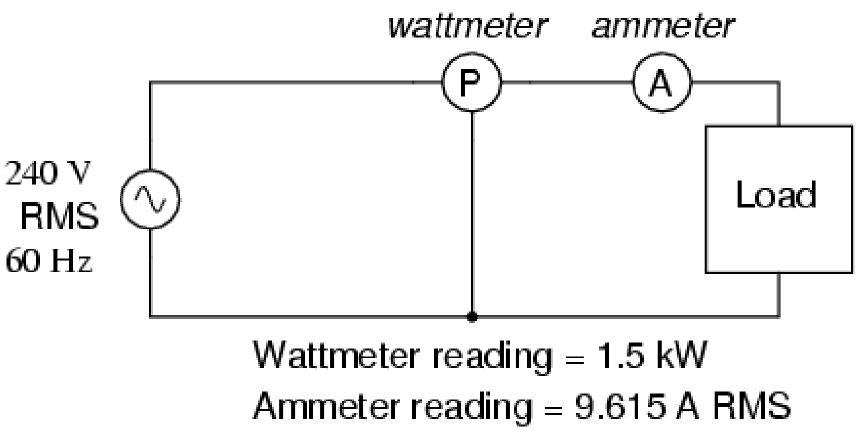
Another common mnemonic is CIVIL – in a capacitor (C) the current (I) leads voltage (V), voltage (V) leads current (I) in an inductor (L).

- Power Factor Correction Application Guide
- Power Factor Correction Whitepaper
- Lessons In Electric Circuits - POWER FACTOR
- ON Semiconductor Power Factor Correction Handbook
- Harmonics and how they relate to power factor
- NIST Team Demystifies Utility of Power Factor Correction Devices, NIST, December 15, 2009

Practical power factor correction

When the need arises to correct for poor power factor in an AC power system, you probably won't have the luxury of knowing the load's exact inductance in henrys to use for your calculations. You may be fortunate enough to have an instrument called a *power factor meter* to tell you what the power factor is (a number between 0 and 1), and the apparent power (which can be figured by taking a voltmeter reading in volts and multiplying by an ammeter reading in amps). In less favorable circumstances you may have to use an oscilloscope to compare voltage and current waveforms, measuring phase shift in *degrees* and calculating power factor by the cosine of that phase shift.

Most likely, you will have access to a wattmeter for measuring true power, whose reading you can compare against a calculation of apparent power (from multiplying total voltage and total current measurements). From the values of true and apparent power, you can determine reactive power and power factor. Let's do an example problem to see how this works: (Figure below)



Wattmeter reads true power; product of voltmeter and ammeter readings yields appearant power.

First, we need to calculate the apparent power in kVA. We can do this by multiplying load voltage by load current:

$$S = IE$$

$$S = (9.615\ \mathrm{A})(240\ \mathrm{V})$$

$$S = 2.308\ \mathrm{kVA}$$

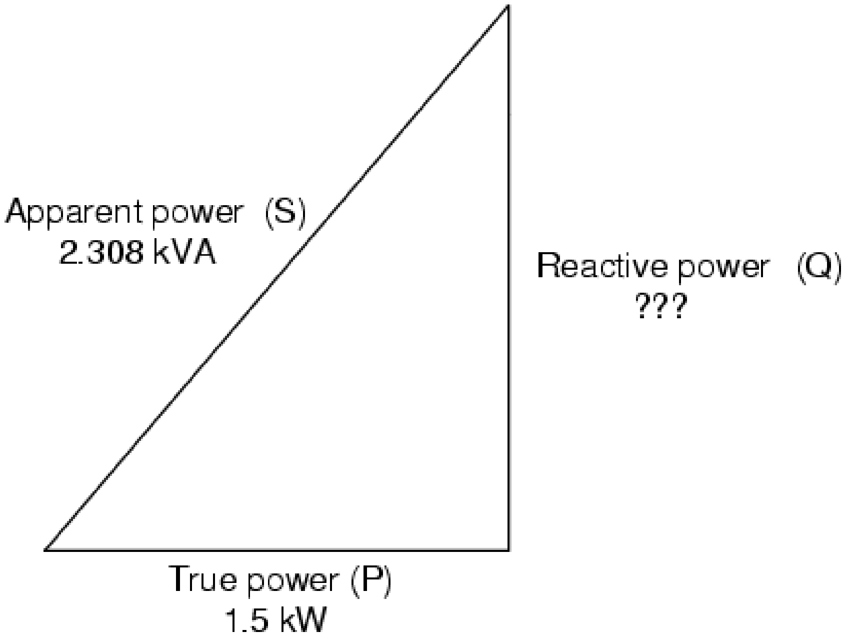
As we can see, 2.308 kVA is a much larger figure than 1.5 kW, which tells us that the power factor in this circuit is rather poor (substantially less than 1). Now, we figure the power factor of this load by dividing the true power by the apparent power:

$$\text{Power factor} = \frac{P}{S}$$

$$\text{Power factor} = \frac{1.5\ \mathrm{kW}}{2.308\ \mathrm{kVA}}$$

$$\text{Power factor} = 0.65$$

Using this value for power factor, we can draw a power triangle, and from that determine the reactive power of this load: (Figure below)



Reactive power may be calculated from true power and appearant power.

To determine the unknown (reactive power) triangle quantity, we use the Pythagorean Theorem “backwards,” given the length of the hypotenuse (apparent power) and the length of the adjacent side (true power):

$$\text{Reactive power} = \sqrt{(\text{Apparent power})^2 - (\text{True power})^2}$$

$$Q = 1.754 \text{ kVAR}$$

If this load is an electric motor, or most any other industrial AC load, it will have a lagging (inductive) power factor, which means that we'll have to correct for it with a *capacitor* of appropriate size, wired in parallel. Now that we know the amount of reactive power (1.754 kVAR), we can calculate the size of capacitor needed to counteract its effects:

$$Q = \frac{E^2}{X}$$

. . . solving for X . . .

$$X = \frac{E^2}{Q}$$

$$X = \frac{(240)^2}{1.754 \text{ kVAR}}$$

$$X = 32.845 \ \Omega$$

$$X_C = \frac{1}{2\pi f C}$$

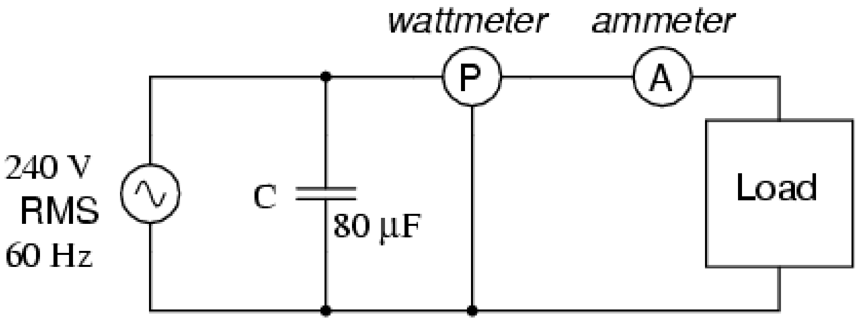
. . . solving for C . . .

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{2\pi(60 \text{ Hz})(32.845 \ \Omega)}$$

$$C = 80.761 \ \mu\text{F}$$

Rounding this answer off to 80 µF, we can place that size of capacitor in the circuit and calculate the results: (Figure below)



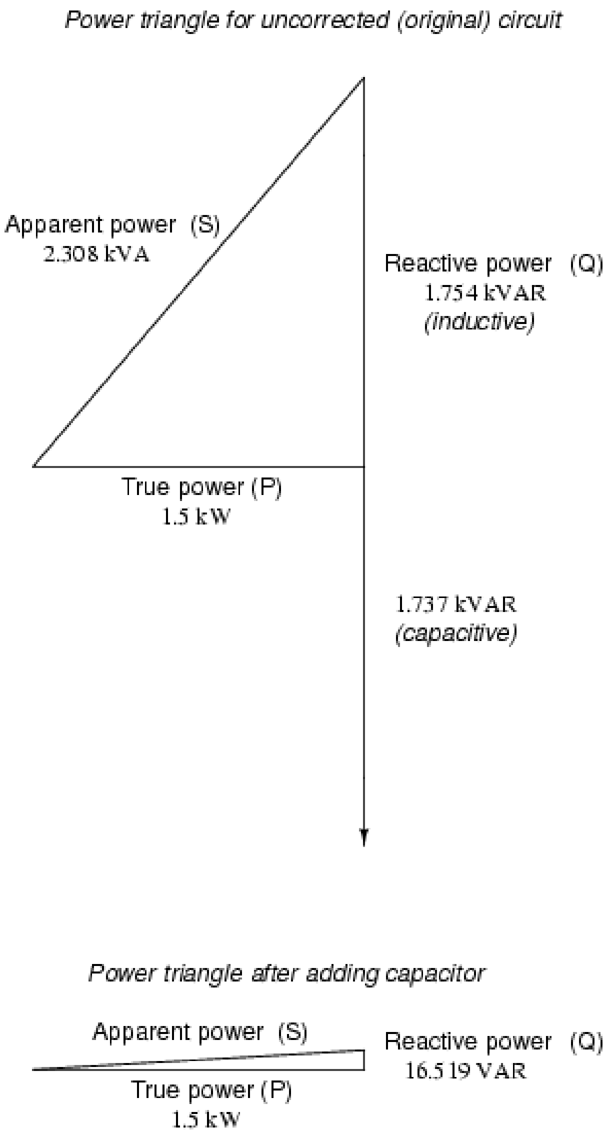
Parallel capacitor corrects lagging (inductive) load.

An 80 µF capacitor will have a capacitive reactance of 33.157 Ω, giving a current of 7.238 amps, and a corresponding reactive power of 1.737 kVAR (for the capacitor *only*). Since the capacitor's current is 180° out of phase from the the load's inductive contribution to current draw, the capacitor's reactive power will directly subtract from the load's reactive power, resulting in:

$$\text{Inductive kVAR} - \text{Capacitive kVAR} = \text{Total kVAR}$$

$$1.754 \text{ kVAR} - 1.737 \text{ kVAR} = 16.519 \text{ VAR}$$

This correction, of course, will not change the amount of true power consumed by the load, but it will result in a substantial reduction of apparent power, and of the total current drawn from the 240 Volt source: (Figure below)



Power triangle before and after capacitor correction.

The new apparent power can be found from the true and new reactive power values, using the standard form of the Pythagorean Theorem:

$$\text{Apparent power} = \sqrt{(\text{Reactive power})^2 + (\text{True power})^2}$$

$$\text{Apparent power} = 1.50009\ \text{kVA}$$

This gives a corrected power factor of (1.5kW / 1.5009 kVA), or 0.99994, and a new total current of (1.50009 kVA / 240 Volts), or 6.25 amps, a substantial improvement over the uncorrected value of 9.615 amps! This lower total current will translate to less heat losses in the circuit wiring, meaning greater system efficiency (less power wasted).

HARMONIC DISTORTION

The Harmonic Problem

Any device with non-linear operating characteristics can produce harmonics in your power system. If you are currently using equipment that can cause harmonics or have experienced harmonic related problems, capacitor reactor or filter bank equipment may be the solution.

Harmonic distortion and related problems in electrical power systems are becoming more and more prevalent in electrical distribution systems.

Problems Created by Harmonics

- Excessive heating and failure of capacitors, capacitor fuses, transformers, motors, fluorescent lighting ballasts, etc.
- Nuisance tripping of circuit breaker or blown fuses
- Presence of the third harmonic & multiples of the 3rd harmonic in neutral grounding systems may require the derating of neutral conductors
- Noise from harmonics that lead to erroneous operation of control system components
- Damage to sensitive electronic equipment
- Electronic communications interference

The following is a discussion of harmonics; the characteristics of the problem; and a discussion of our solution.

Origins of Harmonic Distortion

The ever increasing demand of industry and commerce for stability, adjustability and accuracy of control in electrical equipment led to the development of relatively low cost power diodes, thyristors, SCRs and other power semi-conductors. Now used widely in rectifier circuits for U.P.S. systems, static converters and A.C. & D.C. motor control, these modern devices replace the mercury arc rectifiers of earlier years and create new and challenging conditions for the power engineer of today.

Although solid state devices, such as the thyristor, have brought significant improvements in control designs and efficiency, they have the disadvantage of producing harmonic currents.

Harmonic currents can cause a disturbance on the supply network and adversely affect the operation of other electrical equipment including power factor correction capacitors.

We are concentrating our discussions on harmonic current sources associated with solid state power electronics but there are actually many other sources of harmonic currents. These sources can be grouped into three main areas:

1. Power electronic equipment: Variable speed drives (AC VFDÕs, DC drives, PWM drives, etc.); UPS systems, rectifiers, switch mode power supplies, static converters, thyristor systems, diode bridges, SCR controlled induction furnaces and SCR controlled systems.
2. Arcing equipment: Arc furnaces, welders, lighting (mercury vapor, fluorescent)
3. Saturable devices: Transformers, motors, generators, etc. The harmonic amplitudes on these devices are usually insignificant compared to power electronic and arcing equipment, unless saturation occurs.

Waveform

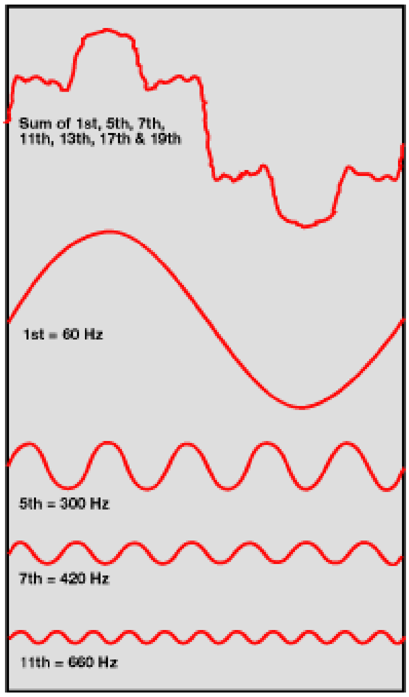
Harmonics are sinusoidal waves that are integral multiples of the fundamental 60 Hz waveform (i.e., 1st harmonic = 60 Hz; 5th harmonic = 300 Hz). All complex waveforms can be resolved into a series of sinusoidal waves of various frequencies, therefore any complex waveform is the sum of a number of odd or even harmonics of lesser or greater value. Harmonics are continuous (steady-state) disturbances or distortions on the electrical network and are a completely different subject or problem from line spikes, surges, sags, impulses, etc., which are categorized as transient disturbances.

Transient problems are usually solved by installing suppression or isolation devices such as surge capacitors, isolation transformers or M.O.V.s. These devices will help solve the transient problems but will not affect the mitigation of low order harmonics or solve harmonic resonance problems.

Harmonic Content

Thyristor and SCR converters are usually referred to by the number of DC current pulses they produce each cycle. The most commonly used are 6 pulse and 12 pulse.

ORDER OF HARMONIC	TYPICAL PERCENTAGE OF HARMONIC CURRENT	
-	6 Pulse	12 Pulse
1	100	100
5	20	-
7	14	-
11	9	9
12	8	8
17	6	-
19	5	-
23	4	4
23	4	4



There are many factors that can influence the harmonic content but typical harmonic currents, shown as a percentage of the fundamental current, are given in the above table. Other harmonics will always be present, to some degree, but for practical reasons they have been ignored.

Harmonic Overloading of Capacitors

The impedance of a circuit dictates the current flow in that circuit.

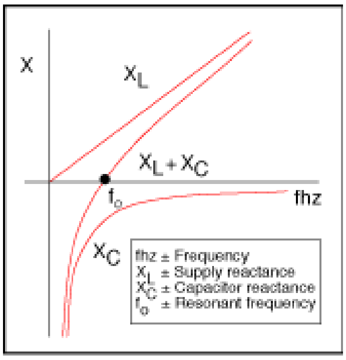
As the supply impedance is generally considered to be inductive, the network impedance increases with frequency while the impedance of a capacitor decreases. This causes a greater proportion of the currents circulating at frequencies above the fundamental supply frequency to be absorbed by the capacitor, and all equipment associated with the capacitor.

In certain circumstances, harmonic currents can exceed the value of the fundamental (60 Hz) capacitor current. These harmonic problems can also cause an increased voltage across the dielectric of the capacitor which could exceed the maximum voltage rating of the capacitor, resulting in premature capacitor failure.

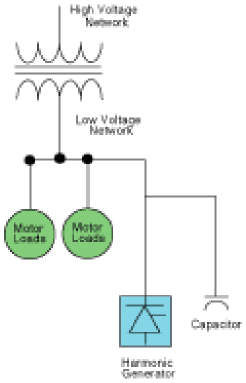
Harmonic Resonance

The circuit or selective resonant frequency is reached when the capacitor reactance and the supply reactance are equal.

Whenever power factor correction capacitors are applied to a distribution network, which combines capacitance and inductance, there will always be a frequency at which the capacitors are in parallel resonance with the supply.



If this condition occurs on, or close to, one of the harmonics generated by solid state control equipment, then large harmonic currents can circulate between the supply network and the capacitor equipment. These currents are limited only by the damping resistance in the circuit. Such currents will add to the harmonic voltage disturbance in the network causing an increased voltage distortion. This results in a higher voltage across the capacitor and excessive current through all capacitor components. Resonance can occur on any frequency, but in general, the resonance we are concerned with is on, or close to, the 5th, 7th, 11th and 13th harmonics for 6 pulse systems.

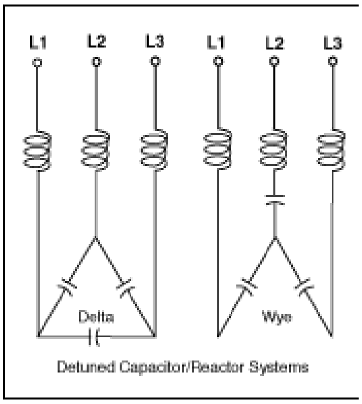


Avoiding Resonance

There are a number of ways to avoid resonance when installing capacitors. In larger systems it may be possible to install them in a part of the system that will not result in a parallel resonance with the supply. Varying the kvar output rating of the capacitor bank will alter the resonant frequency. With capacitor switching there will be a different resonant frequency for each step. Changing the number of switching steps may avoid resonance at each step of switching.

Overcoming Resonance

If resonance cannot be avoided, an alternative solution is required. A reactor must be connected in series with each capacitor such that the capacitor/reactor combination is inductive at the critical frequencies but capacitive at the fundamental frequency. To achieve this, the capacitor and series connected reactor must have a tuning frequency below the lowest critical order of harmonic, which is usually the 5th. This means the tuning frequency is in the range of 175 Hz to 270 Hz, although the actual frequency will depend upon the magnitude and order of the harmonic currents present.



The addition of a reactor in the capacitor circuit increases the fundamental voltage across the capacitor. Therefore, care should be taken when adding reactors to existing capacitors.

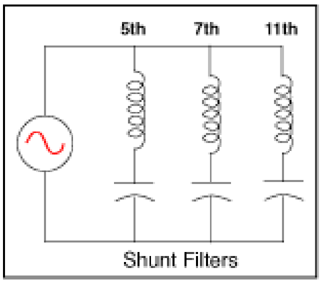
Reduction of Harmonic Distortion

Harmonic currents can be significantly reduced in an electrical system by using a harmonic filter.

In its basic form, a filter consists of a capacitor connected in series with a reactor tuned to a specific harmonic frequency. In theory, the impedance of the filter is zero at the tuning frequency; therefore, the harmonic current is absorbed by the filter. This, together with the natural resistance of the circuit, means that only a small level of harmonic current will flow in the network.

Types of Filters

The effectiveness of any filter design depends on the reactive output of the filter, tuning accuracy and the impedance of the network at the point of connection.



Harmonics below the filter tuning frequency will be amplified. The filter design is important to ensure that distortion is not amplified to unacceptable levels. Where there are several harmonics present, a filter may reduce some harmonics while increasing others. A filter for the 7th harmonic creates a parallel resonance in the vicinity of the 5th harmonic with magnification of the existing 5th harmonic; therefore, a 7th harmonic filter requires a 5th harmonic filter. Consequently, it is often necessary to use a multiple filter design where each filter is tuned to a different frequency.

Experience is extremely important in the design of such filters to ensure:

a.) the most efficient and cost effective solution is selected;
b.) no adverse interaction between the system and the filter.

Load Alteration

Whenever load expansion is considered, the network is likely to change and existing filter equipment should be evaluated in conjunction with the new load condition. It is not recommended to have two or more filters tuned to the same frequency connected on the same distribution system. Slight tuning differences may cause one filter to take a much larger share of the harmonic distortion. Or, it may cause amplification of the harmonic order which the equipment has been designed to reduce. When there is a need to vary the power factor correction component of a harmonic filter, careful consideration of all load parameters is necessary.

Harmonic Analysis

The first step in solving harmonic related problems is to perform an analysis to determine the specific needs of your electrical distribution system. To determine capacitor and filter requirements, it is necessary to establish the impedance of the supply network and the value of each harmonic current. Capacitor, reactor and filter bank equipment are then specified under very detailed and stringent computer analysis to meet your needs.

Power Factor Correction Capacitor Series.

Power factor correction capacitors store and redistribute reactive power. When a capacitor assembly is connected to an electrical system containing an inductive load, e.g., motor, the load will require less reactive power from the utility.

Low power factor caused by inductive loads results in increased line losses and possible surcharges or penalties billed by electric utility providers.

Myron Zucker, Inc. offers a wide range of power factor correction capacitors for various applications to ensure optimal power utilization.

Our products are specified in kilovolt-amperes reactive (kVAR) for three-phase voltages of 240, 480, and 600 VAC. Our capacitor assemblies are also designed for other voltage or phase applications.

Myron Zucker, Inc. offers both ***fixed*** and ***automatic*** products. ***Fixed*** capacitor assemblies are applied to constant load conditions either at the load, branch panel, or service entrance. ***Automatic*** capacitor assemblies correct power factor under varying load conditions, typically at the service entrance for facility-wide correction.

POWER FACTOR CORRECTION CAPACITORS - FIXED

Fixed capacitor systems are ideally suited for power factor correction in applications where the load does not change or where the capacitor is switched with load, such as the load side of a motor starter.

Myron Zucker, Inc. offers several options to meet your application needs.

- **Calmount® series**: Ideally suited for individual motor loads and small or medium substations
- **Traymount® series**: Specifically designed for motor control centers (MCC)
- **Capacibank® series**: Applied to individual motors, large substations, or service entrance applications

POWER FACTOR CORRECTION CAPACITORS - AUTOMATIC

Automatic capacitor banks are the appropriate choice for power factor correction in applications where the electrical load is not constant and requires varying amounts of reactive power. An automatic capacitor bank measures power factor and switches capacitors in and out of service to maintain target power factor.

- **Autocapacibank™ series**: Located strategically located throughout an electrical distribution system or the service entrance when the electrical system has less than 15% non-linear loads
- **ZT Capacibank series**: Designed to improve poor power factor under rapidly changing load conditions. The ZT series utilizes thyristor soft-switching technology which prevents transients.

POWER FACTOR CORRECTION CAPACITOR BENEFITS:

- Improve power factor
- Increase available transformer and distribution capacity
- Eliminate utility penalties or surcharges
- Reduce line losses and associated energy costs

- Decrease downtime while improving power quality

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