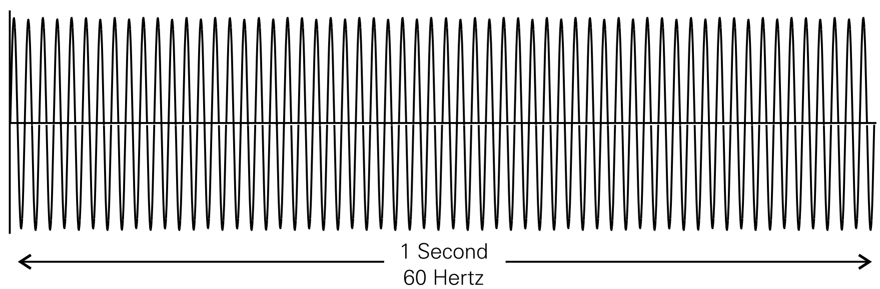
Frequency and Harmonics

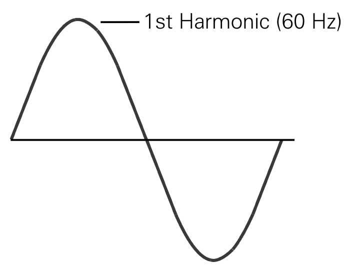
We learned earlier that frequency is a measurement of the number of times voltage and current rises and falls to alternating peak values per second. Frequency is stated in hertz. The standard power line frequency in the United States is 60 hertz (60 cycles per second). In many other parts of the world the standard frequency is 50 hertz.



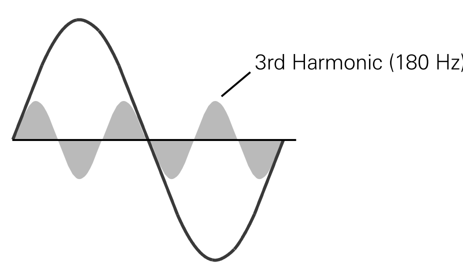
Harmonics

Harmonics are created by electronic circuits, such as, adjustable speed drives, rectifiers, personal computers, and printers. Harmonics can cause problems to connected loads.

The base frequency of the power supply is said to be the fundamental frequency or first harmonic. The fundamental frequency or first harmonic of a 60 Hz power supply is 60 Hz. Additional harmonics can appear on the power supply. These harmonics are usually whole number multiples of the first harmonic. The third harmonic of a 60 Hz power supply, for example, is 180 Hz (60 x 3).

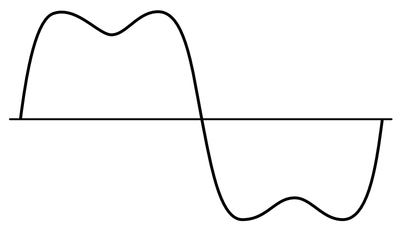


60 Hertz Power Supply
Fundamental Frequency
1st Harmonic Only



60 Hertz Power Supply
With 3rd Harmonic Present

When a harmonic waveform is superimposed on the fundamental sine wave a distinctive waveform is produced. In this example, the third harmonic is seen superimposed on the fundamental frequency. The problem of waveform distortion becomes more complex when additional harmonics are present.



Resultant Waveform

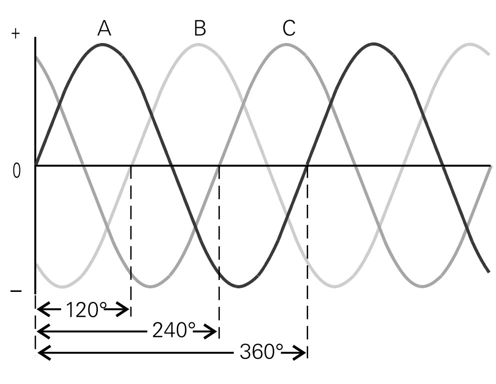
Total Harmonic Distortion

Harmonic distortion is a destructive force in power distribution systems. It creates safety problems, shortens the life span of transformers, and interferes with the operation of electronic devices. Total harmonic distortion (THD) is a ratio of harmonic distortion to the fundamental frequency. The greater the THD the more distortion there is of the 60 Hz sine wave. Harmonic distortion occurs in voltage and current waveforms. Typically, voltage THD should not exceed 5% and current THD should not exceed 20%. Some of the power meters offered by Siemens are capable of reading THD.

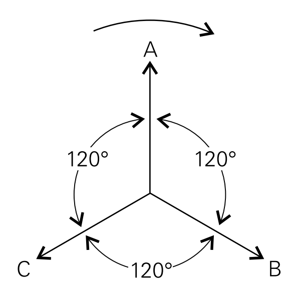
$$\%\text{ of THD} = \frac{\text{RMS of Total Harmonic Distortion Signal}}{\text{RMS of Fundamental Frequency}} \times 100$$

Phasors

Phase rotation describes the order in which waveforms from each phase cross zero. Waveforms can be used to illustrate this relationship. Phasors consist of lines and arrows and are often used in place of waveforms for simplification.



3-Phase Waveform



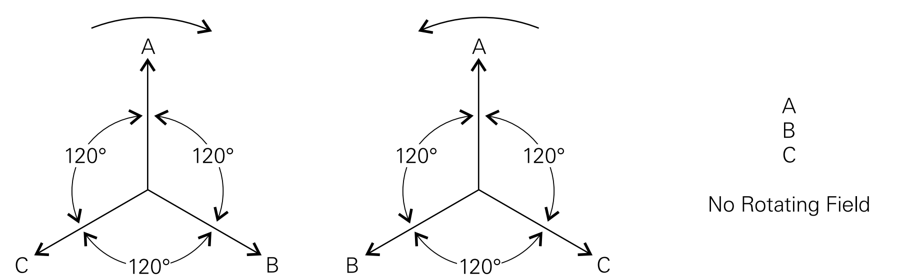
Phase Relationship

Harmonic Sequence

A harmonic's phase rotation relationship to the fundamental frequency is known as harmonic sequence. Positive sequence harmonics (4th, 7th, 10th, ...) have the same phase rotation as the fundamental frequency (1st). The phase rotation of negative sequence harmonics (2nd, 5th, 8th, ...) is opposite the fundamental harmonic. Zero sequence harmonics (3rd, 6th, 9th, ...) do not produce a rotating field.

Harmonic	Frequency	Sequence
1st	**60**	**Fundamental**
2nd	120	Negative
3rd	180	Zero
4th	240	Positive
5th	300	Negative
6th	360	Zero
7th	420	Positive
8th	480	Negative
9th	540	Zero
10th	600	Positive

Odd numbered harmonics are more likely to be present than even numbered harmonics. Higher numbered harmonics have smaller amplitudes, reducing their affect on the power and distribution system.



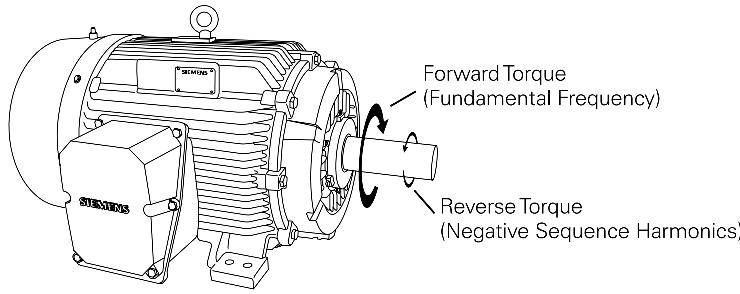
Positive Sequence Harmonics (1st, 4th, 7th, 10th, . . .)

Negative Sequence Harmonics (2nd, 5th, 8th, 11th, . . .)

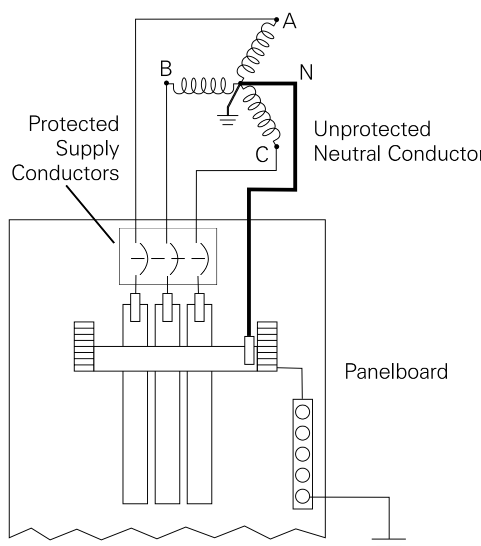
Zero Sequence Harmonics (3rd, 6th, 9th, 12th . . .)

Harmonic Effects

All harmonics cause additional heat in conductors and other distribution system components. Negative sequence harmonics can be problematic in induction motors. The reverse phase rotation of negative harmonics reduces forward motor torque and increases the current demand.

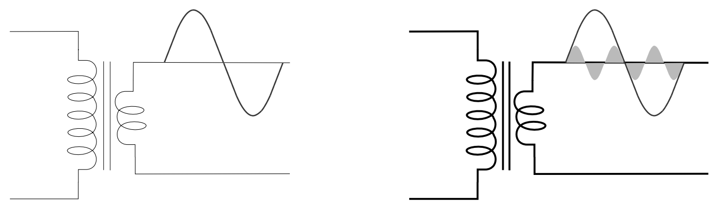


Zero sequence harmonics add together, creating a single-phase signal that does not produce a rotating magnetic field. Zero sequence harmonics can cause additional heating in the neutral conductor of a 3Ø, 4-wire system. This can be a major problem because the neutral conductor typically is not protected by a fuse or circuit breaker.



K Factor

K factor is a simple numerical rating that indicates the extra heating caused by harmonics. A transformer's ability to handle the extra heating is determined by a K factor rating. A standard transformer has a rating of K-1. A transformer might have a rating of K-5, which would be an indication of the transformer's ability to handle 5 times the heating effects caused by harmonics than a K-1 rated transformer.



Standard Transformer
No Harmonics Present

Transformer with K Factor Rating
Harmonics Present

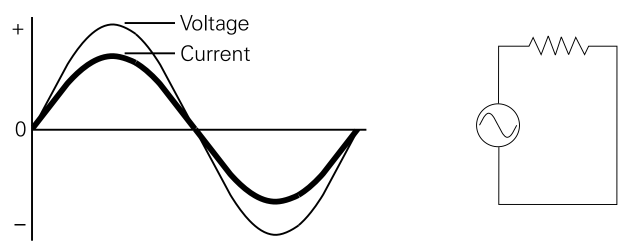
Power and Power Factor

Load Types

Distribution systems are typically made up of a combination of various resistive, inductive, and capacitive loads.

Resistive Loads

Resistive loads include devices such as heating elements and incandescent lighting. In a purely resistive circuit, current and voltage rise and fall at the same time. They are said to be "in phase."

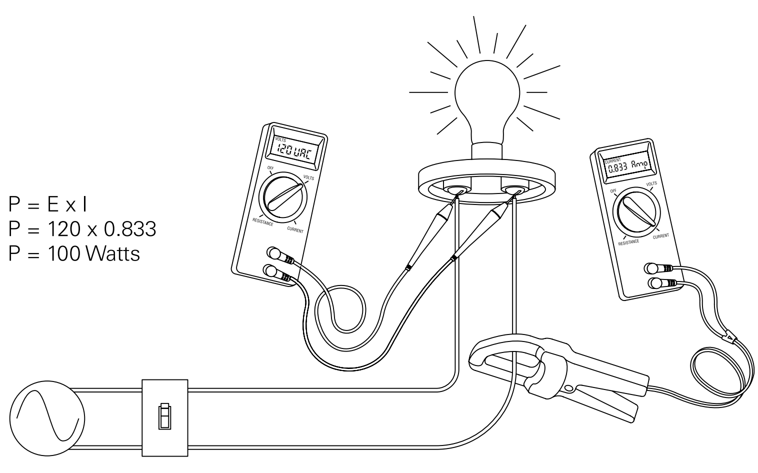


True Power

All the power drawn by a resistive circuit is converted to useful work. This is also known as true power in a resistive circuit. True power is measured in watts (W), kilowatts (kW), or megawatts (MW). In a DC circuit or in a purely resistive AC circuit, true power can easily be determined by measuring voltage and current. True power in a resistive circuit is equal to system voltage (E) times current (I).

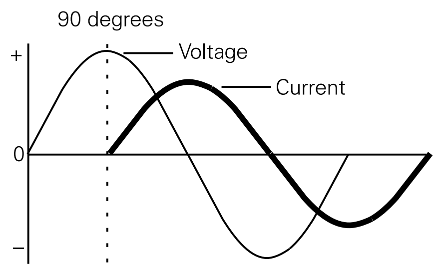
In the following example, an incandescent light (resistive load) is connected to 120 VAC. The current meter shows the light is drawing 0.833 amps. In this circuit 100 watts of work is done (120 VAC x 0.833 amps).

$P = E \times I$
$P = 120 \times 0.833$
$P = 100$ Watts

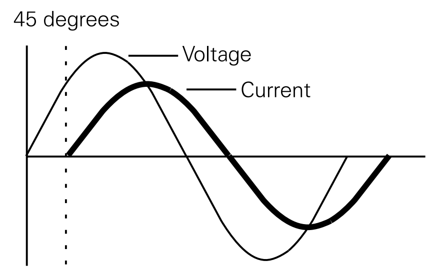


Inductive Loads

Inductive loads include motors, transformers, and solenoids. In a purely inductive circuit, current lags behind voltage by 90°. Current and voltage are said to be “out of phase.” Inductive circuits, however, have some amount of resistance. Depending on the amount of resistance and inductance, AC current will lag somewhere between a purely resistive circuit (0°) and a purely inductive circuit (90°). In a circuit where resistance and inductance are equal values, for example, current lags voltage by 45°.



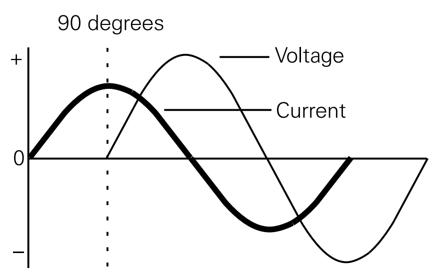
Purely Inductive Circuit



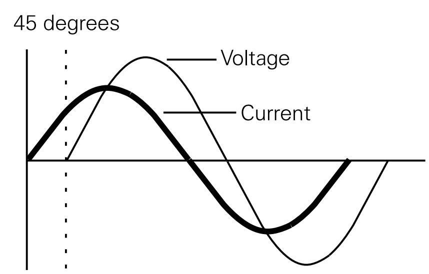
Circuit with Equal Values of Resistance and Inductance

Capacitive Loads

Capacitive loads include power factor correction capacitors and filtering capacitors. In a purely capacitive circuit, current leads voltage by 90°. Capacitive circuits, however, have some amount of resistance. Depending on the amount of resistance and capacitance, AC current will lead voltage somewhere between a purely resistive circuit (0°) and a purely capacitive circuit (90°). In a circuit where resistance and capacitance are equal values, for example, current leads voltage by 45°.



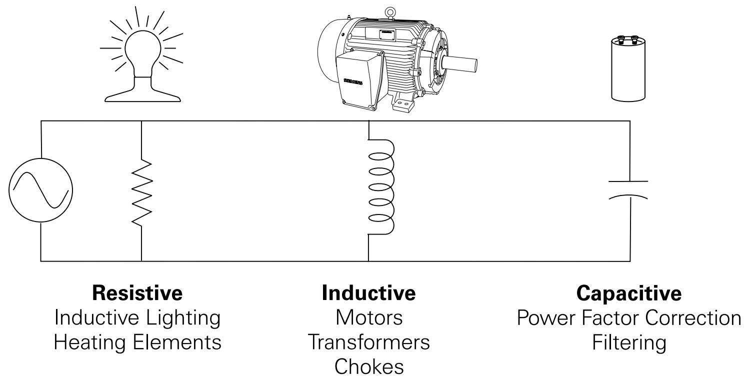
Purely Capacitive Circuit



Circuit with Equal Values of Resistance and Capacitance

Reactive Loads

Circuits with inductive or capacitive components are said to be reactive. Most distribution systems have various resistive and reactive circuits. The amount of resistance and reactance varies, depending on the connected loads.



Reactance

Just as resistance is opposition to current flow in a resistive circuit, reactance is opposition to current flow in a reactive circuit. It should be noted, however, that where frequency has no effect on resistance, it does effect reactance. An increase in applied frequency will cause a corresponding increase in inductive reactance and a decrease in capacitive reactance.

$$R = \frac{E}{I}$$

R = Resitance in Ω
E = Voltage
I = Current

Resistance

$$X_L = 2\pi fL$$

X_L = Inductive Reactance (Ω)
$\pi = 3.14$
f = Applied Frequency (Hz)
L = Inductance (Henrys)

Inductive Reactance

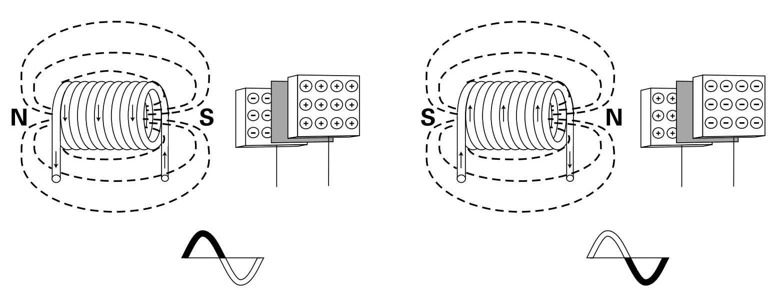
$$X_C = \frac{1}{2\pi fC}$$

X_C = Capacitive Reactance
$\pi = 3.14$
f = Applied Frequency (Hz)
C = Capacitance (Farads)

Capacitive Reactance

Energy in Reactive Circuits

Energy in a reactive circuit does not produce work. This energy is used to charge a capacitor or produce a magnetic field around the coil of an inductor. Current in an AC circuit rises to peak values (positive and negative) and diminishes to zero many times a second. During the time current is rising to a peak value, energy is stored in an inductor in the form of a magnetic field or as an electrical charge in the plates of a capacitor. This energy is returned to the system when the magnetic field collapses or when the capacitor is discharged.

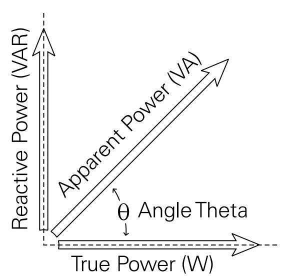


Reactive Power

Power in an AC circuit is made up of three parts; true power, reactive power, and apparent power. We have already discussed true power. Reactive power is measured in volt-amps reactive (VAR). Reactive power represents the energy alternately stored and returned to the system by capacitors and/or inductors. Although reactive power does not produce useful work, it still needs to be generated and distributed to provide sufficient true power to enable electrical processes to run.

Apparent Power

Not all power in an AC circuit is reactive. We know that reactive power does not produce work; however, when a motor rotates work is produced. Inductive loads, such as motors, have some amount of resistance. Apparent power represents a load which includes reactive power (inductance) and true power (resistance). Apparent power is the vector sum of true power, which represents a purely resistive load, and reactive power, which represents a purely reactive load. A vector diagram can be used to show this relationship. The unit of measurement for apparent power is volt amps (VA). Larger values can be stated in kilovolt amps (kVA) or megavolt amps (MVA).



Power Factor

Power factor (PF) is the ratio of true power (PT) to apparent power (PA), or a measurement of how much power is consumed and how much power is returned to the source. Power factor is equal to the cosine of the angle theta in the above diagram. Power factor can be calculated with the following formulas.

$$PF = \frac{PT}{PA}$$

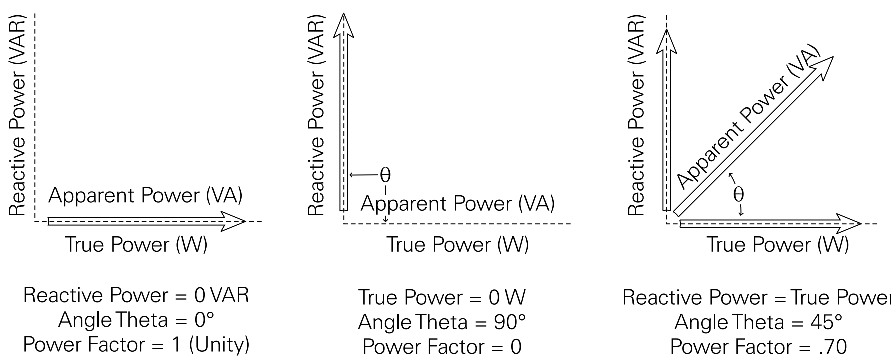
or

$$PF = \cos\theta$$

Power factor can be given as a percent or in decimal format. The following table shows the power factor for a few sample angles.

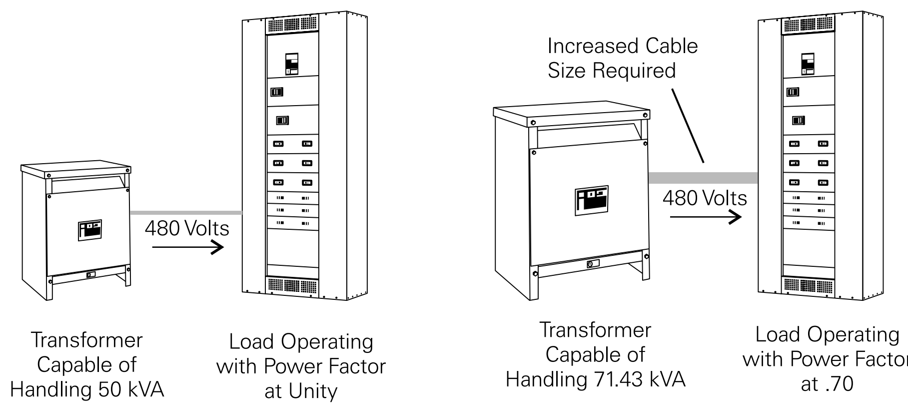
Angle Theta	Cosine of Angle Theta	Power Factor (%)	Power Factor (Decimal)
0	1	100%	1
10	0.98	98%	.98
20	0.94	94%	.94
30	0.87	87%	.87
45	0.70	70%	.7
60	0.50	50%	.5
70	0.34	34%	.34
80	0.17	17%	.17
90	0	0%	0

In purely resistive circuits, apparent power and true power are equal. All the power supplied to a circuit is consumed or dissipated in heat. The angle of theta is 0° and the power factor is equal to 1. This is also referred to as unity power factor. In purely reactive circuits, apparent power and reactive power are equal. All power supplied to a circuit is returned to the system. The angle theta is 90° and the power factor is 0. In reality, all AC circuits contain some amount of resistance and reactance. In a circuit where reactive power and true power are equal, for example, the angle of theta is 45° and power factor is 0.70.



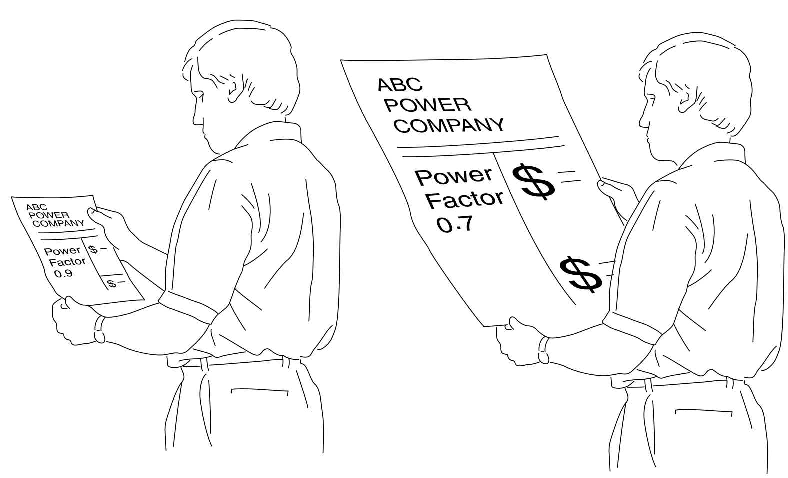
Power Factor Problems

It can be seen that an increase in reactive power causes a corresponding decrease in power factor. This means the power distribution system is operating less efficiently because not all current is performing work. For example, a 50 kW load with a power factor of 1 (reactive power = 0) could be supplied by a transformer rated for 50 kVA. However, if power factor is 0.7 (70%) the transformer must also supply additional power for the reactive load. In this example a larger transformer capable of supplying 71.43 kVA (50 ÷ 70%) would be required. In addition, the size of the conductors would have to be increased, adding significant equipment cost.



The Cost of Power

Utility companies sell electrical power based on the amount of true power measured in watts (W). However, we have learned that in AC circuits not all power used is true power. The utility company must also supply apparent power measured in volt-amps (VA). Typically utilities charge additional fees for increased apparent power due to poor power factor.



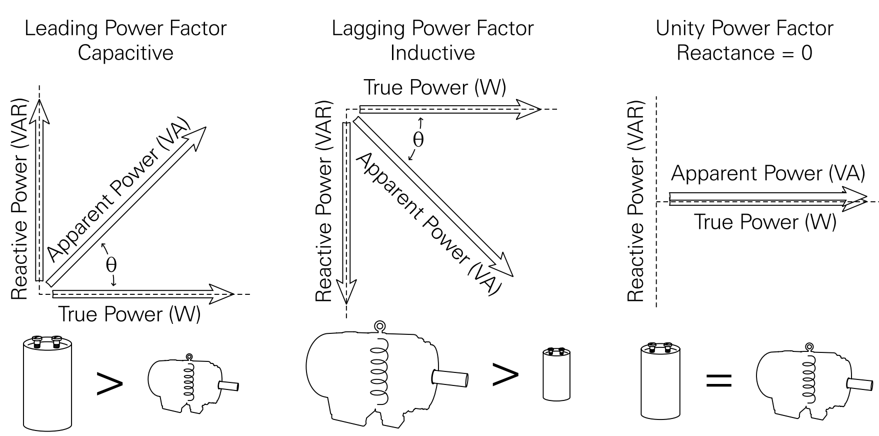
The following table shows the amount of apparent power (VA = W ÷ PF) required for a manufacturing facility using 1 MW (megawatt) of power per hour for a few sample power factors. If, for example, a manufacturing facility had a power factor of 0.70 the utility company would have to supply 1.43 MVA (mega volt-amps) of power. If the power factor were corrected to 0.90 the power company would only have to supply 1.11 MVA of power.

True Power (MW)	Power Factor	Apparent Power (MVA)
True Power	**÷ Power Factor**	**= Apparent Power**
	1	1
	0.95	1.053
	0.90	1.11
1	0.85	1.18
	0.80	1.25
	0.75	1.33
	0.70	1.43

Leading and Lagging Power Factor

Since current leads voltage in a capacitive circuit, power factor is considered leading if there is more capacitive reactance than inductive reactance. Power factor is considered lagging if there is more inductive reactance than capacitive reactance since current lags voltage in a inductive circuit. Power factor is unity when there is no reactive power or when inductive reactance and capacitive reactance are equal, effectively cancelling each other.

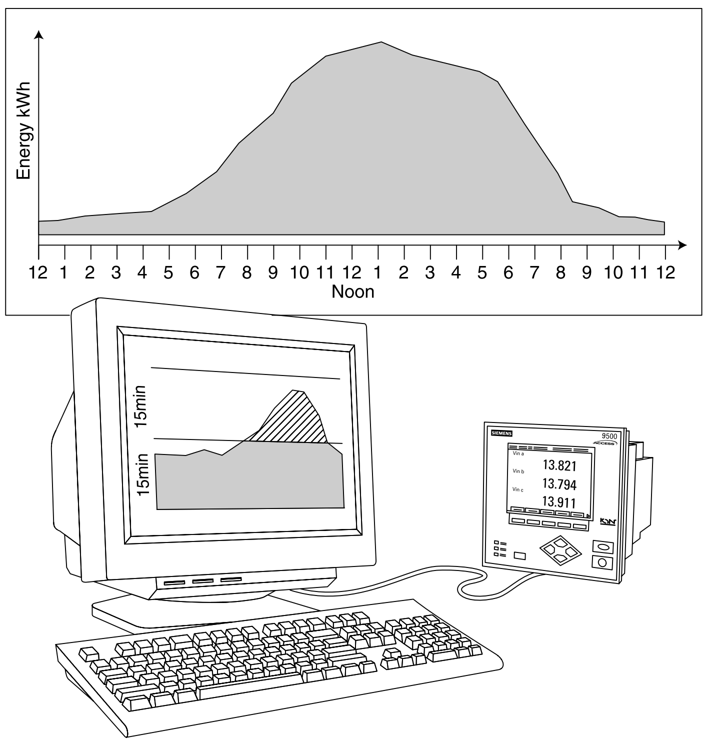
It is usually more economical to correct poor power factor than to pay large utility bills. In most industrial applications motors account for approximately 60% or more of electric power consumption, resulting in a lagging power factor (more inductive than capacitive). Power factor correction capacitors can be added to improve the power factor.



Power Demand

Demand is the average energy consumed over a specified period of time. The interval is usually determined by the utility company and is typically 15 or 30 minutes. The utility measures the maximum demand over the 15 or 30 minute period. Utility companies must install larger equipment to handle irregular demand requirements. For this reason utility companies may charge large customers an additional fee for irregular power usage during peak times. If the maximum demand is greater than the average consumption, the utility company will need to provide increased generating capacity to satisfy the higher demand. Demand is usually low in the morning and evening. During the day there is more demand for electrical power.

Siemens power meters have a sliding window adjustment that allows the user to monitor time segments specified by the utility company.



Solutions

As we have learned, there are a number of things that can affect power quality. The following table provides some basic guidelines to solve these problems. It should be remembered that the primary cause and resulting effects on the load and system should be considered when considering solutions.

Problem	Effect	Solution
Sag	Computer shutdown resulting in lost data, lamp flicker, electronic clock reset, false alam.	Voltage regulator, power line conditioner, proper wiring.
Swell	Shorten equipment life and increase failure due to heat.	Voltage regulator, power line conditioner.
Undervoltage	Computer shutdown resulting in lost data, lamp flicker, electronic clock reset, false alam.	Voltage regulator, power line conditioner, proper wiring.
Overvoltage	Life expectency of motor and other insulation resulting in equipment failure or fire hazard. Shorten life of light bulbs	Voltage regulator, power line conditioner.
Momentary Power Interruption	Computer shutdown resulting in lost data, lamp flicker, electronic clock reset, false alam, motor circuits trip.	Voltage regulator, power line conditioner, UPS system.
Noise	Erractic behavior of electronic equipment, incorrect data communication between computer equipment and field devices.	Line filters and conditioners, proper wiring and grounding.
Transients	Premature equipment failure, computer shutdown resulting in lost data.	Surge suppressor, line conditioner, isolation transformers, proper wiring, grounding.
Harmonics	Overheated neutrals, wires, connectors, transformers, equipment. Data communication errors.	Harmonic filters, K-rated transformers, proper wiring and grounding.
Power Factor	Increased equipment and power costs	Power factor correction capacitors.

Review 3

1. The second harmonic of a 60 Hz power supply is ___________ Hz.

2. Typically, the total harmonic distortion (THD) of a voltage waveform should not exceed ___________ %.

3. ___________ sequence harmonics do not produce a rotating magnetic field.

   a. Positive
   b. Negative
   c. Zero

4. A transformer's ability to handle the extra heating caused by harmonics is determined by a ___________ rating.

5. In a purely ___________ circuit, voltage and current are in phase.

   a. resistive
   b. inductive
   c. capacitive

6. ___________ power represents a load which includes reactive power and true power.

7. ___________ is the ratio of true power to apparent power.

8. An increase in reactive power would require a corresponding ___________ in transformer size.

   a. increase
   b. decrease

9. It is possible to correct for sag with the addition of a ___________ .

   a. voltage regulator
   b. power line conditioner
   c. proper wiring
   d. all of the above

ACCESS System

Up to this point we have looked at how various factors effect power quality. The following sections will focus on components of the ACCESS system and how they can be used as a complete power monitoring and management system.

Supervisory Devices

In general, ACCESS works on two levels: supervisory and field. Supervisory devices, such as WinPM™, collects and displays information from a network of field devices. A supervisory device sends requests and receives feedback from field devices over a serial network. This process, called polling, allows the supervisory and field devices to exchange information. Siemens WinPM software runs on a personal computer (PC).

Field Devices

Field devices include meters, circuit breakers, protective relays, I/O devices, motor protectors, and personal computers (PCs). Field devices send and receive information about an electrical system.

In the following sections we will look at ACCESS system products used as supervisory devices, in network communication, and field devices.