
Power Factor in Electrical Energy Management

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Power Factor in Electrical Energy Management

Abstract

Power factor is a measure of how effectively electrical power is being used. A high power factor (approaching unity) indicates efficient use of the electrical distribution system while a low power factor indicates poor use of the system.

The traditional textbook explanation of power factor is $\cos \theta$ when reactive components of capacitors and inductors were in the load. The current either lags or leads the voltage. In inductive circuits, the most commonly found industrial electrical loading, the current lags the voltage in time. The inductance is created by motors of every type, transformers, pull-in coils for relays, contactors and ballast coils.

The inductive portion creates no use of electrical energy, but the inductance requires a current flow. The current flow causes additional loading on the electrical generating equipment. The electrical distribution system must carry the extra current, which results in more loss in wires carrying the energy to the load, and reduces the energy available to the load. The power in the load is described by:

$$\text{Watts} = E * I * \cos \theta$$

The $\cos \theta$ is the lead or lag time created by the reactance which can be expressed as a shunt component to the resistive load. Thus, the power factor expressed as the $\cos \theta$, states how closely the load is resistive.

When the power factor ($\cos \theta$) is 1.0, the current is in phase with the voltage and the circuit is resistive. If $\cos \theta = 1$, the transmission of 500kW in a 400V three phase mains requires a current of 722 A. The transmission of the same effective power at a $\cos \theta = 0.6$ would require a far higher current, namely 1203 A. Accordingly, distribution and transmission equipment as well as feeding transformers have to be derated for this higher load. Furthermore their useful life may also be decreased.

This course describes the concept of power factor in electrical energy management.

Power Factor in Electrical Energy Management

Every electric load that works with magnetic fields (motors, chokes, transformers, inductive heating, arc-welding generators) produces a varying degree of electrical lag, what is called inductance. The line current drawn by an inductive load consists of two components: magnetizing current and power-producing current. The magnetizing current is the current required to sustain the electro-magnetic flux or field strength in the machine. This component of current creates reactive power that doesn't do useful "work," but circulates between the generator and the load. It places a heavier drain on the power source, as well as on the power source's distribution system.

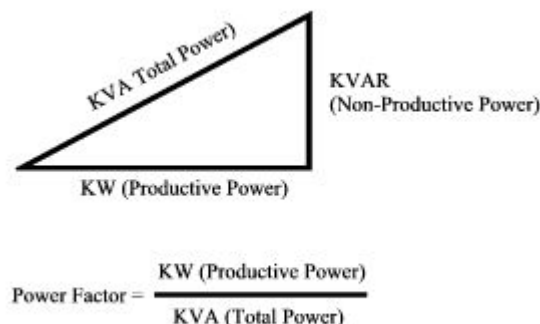
The real (working) power-producing current is the current that reacts with the magnetic flux to produce the mechanical output of the motor. Real power is measured in kilowatts (kW) which together with reactive power (KVAR) make up apparent power expressed in kilovolt-amperes (kVA).

Power factor is the inefficiency expressed as the ratio of active or useful power to total or apparent power (KW/KVA).

$$\text{Power factor} = \frac{\text{Active Power}}{\text{Apparent Power}} \quad \text{or} \quad \frac{\text{kW}}{\text{kVA}}$$

The apparent power is always in excess of the active power for inductive loads and is dependent on the type of machine in use.

Graphically it can be represented as:



The cosine of the phase angle θ between the KVA and the KW components represents the power factor of the load. KVAR represents the non-productive reactive power and θ is lagging phase angle.

The Relationship between KVA, KW and KVAR is non-linear and is expressed as:

$$\text{KVA}^2 = \text{KW}^2 + \text{KVAR}^2$$

A power factor of 0.72 would mean that only 72% of your power is being used to do useful work. Perfect power factor is 1.0, (unity); meaning 100% of the power is being used for useful work.

Power factor is also referred to as leading or lagging. In the case of the magnetizing current, the power factor is lagging, in that the current follows the voltage waveform. The amount of lag is the electrical phase angle between the voltage and the current. Power factor is equal to the cosine of the phase angle between the voltage and current waveforms.

Terminology

Apparent Power: This value is determined by multiplying the current times voltage. In a three-phase circuit, multiply the average phase-to-phase voltage, times the average line current, times the square root of 3 divided by 1,000. The units are kilovolt-amperes (kVA).

$$P_{\text{Apparent}} = \frac{V \times I \times \sqrt{3}}{1000}$$

Reactive Power: This term describes the magnetizing requirements of an electric circuit containing inductive loads. The value of magnetizing power is determined by multiplying the Apparent Power by the sine of the phase angle, θ , between the voltage and the current. Units are kilovolt-amperes reactive (kVAR).

$$P_{\text{Reactive}} = P_{\text{Apparent}} \times \sin \theta$$

Real Power: This term is what electricians deal with in plant loads. Real power is related to Apparent Power by the cosine of the phase angle, θ , between voltage and current. Units are kilowatts (kW).

$$P_{\text{Real}} = P_{\text{Apparent}} \times \cos \theta$$

Or

$$P_{\text{Real}} = P_{\text{Apparent}} \times \text{PF}$$

Note that:

- Real or active power is measured in KW (1000 Watts)
- Reactive power is measured in kVAR (1000 Volt-Amperes Reactive)
- Total Power is measured in KVA (1000 Volt-Amperes)

Typical Un-improved Power Factor by Industry

The typical 'un-corrected power factor' by different sectors of industry are as follows:

Industry	Power Factor
Auto Parts	75-80
Brewery	75-80
Cement	80-85
Chemical	65-75
Coal Mine	65-80
Clothing	35-60
Electroplating	65-70
Foundry	75-80
Forging	70-80
Hospital	75-80
Machine Manufacturing	60-65
Metalworking	65-70
Office Building	80-90
Oil field Pumping	40-60
Paint Manufacturing	65-70
Plastic	75-80
Stamping	60-70
Steel Works	65-80
Tool, dies, jigs industry	65-75

Typical uncorrected industrial power factor is 0.8. This means that a 1MVA transformer can only supply 800KW or that a consumer can only draw 80 useful Amps from a 100Amp supply. To put it the other way, a 3-phase 100KW load would draw 172A per phase instead of the 139A expected.

For inherently low power factor equipment, the utility company has to generate much more current than is theoretically required. Say for instance, in a situation where real power demand (kW) at two plants is the same, but one plant has an 85 percent

power factor while the other has a 70 percent power factor, the utility must provide 21 percent more current to the second plant to meet that same demand. This excess current flows through generators, cables, and transformers in the same manner as the useful current. If steps are not taken to improve the power factor of the load, all the equipment, conductors and transformers serving the second plant would need 21 percent more carrying capacity than those provided to the first plant. Additionally, resistance losses (I^2R) in the distribution conductors would be 46 percent greater in the second plant. A utility is paid primarily on the basis of energy consumed and peak demand supplied. Without a power factor billing element, the utility would receive no more income from the second plant than from the first. To discourage these inefficiencies and to compensate for the burden of supplying extra current, the utilities typically establish a "power factor penalty" in their rate schedules. These penalties appear on electricity bills as "reactive power charges", "KVA maximum demand" or "KVA availability charges". For instance known information taken from billing about electrical system:

KVA = 1000, KW = 800, KVAR = 600, PF = .80

Typical Utility Billing Structure Examples:

- 1) **90% Billing Structure** - Where demand billed is based on 90% of the KVA or 100% of the KW, whichever is greater. Because the facility has a power factor of 0.80 they will pay demand rates on 90% of the KVA $1000 \times .90 = 900$ KVA because it is the larger number ($900 \text{ KVA} > 800 \text{ KW}$). Thus the facility is paying a penalty on 100 KVA of unproductive power. Correcting the facility's Power Factor to 90% + will eliminate this penalty cost.
- 2) **100% KVA + 100% KW Billing Structure** - Where one rate is applied to 100% of the KVA and another rate is applied to 100% of the KW. Both are then added together to determine the total demand charged on the bill. If we correct the power factor to unity ($\text{KVA} = \text{KW}$ or $800 \text{ KVA} = 800 \text{ KW}$) we can recover costs paid on 200 KVA at *KVA rates, assuming an equal rate is being paid for KVA and KW

Rather than pay demand costs on $1000 \text{ KVA} + 800 \text{ KW} = 1800$, if the Power Factor = Unity we will pay demand costs on $800 \text{ KVA} + 800 \text{ KW} = 1600$. Savings = $1800 - 1600 = 200$. (More examples are provided later in this course).

*Note: Generally the cost per KVA is greater than the cost for KW. Thus the savings would be greater by correcting the power factor to unity.

The reactive power charges levied as penalties in the billing should always be regulated. The excess reactive currents and associated charges can be removed by a well established technology called "Power factor correction". Simply put, this technology offsets the inductive reactive currents by introducing equal and opposite capacitive reactive currents. Typically this can reduce electricity bills by 5-8%, with a payback period of 12 to 18 months. In addition, the consumer shall gain from improved supply availability, improve voltage and reduced power losses.

To improve the power factor, equipment drawing KVAR of approximately the same magnitude as the load KVAR, but in phase opposition 'Leading' is connected in parallel with the load. The resultant KVA is now smaller and the new power factor, $\cos\theta_2$ is increased. Thus any value of $\cos\theta_2$ can be obtained by controlling the magnitude of the leading KVAR added.

It is never economic to attempt to improve the power factor to unity, since the nearer the approach to unity the more KVAR that must be installed for a given improvement.

Disadvantages of low power factor

For systems with a low power factor the transmission of electric power in accordance with existing standards results in higher expenses both for the supply distribution companies and the consumer. Many engineers are oblivious to the effects of low power factor. They view it only as a direct charge on their electrical bill, and only when stated as such. Low power factor is a direct cost to the utility company and must be paid for.

Direct costs of low power factor

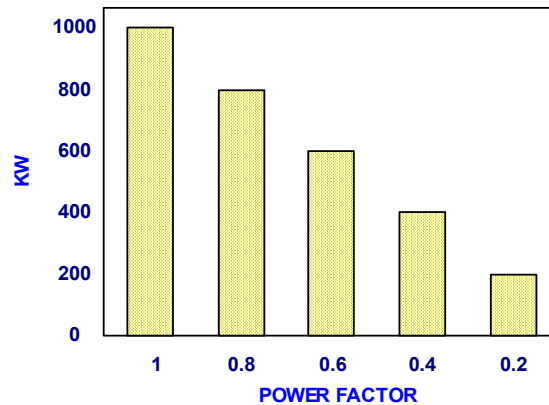
Power factor may be billed as one of or combination of, the following:

- 1) A penalty for power factor below and a credit for power factor above a predetermined value,
- 2) An increasing penalty for decreasing power factor,
- 3) A charge on monthly KVAR Hours,
- 4) KVA demand: A straight charge is made for the maximum value of KVA used during the month. Included in this charge is a charge for KVAR since KVAR increase the amount of KVA.

Indirect costs of low power factor

Loss in efficiency of the equipment: When an installation operates with a low power factor, the amount of useful power available inside the installation at the distribution

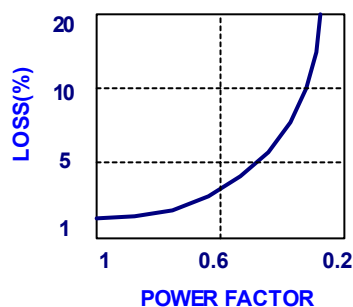
transformers is considerably reduced due to the amount of reactive energy that the transformers have to carry. The figure below indicates the available actual power of distribution equipment designed to supply 1000 KW.



Loss in distribution capacity

In general terms, as the power factor of a three phase system decreases the current **rises**. The heat dissipation in the system rises proportionately by a factor equivalent to the square of the current rise.

The figure below graphically displays the variation of the I^2R losses in feeders and branches. Losses are expressed in percent as a function of power factor.



Larger Investment

In case of expansion, a larger investment is required in the equipment needed to increase distribution capability of the installation, such as oversized transformers and switchgears.

Transformers

For an installation which requires 800KW, the transformer should be approximately:

800KVA for power factor = 100%

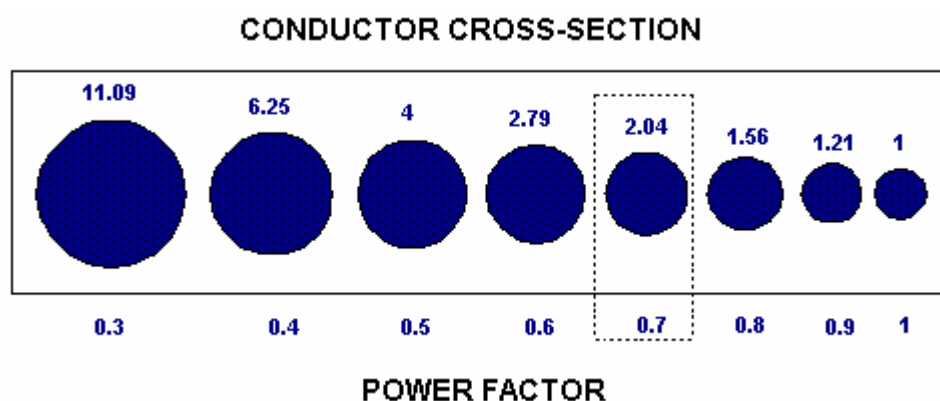
1000 KVA for power factor = 80%

1600 KVA for power factor = 50%

Large size conductors

The figure below shows a variation of a cross section of a conductor as a function of the power factor for a given useful power. This illustrates that when the power factor of an installation is low, the surcharge on the electricity bill is only part of the problem.

For instance, in an installation where no correction has been made and which has a power factor of 70%, the cross-section of the conductor must be twice as large as it would be if the power factor were 100%.



Practically speaking, when an installation uses its rated power capacity, the distribution cables within the installation are rapidly loaded to their full carrying capacity if the power factor decreases. Most often, as the need for energy in an installation expands, the first reaction is to double the distribution system although it would be less expensive to perform a correction of power factor on each load or group of loads.

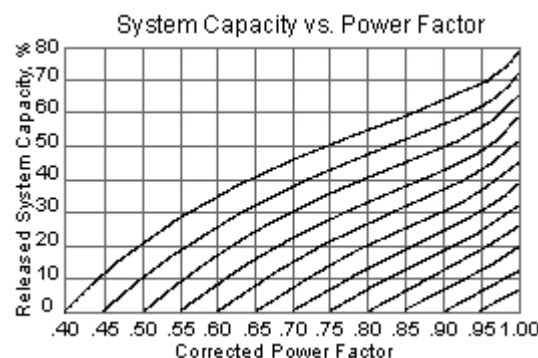
Benefits of Power Factor Correction

Benefit 1 - Reduce Utility Power Bills

In areas where a KVA demand clause or some other form of low power factor penalty is incorporated in the electric utility's power rate structure, removing system KVAR improves the power factor, reduce power bills by reducing the KVA. Most utility bills are influenced by KVAR usage.

Benefit 2 – Increase System Capacity

The power factor improvement releases system capacity and permits additional loads (motors, lighting, etc.) to be added without overloading the system. In a typical system with a 0.80 PF, only 800 KW of productive power is available out of 1000 KVA installed. By correcting the system to unity (1.0 PF), the KW = KVA. Now the corrected system will support 1000 KW, versus the 800 KW at the .80 PF uncorrected condition; an increase of 200 KW of productive power. This is achieved by adding capacitors which furnish the necessary magnetizing current for induction motors and transformers. Capacitors reduce the current drawn from the power supply; less current means lesser load on transformers and feeder circuits. Power factor correction through devices such as capacitors can avoid an investment in more expensive transformers, switchgear and cable, otherwise required to serve additional load. The figure below shows the empirical relationship of system capacity vs. power factor. From the figure one can see that improving power factor from .8 to .9 or .8 to .95 shall release approximately 12% or 20% system capacity respectively.



Benefit 3 - Improve System Operating Characteristics (Gain Voltage)

A good power factor (0.95) provides a "stiffer" voltage, typically a 1-2% voltage rise can be expected when power factor is brought to +\-0.95. Excessive voltage drops can make your motors sluggish, and cause them to overheat. Low voltage also interferes with lighting, the proper application of motor controls and electrical and electronic instruments. Motor performance is improved and so is production.

An estimate of voltage rise from the improved power factor with the installation of power capacitors can be made using following equation:

$$\% \text{ of Voltage Rise} = \frac{\text{kVAR of capacitors} \times \% \text{ Impedance of Transformer}}{\text{kVA of Transformer}}$$

Benefit 4 - Improve System Operating Characteristics (Reduce Line Losses)

Improving power factor at the load points shall relieve the system of transmitting reactive current. Less current shall mean lower losses in the distribution system of the facility since losses are proportional to the square of the current (I^2R). Therefore, fewer kilowatt-hours need to be purchased from the utility.

An estimate of reduction of power losses can be made using following equation:

$$\% \text{ Reduction of Power Losses} = 100 - 100 \left(\frac{\text{Original Power Factor}}{\text{Improved Power Factor}} \right)^2$$

Equipment Creating Poor Power Factor

It is useful to have an idea of the value of the power factor of commonly used electrical equipment. This will give an idea as to the amount of reactive energy that the network will have to carry. Find below is the summary of power factor of commonly used electrical equipment.

Lighting

Incandescent Lamps: The power factor is equal to unity.

Fluorescent Lamps: Usually have a low power factor; for example, 50% power factor would not be unusual. They are sometimes supplied with a compensation device to correct low power factor.

Mercury Vapour Lamps: The power factor of the lamp is low; it can vary from 40% to 60%, but the lamps are often supplied with correction devices.

Distribution Transformer

The power factor varies considerably as a function of the load and the design of the transformer. A completely unloaded transformer would be very inductive and have a very low power factor.

Electrical Motors

Induction Motors: The power factor varies in accordance with the load. Unloaded or lightly loaded motors exhibit a low power factor. The variation can be 30% to 90%.

Synchronous Motors: Very good power factor when the excitation is properly adjusted. Synchronous motors can be over excited to exhibit a leading power factor and can be used to compensate a low power system.

Industrial Heating

With resistance, as in ovens or dryers, the power factor is often closed to 100%.

Welding

Electric arc welders generally have a low power factor, around 60%.

Other types of machinery or equipment which are likely to have a low power factor include:

Typical Un-improved Power Factor by Equipment	
Equipment	Power Factor
Air Compressor & Pumps (external Motors)	75-80
Hermetic Motors (compressors)	50-80
Arc Welding	35-60
Resistance Welding	40-60
Machining	40-65
Arc Furnaces	75-90
Induction Furnaces (60Hz)	100
Standard Stamping	60-70
High Speed Stamping	45-60
Spraying	60-65

What causes low power factor?

From the above list, we can see that a low power factor can be a result of the design of the equipment, as in the case of welders. Also, it can be a result from the operating conditions under which the equipment is used, as in lightly loaded induction motors which are probably the worst offenders.

Equipment Design

In an old installation, one is limited by the inefficiency of the existing system. However, given the opportunity to expand and purchase new equipment, one should consider some of the energy efficient electric motors that are available today.

Operating Conditions

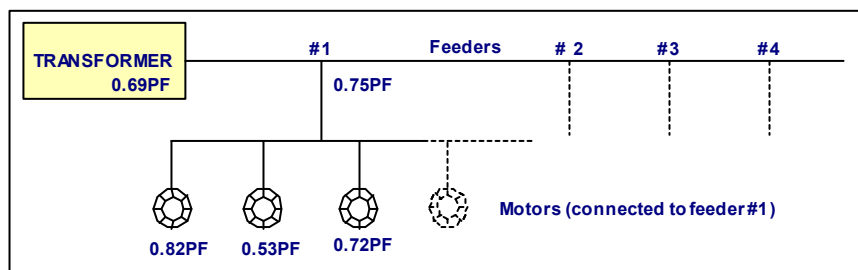
Load: The power factor of an electrical motor reaches its maximum value under full load. The power factor decreases rapidly when the load decreases. The figure below symbolically illustrates the effect of the load on the power factor of a motor.

Motor Load Factor	Power Factor
Unloaded	17%
$\frac{1}{4}$ Loaded	55%
$\frac{1}{2}$ Loaded	73%
$\frac{3}{4}$ Loaded	80%
Fully Loaded	84%
Overloaded (25%)	86%

Line voltage: Increasing the line voltage on motors and transformers above the rated voltage will increase the consumption of reactive energy. The result will be reduction of power factor. For example, an increase of 10% on the rated voltage can result in 20% reduction of the power factor.

Measurement of Power Factor

The measurement of power factor is the first step in planning any correction. Since each load has its own power factor, the measurements should start with each individual machine and move upward to each distribution panel and finish at the feeder and than to transformer as shown in the figure below.



Measuring power factor is a costly procedure when it is required to shut the load down and connect in a metering system to measure the current, voltage and power. So as to avoid the costly shutdown and time consuming measurement, it is preferable to use a clamp on power factor meter.

To connect the meter, the voltage leads are first connected to the meter and then clipped to the phases supplying the load. The clamp-on current transformer is then clamped on to the phase supplying the load. To select the appropriate clamp on CT, a conventional clamp tester is used to measure the load current. The voltage is also measured. Now using the clamp-on, power factor meter with appropriate CT, the power factor reading is noted.

The necessary data for desired power factor correction is current, line voltage and existing power factor. Now that the survey has been completed and it has been determined that power factor is a problem, the final step is to improve it. There are several approaches:

Power Factor Correction

Power factor correction can be made in two ways:

- 1) Reduce the amount of reactive energy
 - a. Avoid supplying equipment with voltage in excess of the rated voltage;
 - b. Use the highest-speed motor that an application can accommodate. Two-pole (nominal 3600 rpm) motors have the highest power factors. Note that power factor decreases as the number of poles increases;
 - c. Eliminate unloaded motors and transformers. Size motors as close as possible to the horsepower demands of the load. A lightly loaded motor requires little real power. A heavily loaded motor requires more real power. Since the reactive power is almost constant, the ratio of real power to reactive power varies with induction motor load, and ranges from about 10 percent at no load to as high as 85 percent or more at full load. An oversized motor, therefore, draws more reactive current at light load than does a smaller motor at full load;
 - d. Low power factor results when motors are operated at less than full load. This often occurs in cyclic processes (such as circular saws, ball mills, conveyors, compressors, grinders, extruders, or punch presses) where motors are sized for the heaviest load. In these applications, power factor varies from moment to moment. Examples of situations include a surface grinder performing a light cut, an unloaded air compressor, and a circular saw spinning without cutting.
- 2) Compensate artificially for the consumption of reactive energy with power factor capacitors. Power capacitors serve as leading reactive current generators and counter the lagging reactive current in the system. By providing reactive current, they reduce the total amount of current your system must draw from the utility. In practice, two type of equipment are available for power factor correction:
 - a. Rotary Equipment: Phase advancers, synchronous motors and synchronous condensers. Where auto-synchronous motors are employed the power factor correction may be a secondary function.

- b. Capacitors: Power factor correction is achieved by the addition of capacitors in parallel with the connected motor circuits and can be applied at the starter, or applied at the switchboard or distribution panel. Capacitors connected at each starter and controlled by each starter is known as "Static Power Factor Correction" while capacitors connected at a distribution board and controlled independently from the individual starters are known as "Bulk Correction".

Generally the cost of rotating machinery, both synchronous and phase advancing, makes its use uneconomical, except where one is using rotating plant for a dual function: drive and power factor correction. In addition, the wear and tear inherent in all rotating machines involves additional expense for upkeep and maintenance.

Capacitors have none of these disadvantages. Compared with other forms of correction, the initial cost is very low, upkeep costs are minimal and they can be used with the same high efficiency on all sizes of installation. They are compact, reliable, highly efficient & convenient to install and lend themselves to individual, group or automatic method of correction. The static capacitor owing to its low losses, simplicity and high efficiency is now used almost universally for power factor correction.

What is a Capacitor?

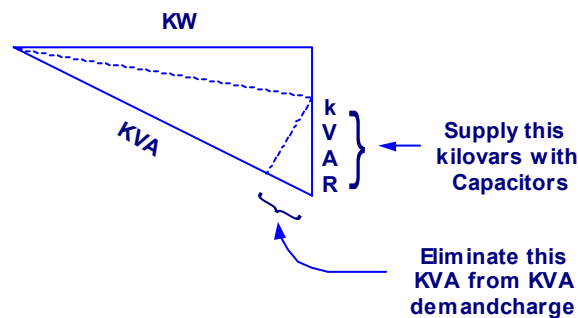
Simply put, a capacitor is an electric device that can store electric charge for later release. Generally, capacitors are used in one of the three ways: to store and release energy, to discriminate between DC (direct current) and AC (alternating current) frequencies, and to discriminate between higher and lower AC frequencies.

A simple capacitor consists of two metal plates that are held parallel to each other with a small space between them. The space is occupied by an insulating material called dielectric. This insulating material can be made of many materials including oil, paper, glass, ceramics, mica, plastic, or even air. Capacitance is a measure of the energy that a capacitor is capable of storing. The capacitance of a device is directly proportional to the surface areas of the plates and inversely proportional to the plates' separation.

How Capacitors Work

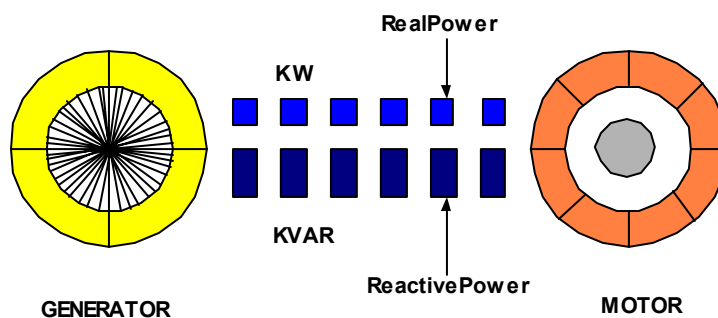
Induction motors, transformers and many other electrical loads require magnetizing current (KVAR) as well as actual power (KW). By representing these components of apparent power (KVA) as the sides of a right triangle, we can determine the apparent power from the right triangle rule: $KVA^2 = KW^2 + KVAR^2$. To reduce the KVA required

for any given load, you must shorten the line that represents the KVAR. This is precisely what capacitors do.

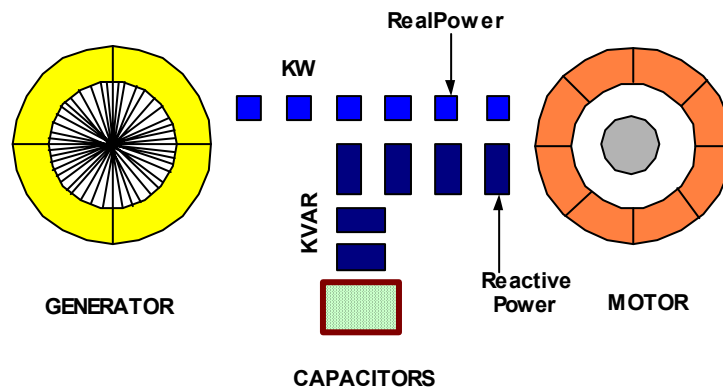


The capacitor performs the function of an energy storage device. By supplying KVAR right at the load, the capacitors relieve the utility of the burden of carrying the extra KVAR. This makes the utility transmission/distribution system more efficient, reducing cost for the utility and their customers.

The figure below shows an induction motor operating under partially loaded conditions without power factor correction. Here the feeder line must supply both magnetising (reactive) and useful currents.



The figure below shows the results of installing a capacitor near the same motor to supply the magnetising current required to operate it. The total current requirement has been reduced to the value of the useful current only, thus either reducing power cost or permitting the use of more electrical equipment on the same circuit.



In the illustration above, addition of the capacitor has improved line power factor and subtracted the non-working current from the lines. Rather than transfer energy back and forth between load and generator, the reactive energy to supply the magnetizing current is now stored in a capacitor at the load, thus reducing the distribution requirements for excessive current. This reactive current supplied by the capacitor rather than the utility.

Correction Methods

Static or fixed Power Factor correction

Static or fixed capacitors provide a constant amount of reactive power to an electrical system on the load side of the AC motor starter (motor switched or "at the load"). Primarily, fixed capacitors are applied to individual motor loads, but they can also be applied to the main power bus with proper treatment. Fixed capacitors are suitable for indoor or outdoor use. Fixed capacitors are available in low voltages (832 volt and below), from .5 KVAR up to 400 KVAR (If more than 400 KVAR is required, smaller units are paralleled together). Advantages of individual capacitors at the load include:

- Complete control. Capacitors don't cause problems on the line during light load conditions;
- No need for separate switching. The motor always operates with its capacitor;
- Improved motor performance due to reduced voltage drops;
- Motors and capacitors can be easily relocated together;
- Easier to select the right capacitor for the load;
- Reduced line losses;
- Increased system capacity.

Central or Bulk Power Factor correction

Central power factor compensation is applied for electrical systems with fluctuating loads. The central power factor correction is usually installed at the main power distribution. The capacitors are controlled by a microprocessor based relay which continuously monitors the power factor of the total current supplied to the distribution board. The relay then connects or disconnects capacitors to supply capacitance as needed in a fashion to maintain a power factor better than a preset limit (typically 0.95). Ideally, the power factor should be as close to unity as possible.

When harmonic distortion is a concern, systems are built based on the principles explained under 'Harmonic Distortion and Power Factor Correction' later in this course. The advantages of bank installations at the feeder or service entry are:

- Lower cost per kVAR;
- Lower installation costs;
- Total plant power factor improves which reduces or eliminates utility power factor penalty charges;
- Total kVAR may be reduced, as all capacitors are on-line even when some motors are switched off;
- Automatic switching ensures the exact amount of power factor correction and eliminates over-capacitance and resulting over-voltages.

Choice between Static and Bulk Connection

If your facility operates at a constant load around-the-clock, fixed capacitors are the best solution. If load is variable such as eight-hour shifts five days a week, you'll require switched units to decrease capacitance during times of reduced load.

If your feeders or transformers are overloaded, or if you wish to add additional load to already loaded lines, you should apply power factor correction at the load. If your facility has excess current carrying capacity, you can install capacitor banks at main feeders.

Determining Capacitor Requirements

The total KVAR rating of capacitors required to improve the power factor to any desired value can be calculated by using the tables published by leading power factor capacitor manufacturers.

Calculation Table for Capacitor Selection

Power factor $\text{Cos}\theta_2$ after improvement														
Power factor $\text{Cos}\theta_1$ before improvement														
		1.0	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90	0.85	0.80
	0.5	1.73	1.59	1.53	1.48	1.44	1.40	1.37	1.34	1.30	1.28	1.25	1.11	0.98
	0.52	1.64	1.50	1.44	1.39	1.35	1.32	1.28	1.25	1.22	1.19	1.16	1.02	0.89
	0.55	1.52	1.38	1.32	1.27	1.23	1.19	1.16	1.12	1.09	1.06	1.04	0.90	0.77
	0.57	1.44	1.30	1.24	1.19	1.15	1.11	1.08	1.05	1.01	0.99	0.96	0.82	0.69
	0.6	1.33	1.19	1.13	1.08	1.04	1.01	0.97	0.94	0.91	0.88	0.85	0.71	0.58
	0.62	1027	1.23	1.06	1.01	0.97	0.94	0.90	0.87	0.84	0.81	0.78	0.65	0.52
	0.65	1.17	1.03	0.97	0.92	0.88	0.84	0.81	0.77	0.74	0.71	0.69	0.55	0.42
	0.67	1.11	0.97	0.91	0.86	0.82	0.78	0.75	0.71	0.68	0.65	0.62	0.49	0.36
	0.7	1.02	0.88	0.81	0.77	0.73	0.69	0.66	0.62	0.59	0.56	0.54	0.40	0.27
	0.72	0.96	0.82	0.75	0.71	0.67	0.63	0.60	0.57	0.53	0.51	0.48	0.34	0.21
	0.75	0.88	0.74	0.67	0.63	0.58	0.55	0.52	0.49	0.45	0.43	0.40	0.26	0.13
	0.77	0.83	0.69	0.62	0.58	0.54	0.50	0.47	0.43	0.40	0.37	0.35	0.21	0.08
	0.8	0.75	0.61	0.54	0.50	0.46	0.42	0.39	0.35	0.32	0.29	0.27	0.13	
	0.82	0.70	0.56	0.49	0.45	0.41	0.37	0.34	0.30	0.27	0.24	0.21	0.08	
	0.85	0.62	0.48	0.42	0.37	0.33	0.29	0.26	0.22	0.19	0.16	0.14		
	0.87	0.57	0.42	0.36	0.32	0.28	0.24	0.20	0.17	0.14	0.11	0.08		
	0.90	0.48	0.34	0.28	0.23	0.19	0.16	0.12	0.09	0.06	0.02			

0.91	0.45	0.31	0.25	0.21	0.16	0.13	0.09	0.06	0.02				
0.92	0.43	0.28	0.22	0.18	0.13	0.10	0.06	0.03					
0.93	0.40	0.25	0.19	0.15	0.10	0.07	0.03						
0.94	0.36	0.22	0.16	0.11	0.07	0.04							
0.95	0.33	0.18	0.12	0.08	0.04								
0.96	0.29	0.15	0.09	0.04									
0.97	0.25	0.11	0.05										
0.98	0.20	0.06											
0.99	0.14												

To properly select the amount of KVAR required to correct the lagging power factor of a 3-phase motor you must follow the steps below:

Step #1: Determine KW and Existing Power Factor.

Step # 2: Existing Power Factor on Table, move across table to Desired Power Factor. The number represented is your multiplier number.

Step #3: Multiply KW by the multiplier of the Desired Power Factor.

Example-1

Assume factory load: 200 KW

Power factor before improvement: $\cos \theta_1 = 0.80$

Expected power factor: $\cos \theta_2 = 0.95$

Ratio of needed power capacity calculated from the above table is 0.42 thus needed capacity $C = 200 \times 0.42 = 84$ KVAR

If KW or present power factor is not known you can calculate from the following formulas (applicable for 3-phase supply) to get the three basic pieces of information required to calculate KVAR:

$$PF = \frac{kW}{kVA}$$

$$kVA = \frac{1.73 \times I \times E}{1000}$$

$$kW = \frac{1.73 \times I \times E \times PF}{1000} \quad \text{or} \quad kW = \frac{HP \times .746}{\text{eff.}}$$

Where

- I = full load current in amps
- E = voltage of motor
- PF = Present power factor as a decimal (80% = 0.80)
- HP = rated horsepower of motor
- eff. = rated efficiency of motor as a decimal (83% = .83)

If desired power factor is not provided, 95% is a good economical power factor for calculation purposes.

Example-2

How many KVAR are needed to correct an existing power factor of 62% to 95% for a three-phase induction motor operating at 480V and 62A?

Solution

1. Actual power:

$$KW = 480 \times 62 \times 0.62 \times 1.732 / 1000 = \sim 32 \text{ KW}$$

2. The leading reactive power KVAR necessary to raise the power factor to 95% is found by multiplying 32 KW by the factor found from the correction table for capacitor selection (refer above) , which is 0.937

$$32 \text{ KW} \times 0.937 = 29.98 \text{ KVAR}$$

Use 30 KVAR

Example-3

An energy audit for a facility indicates following measurements at the load side of the transformer; 480V, 1200A and 800 KW operating load.

- a. What is the Power Factor?
- b. How much Reactive Power (KVAR) is in the system?

Solution

- a. To calculate the Power Factor, first calculate the KVA in the system.

$$\text{KVA} = \frac{V \times A \times \sqrt{3}}{1000} = \frac{480 \times 1200 \times \sqrt{3}}{1000} = \mathbf{1000kVA}$$

Substitute the KVA into the Power Factor Formula

$$\text{P.F.} = \frac{\text{KW}}{\text{kVA}} = \frac{800}{1000} = \mathbf{.80 \text{ or } 80\% \text{ P.F.}}$$

- b. To calculate the Reactive Power (KVAR) in the system requires re-arranging the formula $\text{kVA}^2 = \text{KW}^2 + \text{kVA}^2$ and solving for KVAR.

Example - 4

The measurement at the main distribution board of a manufacturing industry indicates 1000 KVA and 800 KW. Determine the system KVAR and PF of the facility. Determine also the KVAR required for achieving power factor of 0.95 while providing the same productive power of 800 KW?

Solution

Measured KVA = 1000

Measured KW = 800

- a. System KVAR and PF of the facility

$$\text{kVAR} = \sqrt{\text{kVA}^2 - \text{KW}^2} = \sqrt{1000^2 - 800^2} = \mathbf{600kVAR}$$

$$\text{P.F.} = \frac{\text{KW}}{\text{kVA}} = \frac{800}{1000} = \mathbf{.80 \text{ or } 80\% \text{ P.F.}}$$

- b. System KVAR after power factor correction to .95

System KVA after correction

$$\text{kVA} = \frac{\text{KW}}{\text{PF}} = \frac{800}{.95} = \mathbf{843}$$

System KVAR after correction

$$\text{kVAR} = \sqrt{\text{kVA}^2 - \text{KW}^2} = \sqrt{843^2 - 800^2} = \mathbf{265kVAR}$$

- c. Power capacitor KVAR rating

Power Capacitor KVAR = KVAR (uncorrected) – KVAR (corrected)

$$= 600 - 265 = 335 \text{ KVAR}$$

Use the multiplier table above for capacitor selection, when the KW load, uncorrected power factor and the desired power factor are known as shown in the examples above.

Example - 5:

Billing based on KW Demand Charges

An industrial plant has a demand of 1000 KW and operates at 80% power factor. The utility company supplying power to this unit requires minimum power factor of 85% and levies a KW demand charge of \$8.00 in the electricity bill. Determine the savings possible by improving the power factor to a minimum required target of 0.85 along with the payback period of putting any investment on power factor correction.

Solution

- a. The monthly KW billing is determined by the ratio of target power factor to the existing power factor times KW demand.

KW billing on power factor of 0.80

The amount of monthly KW billing: $1000\text{KW} \times 0.85 \text{ target PF} / 0.80 \text{ existing PF} = 1062 \text{ KW}$

Total demand charge @ \$ 8.00 = $1062\text{KW} \times \$ 8.00 = \8496

- b. KVAR required to increase power factor from 0.8 to 0.85

The multiplying factor = 0.13 (from the capacitor estimation table above)

Therefore KVAR required = $0.13 \times 1000 = 130 \text{ KVAR}$

- c. Capacitor Investment

Cost of 130 KVAR of capacitors (on a 480 volt system, installed capacitor cost is approx \$15/KVAR)

$130\text{KVAR} \times \$ 15.00 = \$ 1950$

- d. KW billing on new Power Factor of 0.85

The amount of monthly KW billing: $1000\text{KW} \times 0.85 \text{ target PF} / 0.85 \text{ modified PF} = 1000 \text{ KW}$

Modified demand charge @ \$ 8.00 = $1000 \text{ KW} \times \$ 8.00 = \8000

e. Payback Period

Monthly savings on demand charge = \$8496 - \$8000 = \$496

Investment on capacitors = \$ 1950

Simple Payback = First cost/ savings = \$1950 / \$496 = approx 3.9 months. The savings shall continue thereafter.

Example - 6:

Billing based on KVA Demand Charges

An industrial plant is operating at 400 KW and maximum demand of 520 KVA. The facility has a power contract based KVA demand charges which shall reduce as the power factor is improved. The demand charges rates have been fixed at \$3.00 per month per KVA. Determine the savings possible by improving the power factor along with the payback period of putting any investment on power factor correction.

Solution

The KVA demand can be reduced if the power factor is raised. Often 95% is a good economical power factor when the demand charges are based on KVA charges.

- a. The Present Power Factor = KW/KVA = 400/520 = 77%
- b. Present demand charge = 520 x \$ 3 = \$1560
- c. Assuming that we target the new power factor to 95%. This would reduce the present 520 KVA demand down to 421KVA. Calculation as follows:

Reduced KVA = KW/modified power factor = 400/0.95 = 421KVA

- d. Modified demand charge = 421 x \$ 3 = \$1263
- e. Probable Savings = \$1560 - \$1263 = \$297
- f. KVAR required to increase power factor from 0.77 to 0.95

The multiplying factor = 0.5 (from the capacitor estimation table above)

Therefore KVAR required = 0.5 x 400 = 200 KVAR

- g. Capacitor Investment

Cost of 200 KVAR of capacitors (on a 480 volt system, installed capacitor cost is approx \$15/KVAR)

200 KVAR x \$ 15.00 = \$ 3000

h. Payback Period

Monthly savings on demand charge = \$297

Investment on capacitors = \$ 3000

Simple Payback = First cost/ savings = \$ 3000/ \$297 = approx 10 months. The savings shall continue thereafter.

In addition, by installing the 200 KVAR of capacitors an additional 20% capacity is immediately available for new motor and lighting loads without installing any new transformers, power lines or distribution equipment. This is important because in critical times the new transformers and power lines may be difficult to obtain, and their costs, in most cases, would exceed the \$3000 spent for capacitors.

Example – 7

Billing Based on KW & KVAR Demand Charges

A hotel complex with majority of HVAC and lighting load has a contract for power factor which includes an energy charge for KWH, a demand charge based on KW and another demand charge based on KVAR. The KVAR charge is \$1.5 per month for each KVAR of demand in excess of 1/3 of the KW demand. The operating electrical characteristics are 1800 KVA, 1350 kW and 1200 KVAR. Determine the possible savings on reducing the KVAR demand charges by the addition of power factor correction capacitors along with the simple payback.

Solution:

- a. The KVAR demand can be eliminated by the addition of capacitors. KVAR demand in excess of 1/3 of the kW demand can be calculated as:

$$1200 \text{ KVAR} - \frac{1350 \text{ kW}}{3} = 750 \text{ KVAR} \times 1$$

This implies that 750 KVAR supplies, if provided by capacitors can do away with this extra demand charges.

- b. Estimated annual power bill savings

$$\text{\$1.50 demand charge} \times 750 \text{ KVAR} \times 12 \text{ months} = \text{\$13,500 savings per annum}$$

- c. Estimated cost of 750 KVAR capacitors

Probable cost of 480 volt, 60 Hz capacitors shall be \$ 15 per KVAR. Therefore total investment for 750 KVAR capacitors shall be:

$$750 \text{ KVAR} \times \$15 = \$11,250$$

d. Simple Payback Period

\$13,500 annual savings vs. \$11,250 capacitor investment

Capacitors will pay for themselves in 10 months, and continue to produce savings thereafter.

Example - 8:

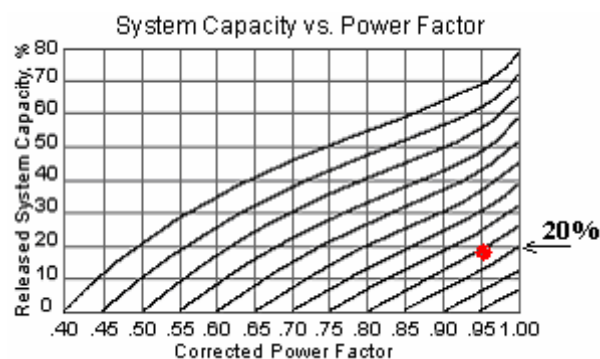
Increased System Capacity

A facility electrical system is operating at following characteristics: KVA = 1000, KW = 800, KVAR = 600, PF = 0.80 Determine how much spare capacity can be released by improving power factor to 0.95.

Solution

The uncorrected system can only support 800 KW of Productive Power at a PF of 0.80

The figure below shows the empirical relationship of system capacity vs. power factor. From the figure one can see that improving power factor from 0.8 to 0.95 shall release approximately 20% system capacity.



The corrected system is now capable of supporting 960 KW of productive power.

The system capacity has been increased by 160 KW.

Example - 9:

Lower Losses

Assume facility system wide losses = 5% with a current power factor of 0.80.

Estimate the reduction in losses when the power factor correction is made at the load points to unity.

Solution:

Improving power factor at the load points shall relieve the system of transmitting reactive current. Less current shall mean lower losses in the distribution system of the facility since losses are proportional to the square of the current (I^2R). Therefore, fewer kilowatt-hours need to be purchased from the utility.

An estimate of reduction of power losses can be made using the following equation:

$$\% \text{ Reduction of Power Losses} = 100 - 100 \left(\frac{\text{Original Power Factor}}{\text{Improved Power Factor}} \right)^2$$

$$\text{Or } 100 - 100(.80 / 1.0)^2$$

$$= 100 - 100(.64) = 36\%$$

The original facility system losses of 5% are reduced by $5 \times 36 / 100 = 1.8\%$

As a result the monthly KWH billing is reduced by 1.8%; an additional saving.

Typical Locations for Power Capacitors (Where/ What Type to Install)

The successful operation of a power factor correction depends largely on the correct positioning of the capacitors in the network. The relevant factors are: tariff in force; metering point; details of light, average and full load KVA, KW and power factor; position of motors, welding equipment, transformers or other equipment causing bad power factor; and supply system problems such as harmonics. The siting of the capacitors, does to some extent, depend on whether each piece of equipment (e.g. a motor or a transformer) is being individually corrected or the installation as a whole or part is being corrected as a block (generally known as bulk or group connection). In the first case the capacitor and the load (motor, transformer etc.) are as close together as possible. In the second case the capacitor is located at some convenient point in the system, such as a substation.

Before power capacitors can be placed, the physical location of the utility meter should be determined since all power capacitors must be installed “downstream” of the meter.

There are three basic locations for Power Capacitors:

Option #1: Individual capacitor installation at the level of each machine:

- Load side of the AC motor, commonly referred to as “at the load” or “motor switched”

When the capacitors are installed directly at the induction motor terminals (on the secondary of the overload relay), the capacitors are turned on and off with the motors, eliminating the need for separate switching devices or over current protection. The capacitors are only energized when the motor is running.

Capacitors installed near the loads in a plant provide spot delivery of magnetizing current (KVAR) just at the load, which eliminates unnecessary reactive current in the feeder lines thereby reducing the line losses, minimizing voltage drops and maximizing system capacity. This is one of the most economical and efficient way of supplying these kilovars, which relieves both you and your utility of the cost of carrying this extra kilovar load.

The drawback is that large number of capacitors may be needed for individual motor correction, increasing the installation costs (\$ per KVAR compensation). Also overload relay settings need to be changed to account for lower motor current draw. If the capacitors are installed between the contactor and the overload relay, the overload relay can be set for nameplate full load current of motor.

Option #2: Group or bank installation:

- Small motors operating from a common starter
- Load side of the utility transformer on the distribution bus
- Bank installation at Feeders, Sub-stations, or Transformers

Installing capacitors between the upstream circuit breaker & the contactor or at the main distribution bus ensures lower installation cost since you install fewer banks in large KVAR blocks. The drawback is that since reactive current must be carried a greater distance, there are higher line losses and larger voltage drops. Another drawback is that overcorrection may occur under lightly loaded conditions. A separate disconnect switch and over current protection is required. It is recommended to consider automatic switched banks with such an installation.

Option #3: Mixed installation, at both the individual and group level:

Installations not operating continuously and which may be supplied at high voltage but with low voltage loads should employ low voltage capacitors for power factor improvement. Low voltage switch gear is much cheaper than high voltage switch gear and obviously is available with much lower ratings which enable relatively small capacitor steps (100 KVAR and below) to be employed for automatically controlled capacitors. This ensures flexibility of operation without excessive switchgear costs.

The advantages and drawbacks of option #3 shall be same as discussed under option #1 and option #2.

In providing the power factor correction it should be remembered that distribution boards and circuits can carry a greater useful load if the capacitors are installed as near as possible to the source of low power factor. For this reason either bulk or individual correction, rather than correction at the intake point, can almost invariably be justified.

In an installation where the low voltage load is supplied from several distribution substations, local automatic control at each substation is generally much cheaper as well as operationally superior to an elaborate method of overall control operated from the point of incoming supply.

After careful consideration of the advantages and disadvantages of the various installation options, care must be taken in sizing and placing power factor correction capacitors. Leading power factor, greater than 100%, must be avoided. The capacitors should only be on line when the load requires KVAR and disconnected when the load is reduced.

Summarizing....

The greatest power factor correction benefits are derived when you place capacitors at the source of reactive currents. It is thus common to distribute capacitors on motors throughout an industrial plant. This is a good strategy when capacitors must be switched to follow a changing load. If your plant has many large motors (25 hp and above), it is usually economical to install one capacitor per motor and switch the capacitor and motor together. Switched capacitors don't require separate switch control equipment when they are located on the load side of motor contactors. Thus, capacitors installed on the larger motors are nearly as economical as fixed banks installed at motor control centres. When some switching is required, the most economical method is to install a base amount of fixed capacitors that are always energized, with the remainder on the larger motors and switched when the motors are energized. Observe load patterns in order to determine good candidate motors to receive capacitors.

If your plant contains many small motors (in the 1/2 to 10 hp size range), it may be more economical to group the motors and place single capacitors or banks of capacitors at, or near, the motor control centres. If capacitors are distributed for loss reduction and also need to be switched, you can install an automatic power factor controller in a motor control centre; this provides automatic compensation and may

be more economical than capacitors on each of the small motors fed from that control center. Often the best solution for plants with large and small motors is to specify both types of capacitor installations. Sometimes, only an isolated trouble spot requires power factor correction. This may be the case if your plant operates welding machines, induction heaters, or DC drives. Facilities with very large loads typically benefit from a combination of individual load, group load, and banks of fixed and automatically-switched capacitor units.

How to Switch Capacitors Separately

When a group of motors are so operated that some run while others idle, single capacitor equipment (containing a number of individual capacitor units) can be connected to the bus to economically supply kilovars to the group. Capacitor equipment of this type need a separate switching device. The interrupting rating of the switching device should be at least as great as the short-circuit current available on the system on which it is applied. The switching device should be sized to exceed the capacitor nominal current as follows:

- magnetic breakers: 135%
- fusible switches: 165%
- moulded case breakers: 150%

For small capacitors, a separate wall-mounted switch or air circuit breaker of the enclosed type can be used. For large capacitors, the breaker or switch can be housed with the capacitors. When connected through metal-clad switchgear, capacitors should be treated as any other load and the breaker added to the existing switchgear.

If a large number of switching operations is expected, a solenoid-operated contactor may be used in place of a circuit breaker. The contactor offers a much longer expected life when switching normal load current. However, it does not provide short-circuit protection, so fuses must be added for this purpose where contactors are used.

Automatic Switching of Capacitors

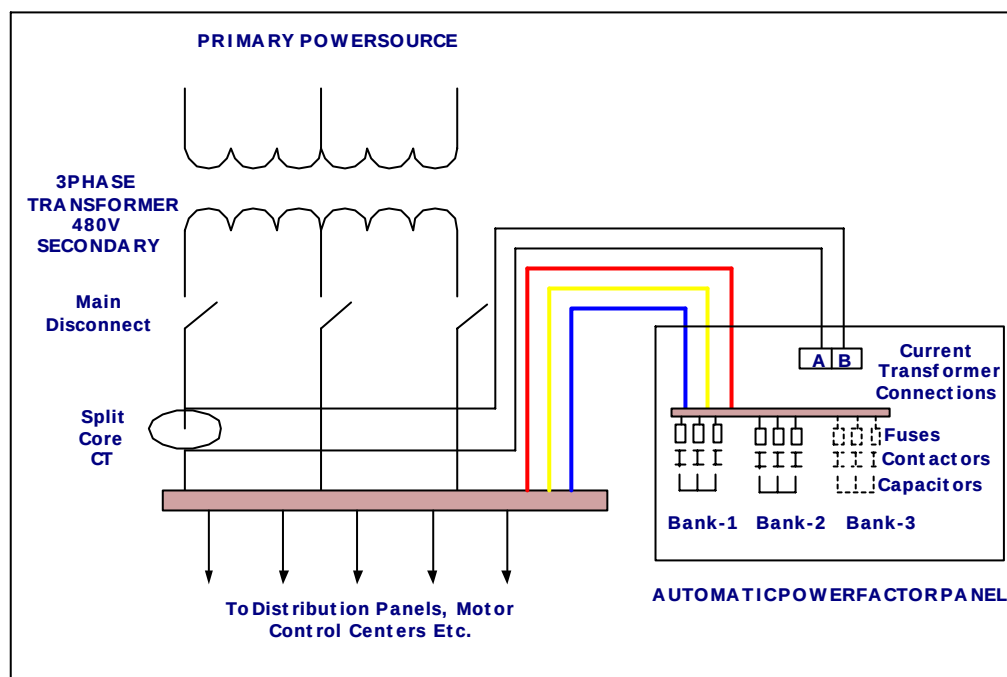
Automatic switching of capacitors is an ideal method of obtaining the full electrical and financial benefits from a capacitor installation. Automatic power factor correction is a microprocessor controlled system designed to continuously regulate the power factor to the specified levels by adjusting the amount of KVAR in relation to the variations in load. The system consists of a capacitor banks subdivided into a

number of equal steps, each step being controlled by a multi-step relay and air break contactors connected to the main bus bars. Each capacitor bank incorporates multiple single-phase cells that are wired in a delta connection for three-phase operation.

The target value of the power factor is adjustable. The operation is controlled by load current (CT) according to the power factor which is determined by the demand to control on/off the capacitors. During initial switch-on, the unit self checks the current and voltage connections and, if incorrect, displays a fault signal. The value of each stage can be programmed in manually or, if a 'self current' CT is fitted, the unit steps through the stages and memorizes the capacitive reactive power of each stage (learning mode). The unit can then select which step to switch to achieve the target power factor with the least switching operations.

Where contactor switching is used, a delay is programmed in to allow previously energized capacitors to discharge before being reconnected. Where thyristor switching is employed, this delay is not necessary as the switching takes place at zero volts.

The auto-control of the capacitor banks ensures that over-correction will not occur.



The number of stages installed is usually a compromise between the technical requirements and cost. Studies indicate that the resulting benefits, economics and convenience of automatic system far outweigh the initial cost.

The power factor controller can be programmed with many additional features. To protect the capacitors, the regulators are equipped with an automatic shutdown facility in the event of excess voltage or excess harmonics. A contact for a remote alarm may be included with programmable delay time. The regulators should have digital display of PF, current, volts; active power, reactive power, network harmonics and KVAR required achieving target power factor.

Size of capacitor bank

Capacitors are rated in kiloVARs or KVAR. Common sizes are 1, 2, 3, 4, 5, 6, 7, 8, 10/12/15/20 and 25 KVAR at 415 or 440V alternating current, 3 phase, 50 Hz.

Usually more than one capacitor is required give the desired degree of power factor correction. Groups of capacitors are factory assembled in various configurations. Standard capacitor ratings are designed for 50 or 60Hz operation. When operated at less than nameplate frequency of 50 or 60Hz, the actual KVAR attained will be less than rated KVAR. If the operating voltage is less than the rated voltage, a reduction in the nameplate KVAR will be realized. The following equation defines the relation:

$$\text{KVAR} = 2\pi f C E^2 \times 10^{-3}$$

$$C = \frac{\text{KVAR}}{2\pi f E^2 \times 10^{-3}}$$

- $\pi = 3.1416$
- $f = \text{Hz}$
- $C = \mu\text{F}$
- $E = \text{KV}$

Capacitor Required for Correction of Individual Motors

For correction to Power Factor of 0.95 of 415 Volts, 3-phase 4-pole motors with average characteristics can be referred from the following tables. Table 1 below contains generic values to be applied as a rule of thumb.

Table 1

MOTOR SIZE (KW)	CORRECTION (KVAR)	CAPACITOR FUSING (Amps)
3.0	1.5	4
4.0	2.0	4
5.5	2.5	6
7.5	3.0	6
11	5.0	10
15	6.25	16
18.5	8.0	16
22	10.0	20
30	12.5	25
37	15.0	32
45	15.0	32
55	20.0	40
75	20.0	40
90	25.0	50
110	25.0	50
132	30.0	63
150	35.0	80
185	40.0	80
220	45.0	100
250	50.0	100

Suggested Capacitor Ratings for T-Frame NEMA Class B Motors

Table - 2

Induction Motor Horsepower Rating	3600 RPM		1800 RPM		1200 RPM		900 RPM		720 RPM		600 RPM	
	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %
2	1	14	1	24	1.5	30	2	42	2	40	3	50
3	1.5	14	1.5	23	2	28	3	38	3	40	4	49
5	2	14	2.5	22	3	26	4	31	4	40	5	49
7.5	2.5	14	3	20	4	21	5	28	5	38	6	45
10	4	14	4	18	5	21	6	27	7.5	36	8	38
15	5	12	5	18	6	20	7.5	24	8	32	10	34
20	6	12	6	17	7.5	19	9	23	10	29	12.5	30
25	7.5	12	7.5	17	8	19	10	23	12.5	25	17.5	30
30	8	11	8	16	10	19	15	22	15	24	20	30
40	12.5	12	15	16	15	19	17.5	21	20	24	25	30
50	15	12	17.5	15	20	19	22.5	21	22.5	24	30	30
60	17.5	12	20	15	22.5	17	25	20	30	22	35	28
75	20	12	25	14	25	15	30	17	35	21	40	19
100	22.5	11	30	14	30	12	35	16	40	15	45	17
125	25	10	35	12	35	12	40	14	45	15	50	17
150	30	10	40	12	40	12	50	14	50	13	60	17
200	35	10	50	11	50	11	70	14	70	13	90	17
250	40	11	60	10	60	10	80	13	90	13	100	17
300	45	11	70	10	75	12	100	14	100	13	120	17
350	50	12	75	8	90	12	120	13	120	13	135	15
400	75	10	80	8	100	12	130	13	140	13	150	15
450	80	8	90	8	120	10	140	12	160	14	160	15
500	100	8	120	9	150	12	160	12	180	13	180	15

Suggested Capacitor Ratings for High-Efficiency motors

Table - 3

Number of Poles and nominal motor speed in RPM												
Induction Motor Horsepower Rating	2 - 3600 RPM		4 - 1800 RPM		6 - 1200 RPM		8 - 900 RPM		10 - 720 RPM		12 - 600 RPM	
	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %	Capacitor kVAR	Current Reduction %
3	1.5	14	1.5	15	1.5	20	2	27	2.5	35	3	41
5	2	12	2	13	2	17	3	25	4	32	4	37
7.5	2.5	11	2.5	12	3	15	4	22	5	30	6	34
10	3	10	3	11	3	14	5	21	6	27	7.5	31
15	4	9	4	10	5	13	6	18	8	23	9	27
20	5	9	5	10	6	12	7.5	16	9	21	12.5	25
25	6	9	6	10	7.5	11	9	15	10	20	15	23
30	7	8	7	9	9	11	10	14	12.5	18	17.5	22
40	9	8	9	9	10	10	12.5	13	15	16	20	20
50	12.5	8	10	9	12.5	10	13	12	20	15	25	19
60	15	8	15	8	15	10	17.5	11	22.5	15	27.5	19
75	17.5	8	17.5	8	17.5	10	20	10	25	14	35	18
100	22.5	8	20	8	20	9	27.5	10	35	13	40	17
125	27.5	8	25	8	30	9	30	10	40	13	50	16
150	30	8	30	8	35	9	37.5	10	50	12	50	15
200	4	8	37.5	8	40	8	50	10	60	12	60	14
250	50	8	45	7	50	8	60	9	70	11	75	13
300	60	8	50	7	60	8	60	9	80	11	90	12
350	60	8	60	7	75	8	75	9	90	10	95	11
400	75	8	60	6	75	8	85	9	95	10	100	11
450	75	8	75	6	80	8	90	9	100	9	110	11
500	75	8	75	6	85	8	100	9	100	9	120	10

Note: These tables are intended for use with three-phase, 600Hz Design B motors (NEMA MG 1-1993) to raise full-load power factor to approximately 95%.

Important Considerations for Static Power Factor Correction

As a large proportion of the inductive or lagging current on the supply is due to the magnetizing current of induction motors, it is easy to correct each individual motor by connecting the correction capacitors to the motor starters. *With static correction, it is important that the capacitive current is less than the inductive magnetizing current of the induction motor.* In many installations employing static power factor correction, the correction capacitors are connected directly in parallel with the motor windings. When the motor is 'Off Line', the capacitors are also 'Off Line'. When the motor is connected to the supply, the capacitors are also connected providing correction at all times that the motor is connected to the supply. This removes the requirement for any expensive power factor monitoring and control equipment. In this situation, the capacitors remain connected to the motor terminals as the motor slows down.

Never overcorrect the motor when static correction is applied:

An induction motor, while connected to the supply, is driven by a rotating magnetic field in the stator which induces current into the rotor. When the motor is disconnected from the supply, there is still for a period of time a magnetic field associated with the rotor. As the motor decelerates, it generates voltage out of its terminals at a frequency which is related to its speed. The capacitors connected across the motor terminals form a resonant circuit with the motor inductance. If the motor is critically corrected, (corrected to a power factor of 1.0) the inductive reactance equals the capacitive reactance at the line frequency and therefore the resonant frequency is equal to the line frequency. If the motor is over corrected, the resonant frequency will be below the line frequency. If the frequency of the voltage generated by the decelerating motor passes through the resonant frequency of the corrected motor, there will be high currents and voltages around the motor/capacitor circuit. This can result in severe damage to the capacitors and motor. It is imperative that motors are never over corrected or critically corrected when static correction is employed. Ideally, static power factor correction should provide capacitive current equal to 80% of the magnetizing current, which is essentially the open shaft current of the motor.

The magnetizing current for induction motors can vary considerably:

Typically, magnetizing currents for large two pole machines can be as low as 20% of the rated current of the motor while smaller low speed motors can have a magnetizing current as high as 60% of the rated full load current of the motor. It is not practical to use a "Standard table" for the correction of induction motors giving

optimum correction on all motors. Tables result in under correction on most motors but can result in over correction in some cases. Where the open shaft current can not be measured, and the magnetizing current is not quoted, an approximate level for the maximum correction that can be applied can be calculated from the half load characteristics of the motor. It is dangerous to base correction on the full load characteristics of the motor as in some cases, motors can exhibit a high leakage reactance, and correction to 0.95 at full load will result in overcorrection under no load, or disconnected conditions.

Providing Static Correction:

Static correction is commonly applied by using one contactor to control both the motor and the capacitors. It is better practice to use two contactors, one for the motor and one for the capacitors. Where one contactor is employed, it should be upsized for the capacitive load. The use of a second contactor eliminates the problems of resonance between the motor and the capacitors.

Where not to use Static Power Factor Correction:

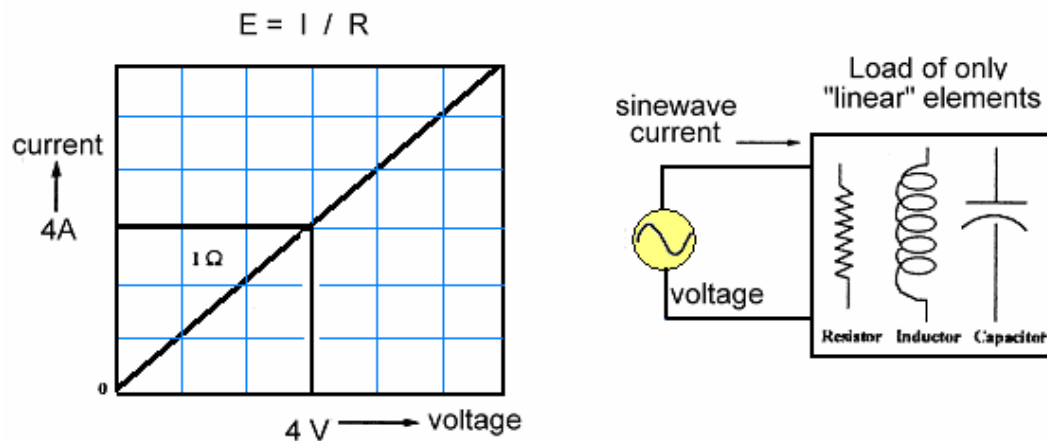
- a) **Inverter:** Static Power factor correction must not be used when the motor is controlled by a variable speed drive or inverter.
- b) **Solid State Soft Starter:** Static Power Factor correction capacitors must not be connected to the output of a solid state soft starter. When a solid state soft starter is used, the capacitors must be controlled by a separate contactor, and switched in when the soft starter output voltage has reached line voltage. Many soft starters provide a "top of ramp" or "bypass contactor control" which can be used to control the power factor correction capacitors.

Harmonic Distortion and Power Factor Correction

The rapid increase of semiconductor technology in electrical systems has led to a phenomenon known as 'Harmonics'. Harmonics are produced by solid-state *electronic devices and other non-linear electronic* loads that alter or control electrical power. Harmonics is referred to as the frequencies that are integer multiples of the fundamental line frequency of 60Hz. These non-linear loads include: adjustable speed drives, programmable controllers, induction furnaces, computers, and uninterruptible power supplies.

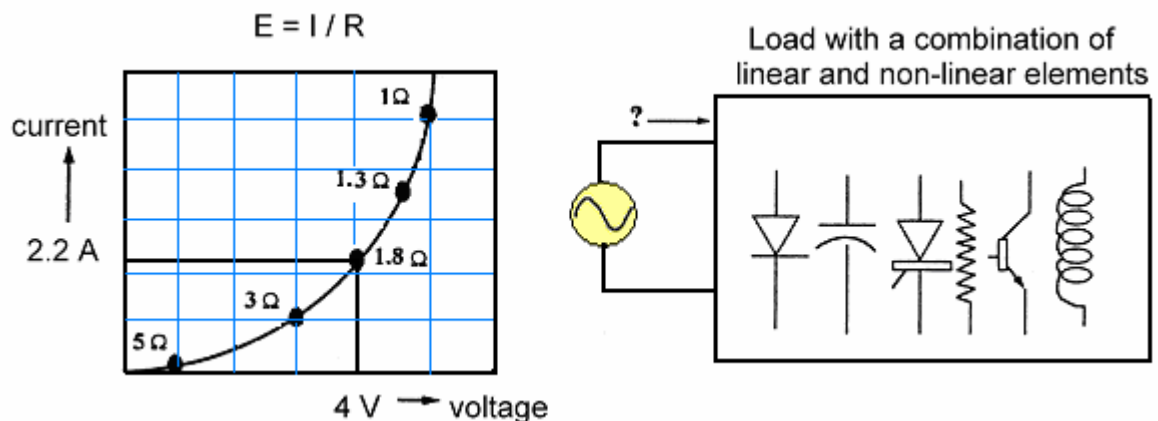
Linear loads

Linear loads occur when the impedance is constant; which implies the current is proportional to the voltage -- a straight-line graph as shown in the figure below. Simple loads, composed of one of the elements do not produce harmonics.



Non-linear loads

Non-linear loads occur when the impedance is not constant; then the current is not proportional to the voltage -- as shown in the figure below. Combinations of the components normally create non-linear loads and harmonics.



The Cause:

The non-linear loads (electronic systems) dramatically increase harmonic noise on the line side of the power distribution plant which impacts the whole electrical distribution system. Typical examples of non-linear loads (harmonic sources) are:

Electronic Switching Power Converters

- o Computers

- o Uninterruptible power supplies (UPS)
- o Solid-state rectifiers
- o Electronic process control equipment, PLC's, etc
- o Electronic lighting ballasts, including light dimmer
- o Neon SCR controlled equipment
- o Reduced voltage motor controllers
- o DC drives

Arcing Devices

- o Discharge lighting, e.g. Fluorescent, Sodium and Mercury vapor
- o Arc furnaces
- o Welding equipment
- o Electrical traction system

Ferromagnetic Devices

- o Transformers operating near saturation level
- o Magnetic ballasts (Saturated Iron core)
- o Induction heating equipment
- o Chokes

Appliances

- o TV sets, air conditioners, washing machines, microwave ovens & vacuum cleaners
- o Fax machines, photocopiers, printers

The Effect:

Harmonics have detrimental effect on the electrical power system in a facility. Overheated neutrals, hot circuit breakers, unexpected breaker tripping, dangerously hot transformers, unexplainable equipment malfunctions, spurious system lockup, and more are now common problems in many facilities. These problems can cause financial losses through added maintenance cost, staff downtime and interrupted production.

Signs of Harmonic Distortion Problems

- o Overheating of motors and transformers
- o Frequent tripping of circuit breakers
- o Frequent fuse blowing
- o Capacitor failures
- o Overloading of transformer neutrals
- o Telephone interference
- o Disoperation of motor variable-speed drives
- o PLC and computer failures – “frozen” screens
- o Electric component & Insulation failures
- o Severe lamp flicker
- o Failure or malfunctioning of computers, motor drives, lighting circuits and other sensitive loads

If any of these conditions exist in your facility, an analysis of your system will pinpoint the problem.

Harmonics and Power Factor Capacitors

With non-linear loads it is extremely difficult to correct for poor power factor without increasing existing harmonic distortion; thereby trading one problem for another. The simple answer is to treat both problems simultaneously.

The harmonics lead to a higher capacitor current, because the higher frequencies are attracted to the capacitor. The impedance of the capacitor decreases as the frequency increases. If the frequency of such a resonating circuit is close enough to a harmonic frequency, the resulting circuit amplifies the oscillation and leads to immense over-currents and over-voltages.

Capacitors themselves do not generate harmonics, but under certain conditions they can amplify existing harmonics. Necessary precautions must be undertaken when selecting the capacitors. If capacitor is installed in a circuit with harmonics, normally it should be equipped with 6% series reactor. For circuit with significant 5th harmonic, it should be equipped with 8% series reactor. For the circuit with 3rd harmonic, like arc furnace, it should be equipped with 13% series reactor. For the capacitor installed as non-fixed use, it should be equipped with 6% series reactor. If the capacitor is

equipped with reactor, its rated voltage should be increased 15% - 20% to ensure safety and extend life-time of capacitor.

To minimize the occurrence of harmonic resonance, the resonant harmonic of the system including the capacitor should be estimated. The resonant frequency can be calculated by:

$$h = \sqrt{\frac{KVA_{sc}}{KVAR}}$$

Where

- h = calculated system harmonic
- KVA_{sc} = short circuit power of the system
- KVAR = rating of the capacitor

In three-phase, low-voltage systems, harmonic values of 5, 7, 11, 13, 17, 19 etc. should be avoided as they correspond to the characteristic harmonics of non-linear loads. This includes all of the odd harmonics except for the multiples of 3. Examples of such devices are variable-speed and variable-frequency ac drives, dc drives, three-phase power-controlled furnaces and many other types of industrial equipment.

In single-phase, low-voltage systems, generally exhibit the following harmonics: 3, 5, 7, 9, 11, 13 etc. Note that this includes all of the odd harmonics. Examples of such devices are those usually powered by 'switch mode power supplies', which include personal computers, fluorescent lighting, and a myriad of other equipment found in the modern office. It also includes equipment found in hospitals, TV and radio stations, and control rooms of large processing plants. The harmonics from these devices are generally richest at the third harmonic and continually decrease as the harmonic number increases.

The Options to Reduce Harmonics:

Harmonic levels that exceed the recommended values set forth by IEEE 519 1992 should be addressed through harmonic filtering. Failure to address these harmonic issues may lead to problems on the electrical distribution system, such as those detailed above. Active harmonic power correction filters are a solution. These sense the critical portions of "dirty" power and inject a correcting element to clean the power. By truly canceling the harmonic component, the true fundamental becomes the only component that is reflected back to the line.

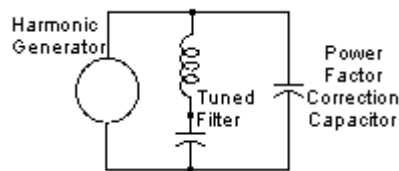
Once identified the resonant harmonics can be avoided in several ways:

1. Change the applied KVAR to avoid unwanted harmonics

Although this is the least expensive way to avoid resonant harmonics, it is not always successful because typically some portion of the applied KVAR is switched on and off as load conditions require. The calculation of system harmonics should be repeated for each level of compensation. Adjusting the size of the capacitor(s) may be necessary to avoid the harmonic values.

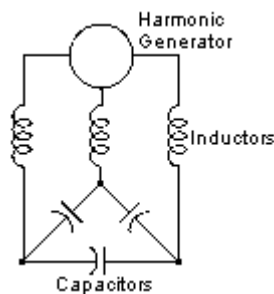
2. Add harmonic filters

In order to filter harmonics at a specific site, tuned harmonic filters can be applied. A capacitor is connected in series with an inductor such that the resonant frequency of the filter equals the harmonic to be eliminated. Tuned filters should never be applied without a detailed analysis of the system. The currents expected to flow in the filter are difficult to predict and are a complex function of the system and load characteristics.



3. Add blocking inductors

Inductors added to the lines feeding the capacitor can be sized to block higher than 4th harmonic currents. This method protects the capacitor from the harmonics but does not eliminate the harmonics from the system. A system study is required to determine correct ratings for the capacitor and inductors.



Harmonic Limits in Electric Power Systems (IEEE 519 1992)

The harmonic voltage limitations set forth by IEEE 519 1992 are:

- 1) Maximum Individual Frequency Voltage Harmonic: 3%
- 2) Total Harmonic Distortion of the Voltage: 5%

Harmonic limitations have been established by IEEE 519 1992 for the following reasons:

- To limit the damage to power factor correction capacitors and harmonic filter systems caused by excessive harmonics.
- To prevent series or parallel resonance in the electrical system
- To keep the level of harmonics at the PCC (Point of Common Coupling) from being excessive and distorting the system voltage and damaging other equipment on the system

The PCC is defined as the electrical connecting point or interface between the utility distribution system and the customer's electrical distribution system.

Refer to the latest revision of IEEE 519 for more details on the harmonic current limitations.

Power Factor Correction Costs

The average installed cost of capacitors on a 480-volt system is about \$30 per kVAR. Automatic power factor controllers or capacitors with harmonic filters cost more. These features are typically associated with capacitors exceeding 100 kVAR. A single, large capacitor bank has a lower installed cost than multiple small installations scattered throughout the plant. The cost per kVAR for small capacitors on motors is substantially higher due to labor and materials costs. The cost for large banks is lower on a per kVAR basis because of the economy of scale. The installed cost per kVAR of capacitance is also lower at higher voltages. At higher voltage levels (2400V and up) unit costs are generally about \$6 - \$12 per kVAR installed.

Conclusions

Depending on your utility and geographic area, a power factor less than 90% will be penalized, and although there are no penalties paid for the level of harmonics, their presence in the system can be far more costly than the Power Factor penalties. System harmonics should be considered when applying power factor correction capacitors.

Active Harmonic Filters with power correction can:

- o Reduce energy costs
- o Increase personnel performance and productivity
- o Create energy savings from 5% to 20%

- o Avoid utility penalties up to an additional 20%
- o Create an economic payback in 1.5 to 3.0 years

Some Questions & Answers about power factor

Q. What is power factor and why is it important?

A. Simply stated, power factor is the percentage of consumed power (KW) versus supplied power (KVA). This is important because a low power factor can waste energy, result in inefficient use of electrical power, and often result in higher energy bills.

Q. Do I have a power factor problem?

A. If you have commercial or industrial premises using more than 75 KW of power and operate a number of electric motors, then indeed you may have a power factor problem. The extent of the problem will depend upon the ratio between the inductive load and the resistive load, and also on the nature of the inductive load.

Q. How significant is power factor correction in industrial settings?

A: Power factor is low in industrial settings where most of the plant energy is used to power electric motors. It is lowest when the induction motors tend to be oversized and under-loaded. A lagging (less than 1.0) power factor causes some additional energy loss because more current is required – compared to an in-phase sinusoidal current – to deliver a certain amount of power. Correcting power factor can be an appropriate and cost-effective measure, but not because of energy savings.

Q. Is my power factor costing me money?

A. This depends on how bad your power factor is and how your utility company charges for its electricity.

Q. How do I know what my power factor is?

A. In those areas where a power factor penalty is applied, the information relative to the power factor should be contained on the electricity bill. It is advisable to have digital power factor meters installed at your substations, for determining load conditions necessary for designing a practical power factor correction scheme.

Q. How much energy can be saved by installing correction capacitors?

A: Power factor correction does not save much energy – usually less than 1 percent of load requirements – but even that benefit depends upon how low the power factor is to begin with and how heavily loaded are in-plant distribution system conductors. Note that power supplied to your motor driven-equipment is proportional to Volts ×

Amps. Energy losses in your in-plant distribution system coincide with your voltage drop. If your transformer supplies power at 480 volts and the voltage at your motor terminals is 470 volts, you have a voltage drop of 10 volts, or approximately 2 percent of 480 volts. The total power loss in the in-plant distribution system upstream of connected load equipment seldom exceeds 2 percent of the load requirement.

The loss fraction saved through the installation of capacitors at the motor is:

$$\{1 - (PF_{\text{initial}}/PF_{\text{final}})^2\} \times 100\%$$

If your original power factor was 80 percent, and the system power factor is raised to 95 percent following the installation of capacitors, then the resistance or I^2R losses in your in-plant distribution wiring will drop by 29.1 percent. Multiplying $(29.1\%/100) \times 2\%$ yields an expected energy savings of 0.58 percent of the load requirement. If you correct power factor at the switchyard or plant service entrance instead of very near the inductive loads (e.g. motors), you do not reduce in-plant distribution system losses at all because the correction only happens on the line side (the upstream, utility side) of where the capacitors are tapped in.

Q. Our utility company does not have a penalty for low power factor, so why should I worry?

A. No one gets a free ride. The costs of low power factor are most obvious to the utility company who are the aggregate recipients of their user's low power factor. On a smaller scale, the user can enjoy the same cost savings and benefits of power factor correction. The user has his/her own distribution, switch gears and transformers that must reflect the added capacity to carry reactive power.

Q. Will I get increased benefits if I add an excessive amount of correction?

A. Definitely not- too much capacity on the line (leading power factor) is bad. Under certain conditions dangerously high transient voltages may prevail on the power lines at points far removed from the actual load. Over compensation will adversely affect lighting systems and other machinery and equipment.

Q. How do I choose the correct amount of correction for my application?

A. There are different ways to arrive at the correct amount of KVAR for a given application depending on the information available to you. The IEEE provides standard tables that allow you to choose a KVAR rating for individual motors based on horsepower and RPM rating. Additionally, some motor manufacturers recommend

a maximum KVAR rating. Also, the required KVAR can be calculated if you have the following information: Current power factor, desired power factor, and total KW input.

Q. If I correct my power factor, will I improve efficiency?

A. Not directly. It must be remembered that efficiency is the ratio of output power/input power whereas power factor is the ratio of actual power/apparent power. The two are not directly related.

Q. Our plant is heated electrically and we do only light assembly work. Can we be penalized for low power factor?

A. Not likely, except in the case of heat pumps and blower motors to circulate the heat, electric heat is essentially a resistive load. Magnetic fields are not associated with resistive loads: consequently, the power factor would be unity or 100%.

Q. Does it make a difference where in the system one connects power factor correction capacitors?

A. That depends on whom you ask. The utility company is only concerned that the power factor correction be on the user side of the watt hour meter. It is often to the user's advantage to correct power factor at each load.

Q. Why should power factor be corrected at the load?

A. The user reaps the same advantages as the utility company for high power factor only on a smaller scale. Also, if each load has been corrected, the power factor remains relatively constant since in plants loads are switched on and off and the dangers of over-correction do not exist. If however, power factor has been corrected at the service entry, system power factor can make relatively wide swings as heavy loads are switched on and off.

In providing for power factor correction it should be remembered that distribution boards and circuits can carry a greater useful load if the capacitors are installed as near as possible to the source of the low power factor. For this reason either bulk or individual correction, rather than correction at the intake point, can be justified.

Q. What is the difference between fixed and automatic Power Factor Correction Capacitors?

A. There are two types of Power Factor Correction Capacitors: Fixed and Automatic. Automatic capacitors are also known as switched capacitors. Automatic capacitors vary the amount of correction (KVAR) supplied to an electrical system, while fixed capacitors supply a constant amount of correction (KVAR). Automatic capacitors are

made up of banks that are switched off and on by a microprocessor controller based on the plant electrical load at any given time. Automatic capacitors are installed at the main incoming power source, while fixed capacitors are generally installed at individual motor loads throughout a plant.

Q. Which are better, fixed or Automatic Power Factor Correction Capacitors?

A. The answer to this varies with each installation. If you have just a limited number of motors that need correction, it would be advisable to put a fixed capacitor at each motor. If you have a large plant with varying loads and numerous motors, an automatic capacitor may be better. Other factors to consider are maintenance and "down-time". A fixed capacitor requires less maintenance and if the unit goes down, you have not lost all of your correction abilities. If you need to replace or work on an automatic capacitor, it may require taking the whole plant down or losing all of your correcting ability for a length of time. Additionally, capacitors cannot be directly connected to some equipment.

Q. Should capacitors used for bulk power factor correction be controlled manually or automatically?

A. Manually controlled capacitors are normally employed for loads which are too small to warrant splitting the total capacitance required, or where high diversity of motor load makes individual correction uneconomic. Manual control can only be justified technically for continuous process work where minimum switching is required and there is sufficient reactive KVA available in the circuit continuously to warrant the capacitors being connected all the time.

Q. In our facility, we have many small machine motors; should each machine be corrected?

A. In this case, it would probably be more advantageous to correct at the branch circuit since smaller capacitor units have higher price per KVAR correction. In general, motors of 10 hp or more are corrected individually, whereas smaller motors are often corrected in groups.

Q. If I decide to install Power Factor correction capacitors, what will my payback time be?

A. For customers who are paying a penalty, generally the payback time can be as little as six months or as much as two years. This depends on the billing structure of your utility.

Q. Do fluorescent lamps contribute to low power factor?

A. Yes and no. Fluorescent lamps do use inductive devices (ballasts) but most lamp manufacturers correct for power factor in the individual fixture. With incandescent bulbs, power factor is not a problem.

Course Summary

This course has attempted to indicate just how power factor can have a significant financial influence on the running of your facility and also upon its overall efficiency.

Without the correct 'Power Factor Correction' costly energy is wasted and has the greatest effect on those who use most energy and an adverse effect on our environment.

To overcome this problem, and at the same time ensure that the electrical system is not overloaded with wattless current (as this excess current is termed), power factor correction is applied to circuits which include induction motors as a means of reducing the inductive component of the current and thereby reduce the losses in the supply. The utility companies often provide incentives or reduce terms to consumers whose power factor is high and impose penalties for those with low power factor. Utility deregulation is changing metering techniques, which now measures KVAR instead of watts. The new meters are more accurately measuring true power factor and penalties are being assessed for insufficient levels. The cost of poor power quality may be much greater than simply the penalties involved.

In the past it has been generally assumed that only utility company derived benefits from power factor correction. In today's high cost energy market, the user receives benefits over and above those of the reduced billing penalties, and the means and equipment for doing this are readily available indigenously.

It is absolutely essential for industries and commercial establishments to adopt a systematic approach to power factor measurement, correction and control consisting of 4 elements:

- 1) Survey
- 2) Plan
- 3) Correct and
- 4) Control

Using a portable digital power factor meter, it is comparatively easy to carry out a power factor survey of any industrial plant. Using the data obtained from this survey, a comprehensive power factor correction plan can be worked out. Based on this plan, automatic power factor correction and control equipment like PLC based auto power factor regulator can be installed. With the cost of energy rising at a fairly alarming rate power factor is not something which can be dismissed lightly.

The addition of power factor correction equipment is a simple, durable and cost effective method for reducing wasted resources. It is common to recover the initial cost of equipment and installation within two years.