PALESTINE POLYTECHNIC UNIVERSITY

COLLEGE OF ENGINEERING & TECHNOLOGY
ELECTRICAL AND COMPUTER DEPARTMENT

INDUSTRIAL AUTOMATION

POWER FACTOR CORRECTION AT INDUSRIAL APPLICATIONS

SUPERVISED BY
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PROJECT TEAM

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HEBRON – PALESTINE

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PALESTINE POLYTECHNIC UNIVERSITY
HEBRON - PALESTINE
ENGINEERING & TECHNOLOGY COLLEGE

The Senior Project Entitled

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PROJECT TEAM

KHALAF ALADAM **SALEM ABU-HASHEESH**

In accordance with recommendations of the project supervisors, and the acceptance of all examining committee members, this project has been submitted to the Department of Electrical and Computer Engineering at Engineering and Technology College in partial fulfillment of the requirements of Department for the degree of Bachelor at industrial automation engineering.

Project Supervisor	**Department Chairman**
………………………	……………………………

الاهداء

الى الأنسان ذو القلب الكبير الذي لا حدود لمحبته ولا نهاية لعطائه.

الى من رباني صغيرا بالعطف والرعاية، ورباني كبيرا بالحب والحنان.

والدينا العزيزين

الى من أسمها أغنيتي في صغري ورضاها أملي في عمري وبرها رجائي في حياتي.

الى نبع العطاء الذي لا ينضب الى من جعل الله جنته تحت قدميها الى الحب والحنان والدفئ.

أمهاتنا الحنونات

ACKNOWLEDGEMENT

We would like to thank our supervisor Dr. ABDEL – KARIM DAUD for his guidance and continuing support throughout the semester. And for all who helped us.

Abstract

"POWER FACTOR CORRECTION AT INDUSTRIAL APPLICATIONS"

Most industrial loads (motors, lights, etc.) are inductive in nature, so they have a lagging power factor. Therefore, these loads draw more current (apparent power) than is required to do the actual work (real power). This result is higher costs to the customer.

Power Factor Correction attempts to improve the power factor by the addition of capacitor(s) in parallel with the load. These capacitors supply some or all of the reactive power to the inductive load, which reduces the reactive power and therefore the current that the power supply delivers.

This project will cover the effects of poor power factor, the advantages of high power factor and the procedure of how to correct the power factor

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CHAPTER ONE

1. Introduction

1.1 Aim and Objectives of Study

The objective of this report is to provide an evaluation of the application of power factor correction based on industrial application. to minimize the level of reactive power whilst minimizing the whole of life cost without adversely impacting on user requirements.

The aim of this guide is to save money for reinvestment in energy consumption.

1.2 Authority

Authority to undertake this report was provided by Dr. abed-alkareem dawood of the Palestine polytechnic university

- Final Report Submission date: Jun- 19-2004

1.3 Estimation cost

This project costs about 3000 NIS.
We need metering devices, capacitors, connecting wires, contactors, interfacing circuit, personal computer, fuses, coils, main switches, and induction motor.

Outline

Power Factor is an electrical term used to rate the degree of the synchronization of power supply current with the power supply voltage. This term is often misunderstood by our customers, or simply ignored. it is important that we clearly understand the meaning of "Power Factor" and its effect on the electrical supply system for the following reasons:

1. Recommendations where power factor correction should be applied.
2. A low power factor can increase the cost of power to the user
3. A customer may request assistance in selecting equipment to correct a low power factor over-correction of power factor by the addition of excessive capacitance is sometimes dangerous to a motor and the driven equipment. (above 95% power factor)

4. A customer may, to some extent, use motor power factor rating as a power factor rating as a criterion in choosing among competing motors, especially when a large motor is involved.

The power factors in industrial plants are usually lagging due to the inductive nature of induction motors, transformers, lighting, induction heating furnaces, etc. This lagging power factor has two costly disadvantages for the power user. First, it increases the cost incurred by the power company because more current must be transmitted than is actually used to perform useful work. This increased cost is passed on to the industrial customer by means of power factor adjustments to the rate schedules. Second, it reduces the load handling capability of the industrial plants electrical transmission system which means that the industrial power user must spend more on transmission lines and transformers to get a given amount of useful power through his plant.

Scope of work

This guide is applicable to all existing electrical equipment loads. It is most cost effectively applied as part of new construction or major redevelopment of site cables, switchboards and substations. However, given the commonly existing poor PF's and the associated high cost penalties, there are still opportunities in carrying out retrofits.

1.7 Definitions and Terms

Power factor (pf)	a figure quantifying the relationship between apparent power and real power. For a linear load it also relates the phase of the current and voltage waveforms through an electrical element; pf = cos (¨) = kw/kva where ¨ is the angle between the current and voltage waveforms.
Real Power	Rate of energy dissipation in the resistive component of an electrical element. Measured in kW.
Apparent Power	The vector summation of the real and reactive power representing the total power usage. Also known as Complex Power. Measured in kVA.
Reactive Power	Rate of energy usage in the inductive/capacitive component of an electrical element. Also known as Imaginary Power. Measured in VAR.
Lagging PF	a system is said to have a lagging power factor when the current waveform lags the voltage waveform. This is experienced with loads with a dominant inductive component.
Leading PF	a system has a leading power factor when the current waveform leads the voltage waveform. This is experienced with loads with a dominant capacitive component.

Power Angle	The angle w̱here cos (¨) = kW/kVA = pf, the ratio of real power to apparent power. For linear loads it is also the phase difference between the current and voltage waveforms. The angle needs to be qualified by stating whether it is a leading or lagging PF.
Induction motor	a common type of motor used in industry. Its name relates to its construction and mode of operation.
Transmission Network	The section of the network from where the electricity is produced (i.e. power station) to the distribution network. The voltages are stepped up to minimize transmission losses for subsequent downstream transmission to end-users.
Distribution Network	The end point of a transmission system where the voltages are stepped back down and distributed at useable voltages to customers.

CHAPTER TWO

2. Power Factor

2.1 Introduction

For over a century now, alternating current (AC) electric power distribution has been used around the world. Some countries use 50 Hz; others 60 Hz, each swearing by the significant advantages their respective systems delivers.

Resistive loads are easy for power distribution systems. The immediate load current is always in proportion to the immediate voltage as defined by Ohm’s Law. The power delivered to the load is expressed in watts and is strictly a product of the voltage (V) and current (I), $P = V \times I$. Both the voltage and current remain sinusoidal; no distortion is caused to either wave and, therefore, no harmonic frequencies are created.

In real life, things are not this straight forward. The wiring alone adds inductance to the system. Many loads, such as induction motors, are reactive, so the true loads are always complex. With the voltage and current remaining sinusoidal and with no harmonic distortion created, the current is rarely in phase with the voltage. The power delivered to the load is no longer the product of the voltage and current, but is reduced by a power factor.

Predictably, there are always people looking for a free lunch, so over the years there have been many schemes to take advantage of the cosine hitting zero at 90° phase and cheating power companies of their revenues. How successful these conspiracies have been you can judge for yourselves. The real problem arises when you use nonlinear loads, where there is no constant ratio between the load voltage and current. Such loads are typically fluorescent lamps, phase angle controlled light dimmers, or DC power supplies. In the past, this was not a problem. But with the proliferation of small electronic appliances, TVs, plug-in power adapters, battery chargers, and untold millions of computers, power companies had to take notice.

The power factor of a system refers to the relationship between real/working power and reactive power. It is a measure of how efficiently electrical power is being used and for linear loads it also relates the phase of the voltage waveform to the current waveform. Electrical power is composed of two orthogonal components – real power (component that does the work) and reactive power (component that develops and maintains electromagnetic fields) which when added vectorally make up apparent power. This is represented on the power triangle below.

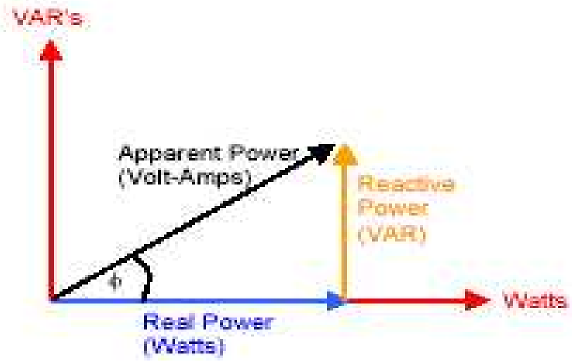

Figure 2-1 Power triangle showing relationship between real power, reactive power, apparent power and power factor

A load typically has a resistive component and a reactive component as depicted in the figure below. Real power, measured in kW is dissipated in the resistive component performing the “work” of the system and provides the motion or heat.

Reactive power is measured in kVAR's and doesn't contribute to work as such but rather sustains the electromagnetic field required for the device to operate. It is this level of reactive power compared to real power that determines the power factor. For a heater (which is a pure resistive load) the reactive power is zero; the voltage and current waveforms are in phase, the power angle is zero and hence the power factor, Pf = cos (¨) = 1. For a motor that requires an electromagnetic field to operate the power factor may be around 0.8.

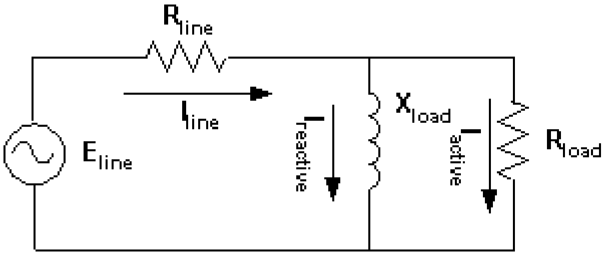

Figure 2-2 Model of a typical load

Although the current through the reactive component (I reactive) dissipates no power (and is hence not measured by a kWh meter), this current still needs to be transmitted along the distribution lines and hence will dissipate energy through other resistive components in the system (cabling, switchgear, distribution boards, etc). By generating/providing this reactive current locally through the use of power factor correction equipment, less power needs to be provided by the distribution network resulting in lower losses, improved line voltage and a lower electricity bill under a kVA tariff structure.

Reactive power can be supplied via a method of power factor correction involving the installation of capacitor banks. Typically these consist of switched capacitor banks providing bulk correction to a whole building with control equipment switching the level of capacitance to optimize the power factor. Another method is static correction in which the capacitors are attached to individual pieces of equipment and are switched in and out as the device is switched on and off.

The capacitors by supplying reactive power have the effect of reducing the magnitude of the line current as shown in figure 2-3.

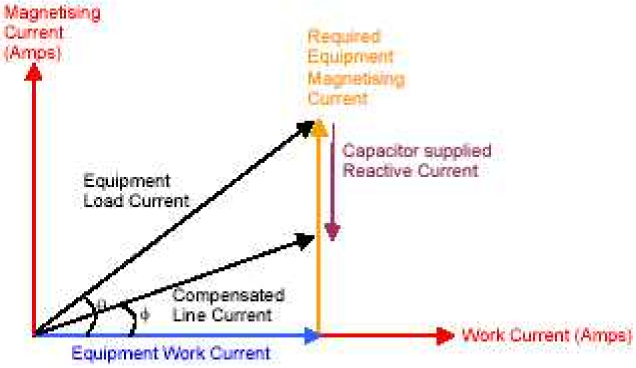

Figure 2-3 Effect of power factor correction on line current

It is clear from the diagram above the effectiveness of power factor correction in reducing the line current and associated losses. The capacitance supplied by the power factor correction equipment provides reactive power locally reducing the power angle from φ to resulting in a reduction in the line current between the power factor equipment and the electricity network. The net effect is a reduced electrical load as seen by the electricity network and for those on KVA electricity tariffs electricity bill savings.

It should be noted that while the line current between the distribution network and power factor correction equipment is reduced, the current between the power factor correction equipment and the equipment remains unaltered. Hence the power supplies and associated cabling to the equipment from the power factor correction equipment needs to be sized for the original equipment requirements. This is illustrated on the following diagram.

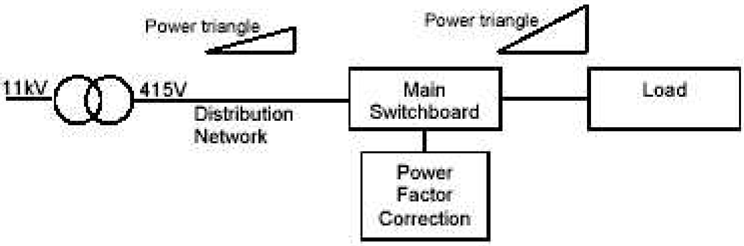

Figure 2-4 Line currents at various points in power network3.2

2.2 Power in resistive and reactive AC circuits

2.2.1 Power in resistive Ac circuit

Consider a circuit of fig 2-5 for a single-phase AC power system, where a 120 volt, 50 Hz AC voltage source is delivering power to a resistive load:

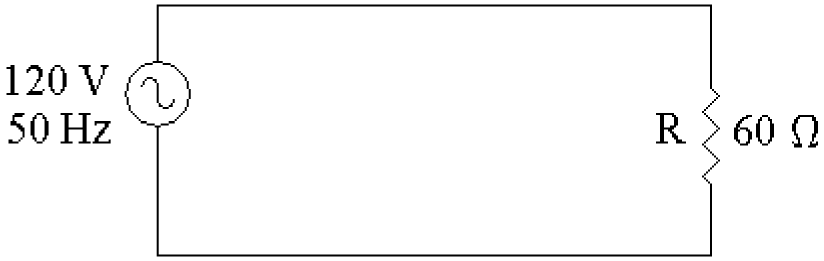

Figure2-5 single phase AC power system

$Z_R = 60 + j0\ \Omega$ or $Z_R = 60\ \Omega\ \angle 0°$

$$I = \frac{E}{Z} = \frac{120\ \text{V}}{60\ \Omega} = 2\ \text{A}$$

In this example, the current to the load would be 2 amps, RMS. The power dissipated at the load would be 240 watts. Because this load is purely resistive (no reactance), the current is in phase with the voltage, and calculations look similar to that in an equivalent DC circuit. If we were to plot the voltage, current, and power waveforms for this circuit, it would look like this:

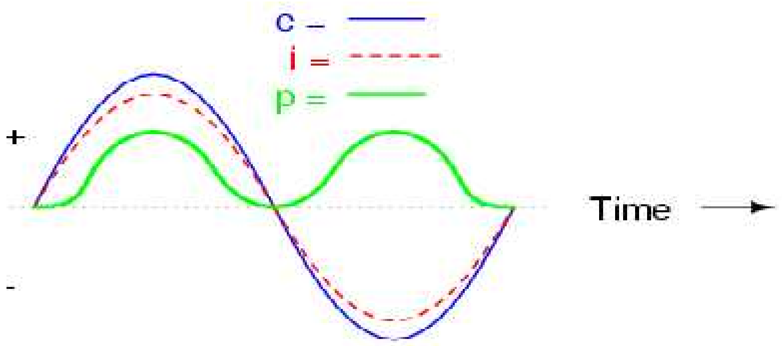

Figure 2-6 single phase AC power system waveforms

Note that the waveform for power is always positive, never negative for this resistive circuit. This means that power is always being dissipated by the resistive load, and never returned to the source as it is with reactive loads. If the source were a mechanical generator, it would take 240 watts worth of mechanical energy (about 1/3 horsepower) to turn the shaft.

Also note that the waveform for power is not at the same frequency as the voltage or current Rather, its frequency is double that of either the voltage or current waveforms. This different frequency prohibits our expression of power in an AC circuit using the same complex (rectangular or polar) notation as used for voltage, current, and impedance, because this form of mathematical symbolism implies unchanging phase relationships. When frequencies are not the same, phase relationships constantly change.

As strange as it may seem, the best way to proceed with AC power calculations is to use scalar notation, and to handle any relevant phase relationships with trigonometry.

2.2.2 Power in reactive AC circuit

Consider a circuit of fig 2-7 for a single-phase AC power system, where a 120 volt, 50 Hz AC voltage source is delivering power to a reactive load:

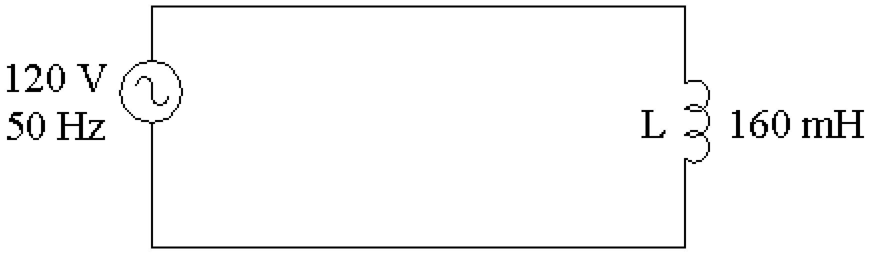

Figure 2-7 simple AC circuit with purely reactive load

$X_L = 2\Pi\ f\ L = 2\Pi * 50 * 160 * 10^{-3} = 50.266\ \Omega$

$Z_L = 0 + j\ 50.266\ \Omega$ or $Z_L = 50.266\ \angle 90^\circ\ \Omega$

$$I = \frac{E}{Z} = \frac{120\ \text{V}}{50.266\ \Omega} = 2.387\ \text{A}$$

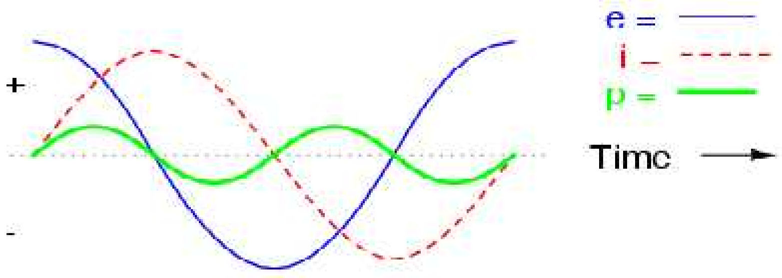

Figure 2-8 simple AC circuit with purely reactive load waveforms

Note that the power alternates equally between cycles of positive and negative. This means that power is being alternately absorbed from and returned to the source. If the source were a mechanical generator, it would take (practically) no net mechanical energy to turn the shaft, because no power would be used by the load. The generator shaft would be easy to spin, and the inductor would not become warm as a resistor would.

2.2.3 Power in resistive and reactive AC circuit

Consider a circuit of fig 2-9 for a single-phase AC power system, where a 120 volt, 50 Hz AC voltage source is delivering power to both inductance and resistance:

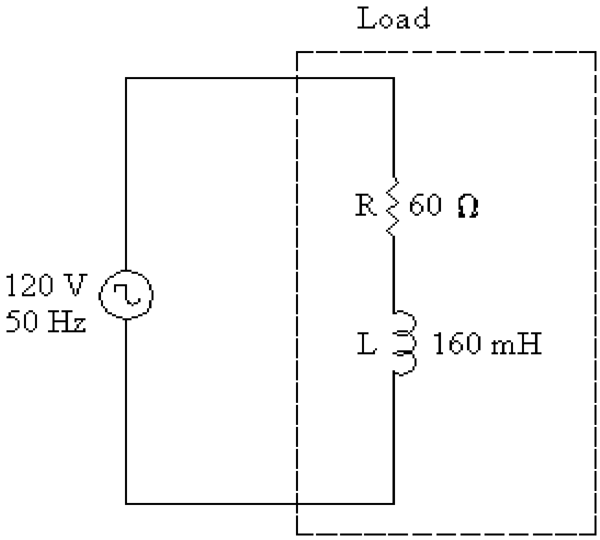

Figure 2-9 AC circuit with a load consisting of both inductance and resistance

$X_L = 50.266\ \Omega$

$Z_{L\,=}\ 0 + j\ 50.266\ \Omega$ or $Z_L = 50.266\ \Omega\angle 90^\circ$

$Z_R = 60 + j\ 0\ \Omega$ or $Z_L = 60\ \ \Omega\ \angle\ 0^\circ$

$Z_{\text{total}} = 60 + j\ 50.266\ \Omega$ or $Z_{\text{total}} = 78.273\ \Omega\angle 90^\circ$

$$I = \frac{E}{Z} = \frac{120\ \text{V}}{78.273\ \Omega} = 1.533\ \text{A}$$

At a frequency of 50 Hz, the 160 mH of inductance give us 50.266 Ω of inductive reactance. This reactance combines with the 60 Ω of resistance to form a total load impedance of 60 + j 50.266Ω, or $78.273\ \Omega\angle 90°$. If we're not concerned with phase angles (which we're not at this point), we may calculate current in the circuit by taking the polar magnitude of the voltage source (120 volts) and dividing it by the polar magnitude of the impedance (78.273 Ω). With a power supply voltage of 120 volts RMS, our load current is 1.533 amps. This is the figure that an RMS ammeter would indicate if connected in series with the resistor and inductor.

We already know that reactive components dissipate zero power, as they equally absorb power from, and return power to, the rest of the circuit. Therefore, any inductive reactance in this load will likewise dissipate zero power. The only thing left to dissipate power here is the resistive portion of the load impedance. If we look at the waveform plot of voltage, current, and total power for this circuit, we see how this combination works:

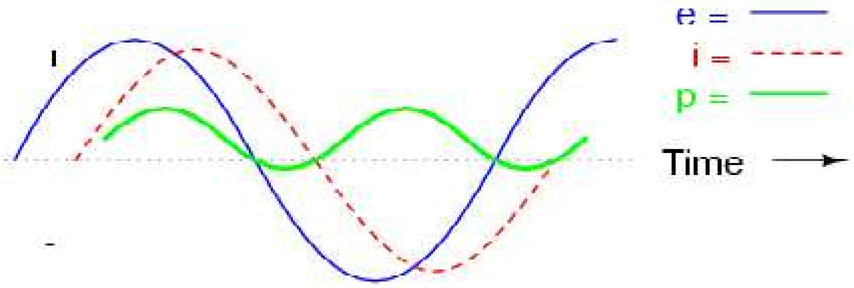

Figure 2-10 AC circuit with a load consisting of both inductance and resistance waveforms

As with any reactive circuit, the power alternates between positive and negative instantaneous values over time. In a purely reactive circuit that alternation between positive and negative power is equally divided, resulting in a net power dissipation of zero. However, in circuits with mixed resistance and reactance like this one, the power waveform will still alternate between positive and negative, but the amount of positive power will exceed the amount of negative power. In other words, the combined inductive/resistive load will consume more power than it returns back to the source.

Looking at the waveform plot for power, it should be evident that the wave spends more time on the positive side of the center line than on the negative, indicating that there is more power absorbed by the load than there is returned to the circuit. What little returning of power that occurs is due to the reactance; the imbalance of positive versus negative power is due to the resistance as it dissipates energy outside of the circuit (usually in the form of heat). If the source were a mechanical generator, the amount of mechanical energy needed to turn the shaft would be the amount of power averaged between the positive and negative power cycles.

Mathematically representing power in an AC circuit is a challenge, because the power wave isn't at the same frequency as voltage or current. Furthermore, the phase angle for power means something quite different from the phase angle for either voltage or current. Whereas the angle for voltage or current represents a relative shift in timing between two waves, the phase angle for power represents a ratio between power dissipated and power returned. Because of this way in which AC power differs from AC voltage or current, it is actually easier to arrive at figures for power by calculating with scalar quantities of voltage, current, resistance, and reactance than it is to try to derive it from vector, or complex quantities of voltage, current, and impedance that we've worked with so far.

2.2.4 Summary

- In a purely resistive circuit, all power circuit is dissipated by the resistor(s). Voltage and current are in phase with each other.
- In a purely reactive circuit, no power circuit is dissipated by the load(s). Rather, power is alternately absorbed from and returned to the AC source. Voltage and current are 90^o out of phase with each other.
- In a circuit consisting of resistance and reactance mixed, there will be more power dissipated by the load(s) than returned, but some power will definitely be dissipated and some will merely be absorbed and returned. Voltage and current in such a circuit will be out of phase by a value somewhere between 0^o and 90^o.

2.3 Real, Reactive, and Apparent power

We know that reactive loads such as inductors and capacitors dissipate zero power, yet the fact that they drop voltage and draw current gives the deceptive impression that they actually do dissipate power. This "phantom power" is called reactive power, and it is measured in a unit called Volt-Amps-Reactive (VAR), rather than watts. The mathematical symbol for reactive power is (unfortunately) the capital letter Q. The actual amount of power being used, or dissipated, in a circuit is called real power, and it is measured in watts (symbolized by the capital letter P, as always). The combination of reactive power and real power is called apparent power, and it is the product of a circuit's voltage and current, without reference to phase angle. Apparent power is measured in the unit of Volt-Amps (VA) and is symbolized by the capital letter S.

As a rule, real power is a function of a circuit's dissipative elements, usually resistances (R). Reactive power is a function of a circuit's reactance (X). Apparent power is a function of a circuit's total impedance (Z). Since we're dealing with scalar quantities for power calculation, any complex starting quantities such as voltage, current, and impedance must be represented by their polar magnitudes, not by real or imaginary rectangular components. For instance, if we are calculating real power from current and resistance, we must use the polar magnitude for current, and not merely the "real" or "imaginary" portion of the current. If we are calculating apparent power from voltage and impedance, both of these formerly complex quantities must be reduced to their polar magnitudes for the scalar arithmetic.

There are several power equations relating the three types of power to resistance, reactance, and impedance (all using scalar quantities):

P = Real power $P = I^2 * R$ $P = \frac{E^2}{R}$ (measured in units of watts)

Q = Reactive power $Q = I^2 * X$ $Q = \frac{E^2}{X}$ (measured in units of volt-amps-Reactive (VAR))

S = Apparent power $S = I^2 * Z$ $S = \frac{E^2}{Z}$ (measured in units of volt-Amps (VA))

Please note that there are two equations each for the calculation of real and reactive power. There are three equations available for the calculation of apparent power, $P = I * E$ being useful only for that purpose. Examine the following circuits and see how these three types of power interrelate:

2.3.1 Resistive load only

Consider the circuit shown in figure 2-5

P = real power = $I^2 * R = 2^2 * 60 = 240$ W

Q = reactive power = $I^2 * X = 0$ VAR

S = apparent power = $I^2 * Z = 2^2 * 60 = 240$ VA

2.3.2 Reactive load only

Consider the circuit shown in figure 2-7

P = real power = $I^2 * R = 0$ W

Q = reactive power = $I^2 * X = 238.73$ VAR

S = apparent power = $I^2 * Z = 238.73$ VA

2.3.3 AC circuit Resistive and reactive load

Consider the circuit shown in figure 2-9

$X_L = 2\,\Pi\, f\, L = 2\,\Pi * 50 * 160*10^{-3} = 50.266\ \Omega$

P = real power = $I^2 * R = 141.005$ W.

Q = reactive power = $I^2 * X = 118.13$ VAR

S = apparent power = $I^2 * Z = 183.95$ VA

These three types of power -- real, reactive, and apparent -- relate to one another in trigonometric form. We call this the power triangle:

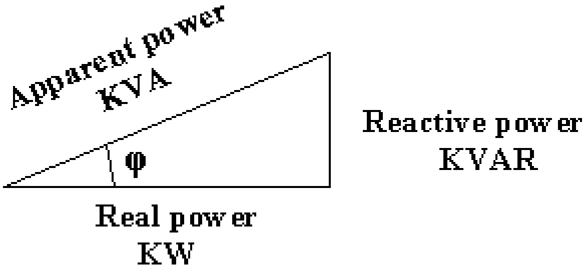

Figure 2-11 Power triangle

Using the laws of trigonometry, we can solve for the length of any side (amount of any type of power), given the lengths of the other two sides, or the length of one side and an angle.

2.3.4 Summary

- Power dissipated by a load is referred to as real power. real power is symbolized by the letter P and is measured in the unit of Watts (W).
- Power merely absorbed and returned in load due to its reactive properties is referred to as reactive power. Reactive power is symbolized by the letter Q and is measured in the unit of Volt-Amps-Reactive (VAR).
- Total power in an AC circuit, both dissipated and absorbed/returned is referred to as apparent power. Apparent power is symbolized by the letter S and is measured in the unit of Volt-Amps (VA).
- These three types of power are trigonometrically related to one another. In a right triangle, P = adjacent length, Q = opposite length, and S = hypotenuse length. The opposite angle is equal to the circuit's impedance (Z) phase angle.

2.4 What is Reactive Power?

In any AC system the current, and therefore the power, is made up of a number of components based on the nature of the load consuming the power. These are resistive, inductive and capacitive components. In the case of a purely resistive load, for example, electrical resistance heating, incandescent lighting, etc., the current and the voltage are in phase that is the current follows the voltage. Whereas, in the case of inductive loads, the current is out of phase with the voltage and it lags behind the voltage. Except for a few purely resistive loads and synchronous motors , most of the equipment and appliances in the present day consumer installation are inductive in nature, for example, inductive motors of all types, welding machines, electric arc and induction furnaces, choke coils and magnetic systems , transformers and regulators, etc. In the case of a capacitive load the current and voltage are again out of phase but now the current leads the voltage. The most common capacitive loads are the capacitors installed for the correction of power factor of the load.

The inductive or the capacitive loads are generally termed as the reactive loads. The significance of these different types of loads is that the active (or true or useful) power can only be consumed in the resistive portion of the load, where the current and the voltage are in phase. The reactive component of the load only consumes (watt less or) reactive power which is necessary for energizing the magnetic circuit of the equipment (and is thus not available for any useful work). Inductive loads require two forms of power - Working/Active power (measured in kW) to perform the actual work of creating heat, light, motion, machine output, etc., and Reactive power (measured in KVAR) to sustain the electromagnetic field. To understand it better, we need to consider that there maybe two currents running through a circuit. One of these currents contains watts (watts produce work) and the other current contains no watts. Why do we need current with no watts (also referred to as watt-less current)? The answer is simple. The current known as watt-less current is required to produce the magnetic field around an electric motor. If there was no watt-less current then an electric motor would not turn. The problems arise due to the fact that we can sometimes have too much watt-less current, in those cases we need to remove some of it.

The vector combination of these two power components (active and reactive) is termed as Apparent Power (measured in KVA), the value of which varies considerably for the same active power depending upon the reactive power drawn by the equipment. The ratio of the active power (kW) of the load to the apparent power (KVA) of the load is known as the power factor of the load.

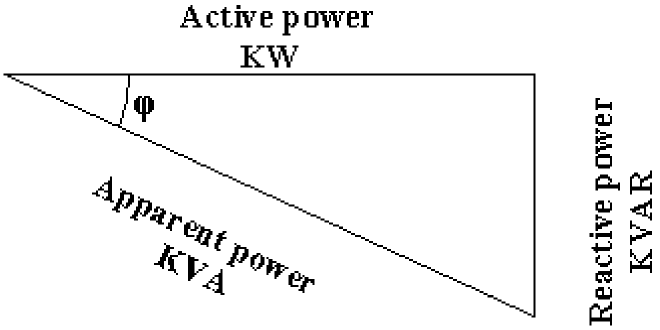

Figure 2-12 determining KVAR from power triangle

$$\text{Power Factor} = \frac{\text{Real Power (kVA)}}{\text{Apparent Power (kVA)}}$$

Thus when the nature of the load is purely resistive the KVAR or the reactive component will be nil and thus the angle will be equal to 0 degrees and the power factor will be equal to unity. For a purely inductive load the power factor will be 0.0 lagging and for a purely capacitive load the power factor will be 0.0 leading.

Thus, it is evident from above that, more the power factor departs from unity the more will be the KVA demand for the same kW load. The more the KVA demand for the same kW load the more shall be the electricity bill of the consumer. To say it otherwise, the customers with a low power factor will pay more for their useful electrical power. (The Billing demand for the month is generally taken to be the actual maximum KVA demand of the consumer during the month or a fixed percentage of the contract demand or a fixed KVA value, whichever is higher, based on the type of the consumer and the tariff structure of the utility.)

2.5 Power factor in Illumination

All Discharge Lamps, such as Fluorescent Lamps, High Pressure Mercury vapor Lamps, Sodium Lamps, Metal Halide Lamps, etc., require ballasts (chokes) or transformers for their operation. These devices are inductive in nature. When a Discharge Lamp is switched on, it draws Apparent Power from the mains. This Apparent Power (VA) has two components; one is the Active Power (W) actually being consumed by the lamp for illuminating it, and the other is the Reactive Power (VAR) feeding the electromagnetic circuit of the control gear.

Power factor is the ratio of Real Power W to the Apparent Power VA

$$\text{Power factor} = \frac{\text{Real Power}}{\text{Apparent Power}}$$

2.6 Resonance

An important but often overlooked issue associated with power factor correction is that of resonance. A series or parallel combination of inductance and capacitance has associated with it a natural frequency at which resonance will occur. Some devices such as antennas use this property to its advantage however in a power system resonance can be very damaging. By adding capacitors in an attempt to improve the power factor, resonance with inherently inductive power lines can occur when excited by harmonics generated by electrical equipment such as switch mode power supplies commonly used in personal computers and UPS systems.

The impact of resonance on a power factor correction system is that it could significantly reduce the life of the capacitors or destroy them. A solution to this is to include detuned reactors in the design of power factor correction equipment. By introducing a known reactance, the resonant frequency of the system can be chosen to filter out harmonics and improve power quality. Systems are commonly tuned to approximately 190 Hz acting as a low pass filter to limit the 5th harmonic (250Hz for 50Hz supply) and higher. Low temperature rise reactors in the detuning circuitry are recommended, to reduce heat load.

2.6.1 Countering the effects of resonance

Capacitors are linear reactive devices, and consequently do not generate harmonics. The installation of capacitors in a power system (in which the impedances are predominantly inductive) can, however, result in total or partial resonance occurring at one of the harmonic frequencies.

The harmonic order ho of the natural resonant frequency between the system inductance and the capacitor bank is given by $\sqrt{Ssc/Q}$ where

Ssc = the level of system short-circuit kVA at the point of connection of the capacitor.

Q = capacitor bank rating in kvar; and

ho = the harmonic order of the natural frequency fo i.e. fo/50 for 50 Hz system, or fo/60 for a 60 Hz system.

Example

$\sqrt{Ssc/Q}$ may give a value for ho of 2.93 which shows that the natural frequency of the capacitor/system-inductance combination is close to the 3^{rd} harmonic frequency of the system, from ho = fo/50 it can be seen that fo = 50 ho = 50 x 2.93 = 146.5 Hz.

The closer a natural frequency approaches one of the harmonics present on the system, the greater will be the (undesirable) effect.

In the above example, strong resonant conditions with the 3rd harmonic component of a distorted wave would certainly occur.

In such cases, steps are taken to change the natural frequency to a value, which will not resonate with any of the harmonics known to be present. This is achieved by the addition of a harmonic-suppression inductor connected in series with the capacitor bank.

On 50 Hz systems, these reactors are often adjusted to bring the resonant frequency of the combination, i.e. the capacitor bank + reactors to 190 Hz. The reactors are adjusted to 228 Hz for a 60 Hz system.

These frequencies correspond to a value for ho of 3.8 for a 50 Hz system, i.e. approximately mid-way between the 3rd and 5th harmonics. In this arrangement, the presence of the reactor increases the fundamental-frequency (50 Hz or 60 Hz) current by a small amount (7-8%) and therefore the voltage across the capacitor in the same proportion.

This feature is taken into account, for example, by using capacitors, which are designed for 440 V operations on 400 V systems.

2.7 Ripple Control

Ripple control signals are used by supply authorities as a load control system for the switching of water heaters, street lighting and meter equipment. Where power factor correction capacitors are installed and the electricity distributor uses ripple control, it may be necessary for the customer to install additional equipment to block the electricity distributor’s ripple control signals.

At audio signal frequencies, capacitors present an impedance of some 10 to 21 times less than at 50Hz. This can result in a significant portion of the signal being absorbed or lost to the system. The effect on the signal voltage of the control system is variable, depending on the size and number of capacitors and their distribution in the high and low voltage network.

In the worst case the capacitor impedance may approach or equal the inductive reactance of the distribution transformer(s), to form a series resonance combination and a virtual short-circuit on the ripple system. This undesirable and unacceptable condition can be avoided by connecting blocking inductors in the capacitor bank.

Shunt capacitors used for power factor correction are likely to cause significant loss to the ripple control signal. Connecting either blocker rejecter must increase their impedance to the frequency or stopper circuits to a value, which will prevent interference to the electricity distributors, ripple control system.

2.8 Heat Load

Power factor correction equipment generates heat loads, which requires extraction to ensure the operating temperature remains within acceptable limits. Capacitors generate in the order of 0.2W/kVAR heat load. The following table outlines the approximate heating loads for some standard size units.

Table 2-2 heating loads for some standard size units

Unit Size (KVAR)	**Approximate Heating Load (W)**
400	800
500	1000
600	1200
650	1300

When choosing a location for the installation of PFC equipment, consideration to present cooling systems available in the area needs to be made.

CHAPTER THREE

3. Power factor correction

Many loads are highly inductive, such a lightly loaded motors and illumination transformers and ballasts. You may want to correct the power factor by adding parallel capacitors. You can also add series capacitors to "remove" the effect of leakage inductance that limits the output current. Since the power bill is based on the usage of the active power – kilo-watt-hour (KWH) while the power system equipment is built to handle the apparent power, the power company may charge a higher rate for loads drawing below a certain power factor, for instance, 0.95. It is mainly applied to large industrial loads/customers. Power factor penalties differ from one company to another. Such penalties serve one important function – to provide incentive to customers for power factor correction. By spending some money on power factor correction at the front end, customers can save money on lower power payment every month. Therefore, in a long run, money can be saved. It is very important to realize the economics of power factor correction.

3.1 What is power factor?

In technical terms, Power Factor is the ratio of real power to total power. It is equivalent to the cosine of the phase shift angle between current and voltage (cos ¨). The phase shift is caused by magnetic fields generated in inductive loads (motors, lights, transformers, etc.) It is called a Reactive Load. Power Factor can be determined by dividing the real power (KW) by apparent or total power (KVA). Many times, this information can be gathered from your electric bill; other times special instrumentation is need to determine Power Factor.

3.2 What is an ideal power factor?

In an ideal world, a Power Factor should be unity (1.0); typically the Power Factor should be between 0.90and 0.95. If the Power Factor is below 0.90, it is economical to install capacitors to correct the Power Factor. If the Power Factor is greater than 0.95, it is not economical to try to approach unity.

3.3 Why to correct the power factor?

The current flow through the circuit (shown below) is increased by the reactive component. Normally, loads are represented by a series combination of a resistance and a purely imaginary reactance. For this explanation, it is easier to contemplate it as an equivalent parallel combination. The diagram below illustrates a partially reactive load being fed from a real system with some finite resistance in the conductors, etc.

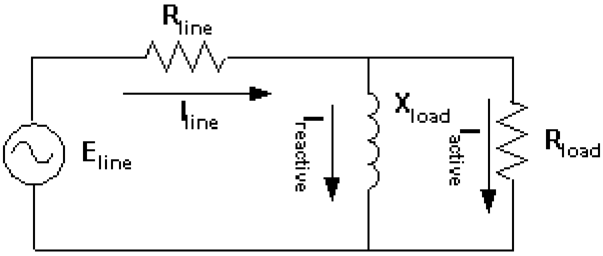

Figure 3-1 series combination of a resistance and a purely reactance

The current through the reactive component (I reactive) dissipates no power, and neither does it register on the watt-hour meter. However, the reactive current does dissipate power when flowing through other resistive components in the system, like the wires, the switches, and the lossy part of a transformer (R line). Switches have to interrupt the total current, not just the active component. Wires have to be big enough to carry the entire current, etc. Correcting the power factor reduces the amount of over sizing necessary.

Correcting power factor

Given the reactive load component (X_{load}), you can calculate the capacitance to exactly match it using the equation:

$$Xc = \frac{1}{wC} = \frac{1}{2\Pi\ f\ C} = \frac{1}{314.159 * C}$$

Or, rearranging: $C = \dfrac{1}{314.159 \ * Xc}$

Power factor correction capacitors are often rated in KVAR, instead of µF, because that is how the power company works. Say a factory has several thousand horsepower worth of motors at .85-power factor. They might have a reactive component of several hundred KVAR. At a distribution voltage of 14,400 volts, this would require a capacitor with an impedance of about 1037 ohms, or about 2.5 microfarads, a reasonable sized and priced package. However, if you were crazy enough to try to compensate this at 230 volts, you would need about .01 Farads (i.e. 10,000 uF), a sizeable package.

For very large systems, even capacitors get unwieldy. One approach is to use large over excited synchronous motors, which look like capacitors, electrically. Another approach is clever systems of thyristors and inductors, which simulate the capacitive reactance by drawing "displacement current".

3.4 Power Factor Correction - Low Power Units

For low power products, the power factor of the power supply is not as important as in the high power applications. This is because the power drawn by the product comprises a small portion of the power on a branch circuit of a facility. A 120-watt product with a power factor of only 0.6 will draw 1.6 amperes, in contrast to a power factor corrected unit which would draw 1.0 ampere. This difference of 0.6 ampere is not significant compared to the 20-ampere capacity of the source.

3.5 Power Factor Correction - High Power Units

Power factor correction is important at higher power levels, as the product's input current approaches the maximum available from the mains.

For example, a product with an input power of 1000 watts would draw 10 amperes from a 100-volt ac source, assuming its power factor is unity (1.0). If the power factor were 0.6, then the input current would be 16.7 amperes (10 amperes ÷ 0.6). It is universally accepted that a given product should not draw more than 80% of the available current, which means that even a 20-ampere mains service would provide 16 amperes, which is less than the 16.7 amperes in the example above.

3.6 The importance of power factor correction

KVA is total power available to you and what you pay for. The lower the Power Factor, the more KVA is needed. Low Power Factors tend to make system voltage unstable, increase heat in electrical apparatus and can cause failure of electrical equipment. Many utility companies bill you for your poor Power Factor, increasing your cost of electricity. Utility companies have multiple rate schedules, and depending upon your rate schedule, Power Factor penalties may be a separate line item as a demand charge or may be considered as part your general electrical usage. To reduce your electrical cost, you can and should negotiate with your utility company to obtain the best rate schedule for your facility with an improved Power Factor. These advantages will be explained more clearly in section 3.10.4.

1. Reductions in the cost of electricity

The installation of power-factor correcting capacitors on installations permits the consumer to reduce his electricity bill by maintaining the level of reactive-power consumption below a value contractually agreed with the power-supply authority.

Here, reactive energy is billed according to the tan ¨ . criterion. As previously noted tan ¨ . = Q (kvarh)/P (kWh) At the supply service position, the power supply distributor delivers reactive energy free, until:

- The point at which it reaches 40% of the active energy (tan ¨ . = 0.4) for a maximum period of 16 hours each day (from 06-00 h to 22-00 h) during the most-heavily loaded period (often in winter).
- Without limitation during light-load periods in winter, and in spring and summer. During the periods of limitation, reactive energy consumption exceeding 40% of the active energy (i.e. tan ¨ . > 0.4) is billed monthly at the current rates.

Thus, the quantity of reactive energy billed in these periods will be:
Kvarh (to be billed) = kWh (tan ¨ . - 0.4) where kWh is the active energy consumed during the periods of limitation, and kWh tan ¨ . is the total reactive energy during a period of limitation, and 0.4 kWh is the amount of reactive energy delivered free during a period of limitation. tan ¨ . = 0.4 corresponds to a PF of 0.93 so that, if steps are taken to ensure that during the limitation periods the PF never falls below 0.93, the consumer will have nothing to pay for the reactive power consumed.

Against the financial advantages of reduced billing, the consumer must balance the cost of purchasing, installing and maintaining the power-factor-improvement capacitors and controlling switchgear, automatic control equipment (where stepped levels of compensation are required) together with the additional kWh consumed by the dielectric losses of the capacitors, etc.

It may be found that it is more economic to provide partial compensation only, and that paying for some of the reactive energy consumed is less expensive than providing 100% compensation. The question of power-factor correction is matter of optimization, except in very simple cases.

2. Economic optimization

A high power factor allows the optimization of the components of an installation. Over rating of certain equipment can be avoided, but to achieve the best results, the correction should be effected as close to the individual items of inductive plant as possible. Good management in the consumption of reactive energy brings with it the following economic advantages.

- Reduction of cable size

Table 2-1 shows the required increase in the size of cables as the power factor is reduced from unity to 0.4.

Table 3-1 required increase in the size of cables as the power factor is reduced

multiplying factor For the cross-sectional Area of the cable core(s)	1	1.25	1.67	2.5
cos ¨	1	0.8	0.6	0.4

- Reduction of losses (P, kW) in cables

Losses in cables are proportional to the current squared, and are measured by the kWh meter for the installation. Reduction of the total current in a conductor by 10% for example, will reduce the losses by almost 20%.

- Reduction of voltage drop

PF correction capacitors reduce or even cancel completely the (inductive) reactive current in upstream conductors, thereby reducing or eliminating voltage drops.

Note: Overcompensation will produce a voltage rise at the capacitors.

- Increase in available power

By improving the power factor of a load supplied from a transformer, the current through the transformer will be reduced, there by allowing more load to be added.

In practice, it may be less expensive to improve the power factor, than to replace the transformer by a larger unit. Since other benefits accrue from a high value of PF, as previously noted.

- Voltage Improvement

When capacitors are added, voltage will increase

– Not a significant economic or system benefit severe over-correction (P.F >1) will cause a voltage rise that can damage insulation & equipment.

3.7 Disadvantages of a low power factor

1. The load draws greater current for the same value of the useful power.

A simple example showing the current required by a single phase electric motor is given below:

Supplied Voltage =240 Volts Single phase.

Motor input = 10 KW

Power Factor = 0.65

Current $(I_1) = \dfrac{\text{Power (kW)}}{\text{Volts (v)} * \text{PF}} = \dfrac{10000}{240 * 0.65} = 64.1\,\text{A}$

If the power factor of the motor is increased to 0.9 the current drawn by the motor is

Current $(I_2) = \dfrac{\text{Power (kW)}}{\text{Volts (v)} * \text{PF}} = \dfrac{10000}{240 * 0.9} = 46.3\,\text{A}$

Thus, as the power factor decreases the current required for the same value of active, or useful, power increases. The result is that the sizes of the equipment, like the switchgear, cables, transformers, etc., will have to be increased to cater the higher current in the circuit. All this adds to the cost.

Further, the greater current causes increased power loss or I2R losses in the circuits. Also due to higher current, the conductor temperature rises and hence the life of the insulation is reduced.

2. Also, with the increased current the voltage drop increases; thereby the voltage at the supply point is reduced. For different loads it causes voltage drop resulting in:

a. Lower output of the illumination system.

b. Less current is drawn by the heating devices so that the operating temperature drops. This results in increased consumption for the same rise of temperature

c. The induction motors slow down and therefore draw more current to produce a fixed torque for the loads. Again more consumption for the same torque.

In the transmission and distribution of the current itself, from the generating station to the consumer, heating losses will be greater at low power factor (varying in proportion to the square of the current) and the voltage drop will be in accordance with relation I*Z (where Z is the impedance, combination of resistance and reactance) . Since the losses in the electricity system due to low power factor will incur additional cost, it is evident that these will have to be reflected to some extent in the charges to the consumers. This is implemented by metering the maximum demand in KVA or by applying a low power factor penalty component in the tariffs.

3.8 Where to install correction capacitors

3.8.1 Global compensation

Principle

The capacitor bank is connected to the bus bars of the main LV distribution board for the installation, and remains in service during the period of normal load.

Advantages

The global type of compensation:

- Reduces the tariff penalties for excessive consumption of kvars.
- Reduces the apparent power kVA demand, on which standing charges are usually based.
- Relieves the supply transformer, which is then able to accept more load if necessary.

Comments

- Reactive current still flows in all conductors of cables leaving (i.e. downstream of) the main LV distribution board,
- For the above reason, the sizing of these cables, and power losses in them, are not improved by the global mode of compensation.

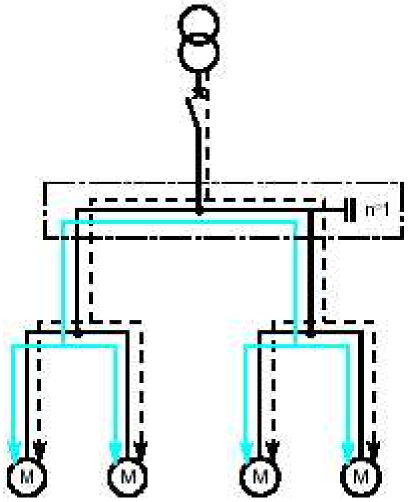

Figure 3-2 global compensation.

3.8.2 Compensation by sector

Principle

Capacitor banks are connected to bus bars of each local distribution board, as shown in figure 3-3.

A significant part of the installation benefits from this arrangement, notably the feeder cables from the main distribution board to each of the local distribution boards at which the compensation measures are applied.

Advantages

The compensation by sector:

- reduces the tariff penalties for excessive consumption of kvars.

- reduces the apparent power kva demand, on which standing charges are usually based.
- relieves the supply transformer, which is then able to accept more load if necessary.
- the size of the cables supplying the local distribution boards may be reduced, or will have additional capacity for possible load increases.
- losses in the same cables will be reduced.

Comments

- reactive current still flows in all cables downstream of the local distribution boards.
- for the above reason, the sizing of these cables, and the power losses in them, are not improved by compensation by sector.
- where large changes in loads occur, there is always a risk of overcompensation and consequent over voltage problems.

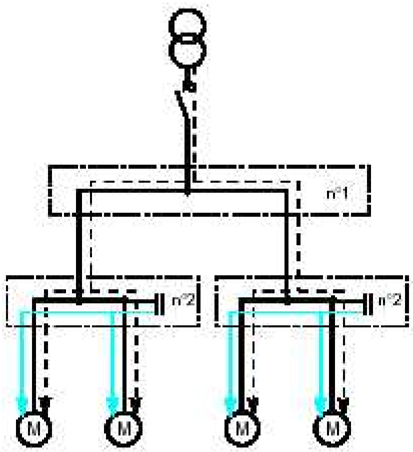

Figure 3-3 Compensation by sector

3.8.3 Individual compensation

Principle

Capacitors are connected directly to the terminals of inductive plant. Individual compensation should be considered when the power of the motor is significant with respect to the declared power requirement (kVA) of the installation.

The kvar rating of the capacitor bank is in the order of 25% of the kW rating of the motor. Complementary compensation at the origin of the installation (transformer) may also be beneficial.

Advantages

Individual compensation:

- reduces the tariff penalties for excessive consumption of kvars,
- reduces the apparent power kVA demand,
- reduces the size of all cables as well as the cable losses.

Comments

- Significant reactive currents no longer exist in the installation.

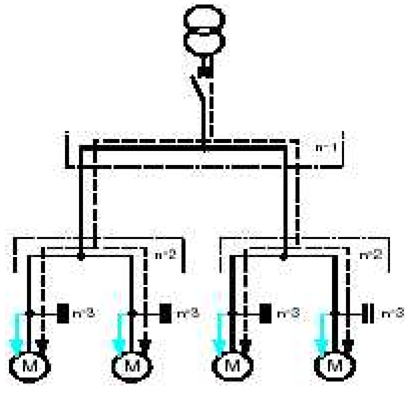

Figure 3-4 Individual compensation

Note: individual compensation should be considered when the power of motor is significant with respect to power of the installation.

3.9 How to apply power factor correction in illumination

3.9.1 Power factor correction

The inductive components, such as ballasts, draw Reactive Power (VAR) from the mains. It lags behind the Active Power (W) by 90^o Figure 3-5 A capacitor, if connected across the mains, will also draw Reactive Power $VAR_{(C)}$, but it leads the Active Power (W) by 90^o. The direction of the capacitive Reactive Power $VAR_{(C)}$ is opposite to the direction of the inductive Reactive Power VAR Figure 3-6.

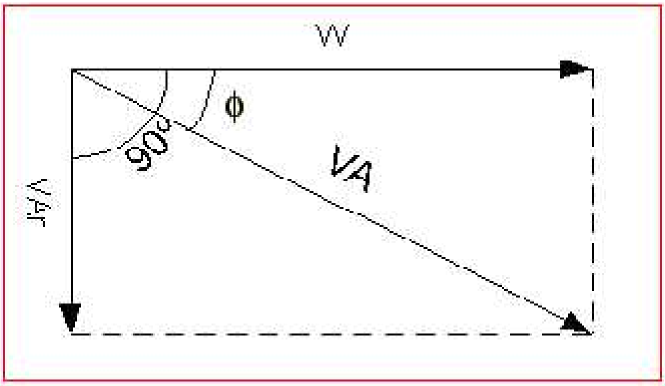

Figure 3-5 ballasts lag the active power by 90°

If a capacitor is connected in parallel with an inductive load, it will draw capacitive Reactive Power [$VAR_{(C)}$]. The effective Reactive Power drawn by the circuit will reduce to the extent of the capacitive Reactive Power [$VAR_{(C)}$], resulting in reduction of Apparent Power from VA to VA_1. The phase angle between the Active Power and the new Apparent Power VA_1 will also reduce from ϕ to ϕ_1 Figure 3-6. Thus the power factor will increase from Cos ϕ to Cos ϕ_1.

$$\text{New pf} = \cos \phi_1 = \frac{W}{VA1}$$

By selecting a capacitor of an appropriate value, the power factor can be corrected to 1. However, in practice, the power factor is improved to fall between 0.9 and 0.95.

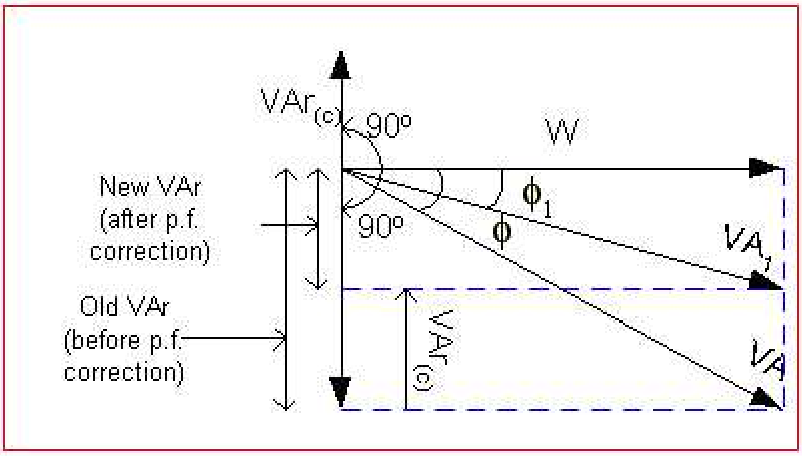

Figure 3-6 direction of capacitive reactive power vs. inductive reactive power

3.9.2 Connection of capacitors

1. Parallel (Shunt) Connection:

This is the most popular method of connection. The capacitor is connected in parallel to the luminary as shown in figures 3-8 and 3-9. The voltage rating of the capacitor is usually the same as (or a little higher than) the system voltage.

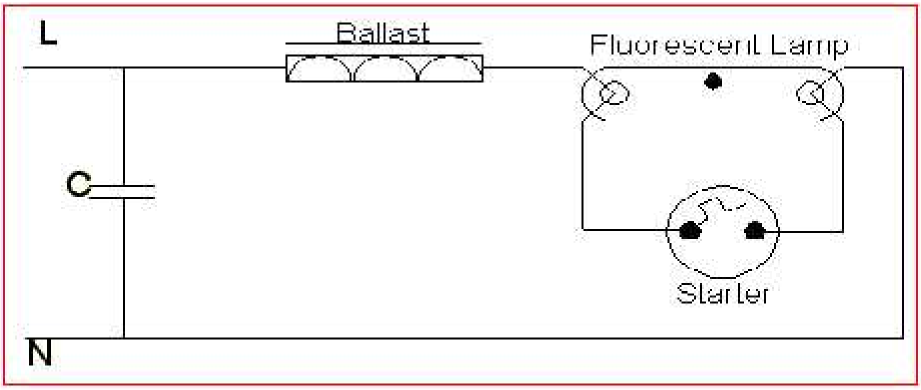

Figure 3 -7 parallel connection of capacitors for fluorescent lamp

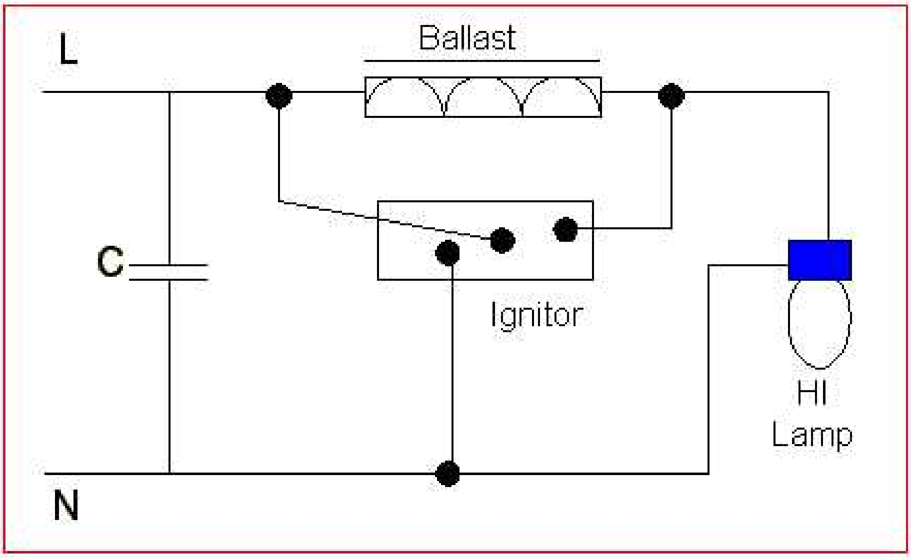

Figure 3-8 parallel connection of capacitor for incandescent lamp

2. Series Connection:

In case of a double (twin) fluorescent luminaire, where two lamps are controlled by two ballasts, it is usual to over-compensate one ballast by connecting a capacitor in series with it, and to leave the other ballast uncompensated. The leading power factor on the first ballast, in conjunction with the lagging power factor of the second ballast, brings the total power factor to near unity. The scheme is shown in figure 5. The voltage rating of series connected capacitors is much higher than the supply voltage and must be correctly selected.

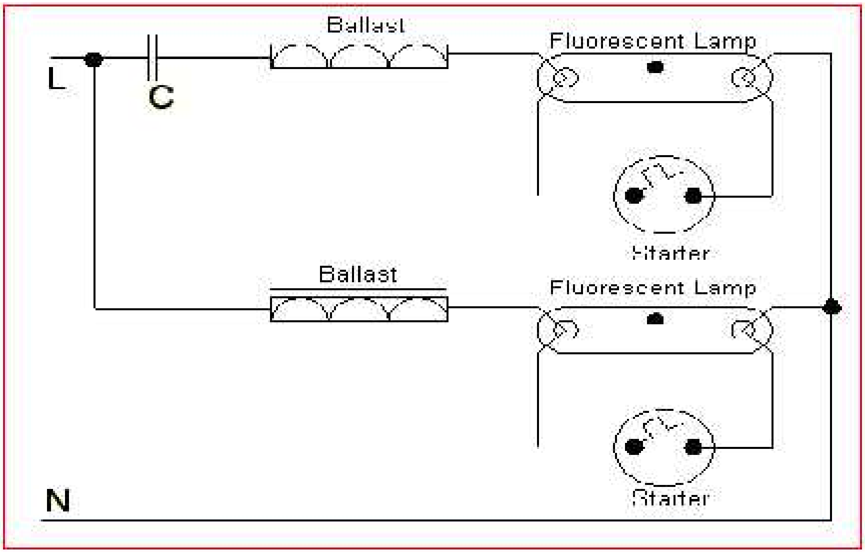

Figure 3-9 series connection of capacitors for fluorescent lamp

3.9.3 Operating instructions

1. The capacitors retain electrical charge, even when the power is switched off. It may be dangerous to touch the terminals of the capacitors, unless the capacitors are fully discharged. For safety requirements, all AMBER lighting capacitors are supplied with internal discharge resistors, so that the capacitor voltage drops to below 50 V within 1 minute of switch off. Even then, care should be exercised in handling the lighting fixtures.

Some times by oversight or by ignorance, capacitors meant for parallel operation are installed in series with the ballasts. Since the capacitors have sufficient safety margin in their insulation ratings, this error may pass unnoticed at the time of commissioning of the installation. However, with passage of time, the capacitor is overburdened and overheated, and may cause catastrophic losses. Therefore, care should be taken in selecting voltage rating of the capacitors, which should strictly be according to the application requirements.

2. As ballasts generate heat, capacitors with thermoplastic cases should be placed as much away from the ballasts as possible. Care should be taken that the capacitor case temperature does not exceed the rated temperature printed on the capacitor. If the heat dissipation within the luminaire is not proper, capacitors

3.10 Application of power factor correction capacitors

Most AC power systems require both kW (kilowatts) and KVAR (kilovars). Capacitors installed near the loads in a plant are the most economical and efficient way of supplying these kilovars. Low voltage capacitors are traditionally a high reliability maintenance-free device.

On the spot delivery of magnetizing current provided by capacitors means that kilovars do not have to be sent all the way from the utility generator to you. This relieves both you and your utility of the cost of carrying this extra kilovar load. The utility charges you for this reactive power in the form of a direct or indirect power factor penalty charge. In addition, you'll gain system capacity, improve voltage and reduce your power losses.

3.10.1 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.

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 ratio of actual power to apparent power is usually expressed in percentage and is called power factor.

$$PF = \frac{KW}{KVA}$$

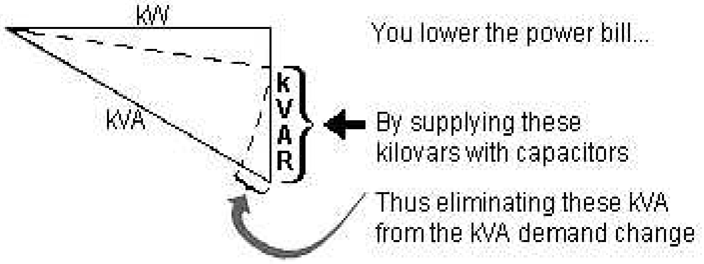

Figure 3-10 KVAR Compensation

In the illustration below, addition of the capacitor has improved line power factor and subtracted the non-working current from the lines. This reactive current is now supplied by the capacitor rather than the utility.

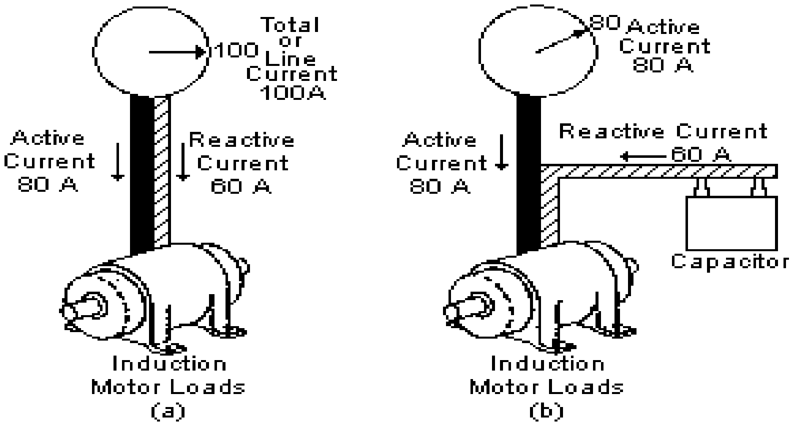

Figure 3-11 the effect of adding capacitors on the current of an induction motor

3.10.2 Selecting KVAR for 3-Phase Motors

To properly select the amount of KVAR required to correct the lagging power factor of a 3-phase motor you must have three pieces of information:

- kW (kilowatts)
- Existing Power Factor in percent
- Desired Power Factor in percent

The formula to calculate the required KVAR is:

Factor from Table 1 below x kW = KVAR of capacitors required.

EXAMPLE

A small machine tool plant used an average of 100 kW with an existing power factor of 80%. Their desired power factor is 95%. The KVAR of capacitors necessary to raise the power factor to 95% is found by using Table 1, which in this case gives .421 as the factor needed to complete the formula referenced above:

.421 x 100 kW = 42 KVAR

The customer may now choose the capacitor catalog number by KVAR and voltage from the complete ratings listed in this catalog.

If kW or Present Power Factor is not known you can calculate from the following formulas to get the three basic pieces of information required to calculate KVAR:

$$\mathrm{PF} = \frac{\mathrm{KW}}{\mathrm{KVA}}$$

$$\text{KVA} = \frac{1.73 * I * E}{1000}$$

$$\text{KW} = \frac{1.73 * I * E * PF}{1000}$$

WHERE

I = full load current in amps

E = voltage of motor

PF = Present power factor as a decimal (80% = .80)

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

3.10.3 Benefits of Power Factor Correction Capacitors

The application of shunt capacitors to industrial power systems has several benefits. Among these are:

Benefit 1 - Reduce 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, capacitors reduce power bills by reducing the KVA or KVAR demand.

EXAMPLE: KVAR Demand Charge

a plant with a demand of 1800 KVA, 1350 kW and 1200 KVAR 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 demand can be eliminated by the addition of capacitors.

In our example, the KVAR charge is $1.50 per month for each KVAR of demand in excess of 1/3 of the kW demand.

Step 1) Calculate KVAR demand in excess of 1/3 of the kW demand.

$$1200\,\text{KVAR} - \frac{1350\,\text{KW}}{3} = 750\,\text{KVAR}$$ (Capacitors can supply this KVAR).

Step 2) Estimated annual power bill savings.

$1.50 demand charge x 750 KVAR x12 months = $13,500 savings

Step 3) Estimate the cost of 750 KVAR of capacitors. (On a 480-volt system installed capacitor cost is approximately $15/kVAR)

750 KVAR x $15 = $11,250 capacitor cost

$13,500 annual savings vs. $11,250 capacitor investment. Capacitors will pay for themselves in 10 months, and continue to produce savings thereafter.

$$\frac{11250}{13500} = 0.833$$

0.833 * 12 = 10 months.

EXAMPLE: kW Demand Charge

A plant with a demand of 1000 kW has an 80% power factor. The serving utility has a target power factor of 85'%o and a kW demand charge. This example will show how the power factor of the plant load helps determine the kW billing charge. Therefore, improving the plant power factor to the targeted 85% can reduce the kW billing.

The utility in our example has a kW demand charge of $9.00 and a target power factor of 85%. The monthly kW billing is determined by the ratio of target power factor to the existing power factor times kW demand.

Step 1) Calculate the amount of monthly kW billing. (as specified by Utility)

$$\frac{100\,\text{KW}*0.85\,\text{needed}\,\text{PF}}{0.80\,\text{exicting}\,\text{PF}} = 1062\ \text{KW}$$

$9.00 kW demand charge x 1062 kW = $9,558 billing.

Step 2) Now determine the amount of KVAR required to improve the power factor to 85%. Simply multiply the kW by the factor obtained from Table 1. The factor to calculate from .80 to .85 power factor is .130.

0.130 x l000 kW = 130 KVAR (required KVAR to meet 85% target pf).

Step 3) Estimate the cost of 130 KVAR of capacitors. (On a 480-volt system, installed capacitor cost is approximately $15/kVAR)

130 KVAR x $15 = $1,950 (capacitor investment)

Step 4) Calculate the amount of kW billing with new power factor.

$$\frac{100\ \text{KW}\,0.85\ \text{needed}\ \text{PF}}{0.85\ \text{new PF}} = 1000\ \text{KW}\,\text{billing demanc}$$

$9.00 kW demand charge x 1000 kW = $9,000 billing.

Step 5) Compare both kW billing charges.

80% → Pf → kW billing → $9,558
85% → Pf → kW billing → $9,000
Savings = $ 558

A monthly power bill savings of $558 with a 3 1/2 month payback on the capacitor investment and continued savings thereafter.

EXAMPLE: KVA Demand Charge

another plant with 400 kW and 520 KVA demands has a power contract which calls for a demand charge based on KVA. This KVA demand can be reduced if the power factor is raised.

The demand charge in our example is $3.00 per KVA per month. The amount of capacitor KVAR to be added can be determined by checking the savings, which can be realized after power factor improvement. Often 95% is a good economical power factor.

Step 1) The Present Power Factor = $\frac{\text{KW}}{\text{KVA}} = \frac{400}{520} = 77\ \%$ (a low power factor)

Step 2) let's assume that we install enough capacitors to raise the power factor to 95%. This would reduce the present 520-kVA demands down to 421 KVA. Calculated as follows:

$$\text{Reduced KVA} = \frac{\text{KW}}{\text{new PF}} = \frac{400}{0.95} = 421\,\text{KVA}$$

Step 3) since the local power rate includes a monthly $3.00/kVA demand charge, you would calculate the savings in demand charge as follows:

KVA Saved = Present KVA—Reduced KVA
KVA Saved x KVA Demand Charge = $ Savings or 520 - 421 = 99

99 x $3.00 = $297.00 savings per month

If annualized, the savings would be $3564 per year.

Step 4) Now calculate the KVAR size of capacitors required to accomplish the 95'%o desired power factor. By referring to Table 1, we find that the multiplier to go from 77'%'to 95% is 0.500. Thus:

KW x Factor from Table 1 = KVAR or   400 x .500 = 200 KVAR

Benefit 2 - Gains in System Capacity

In thermally limited equipment, such as transformers or cable, capacitors release capacity and thus allow a greater payload. By furnishing the necessary magnetizing current for induction motors and transformers, capacitors reduce the current drawn from the power supply. Less current means fewer loads on transformers and feeder circuits. If a system has an existing overload, the capacitors may eliminate it. If the system is not overloaded, capacitors can release capacity and postpone or avoid an investment in more expensive transformers, switchgear and cable, otherwise required serving additional loads.

EXAMPLE

There are four steps to follow to calculate the gain in system capacity:

1) Determine how much load increase is required. Let's assume that 20% more load is expected in the plant.

2) From monthly power bills, determine the present kW demand and power factor. As shown in Benefit 1, the monthly power bill shows a 400 kW demand, 520 KVA demand and a power factor of 75% (power factor = kW demand divided by KVA demand).

3) Determine how high the power factor must be raised to gain the capacity required. In our example, we want 20% additional capacity. The vertical axis on the graph below represents released system capacity percentages. Follow the horizontal line for 20% to the right until you reach the original power factor of .75. Then follow down to the corrected power factor line, which shows approximately 90%. This is the new power factor required to gain the targeted increase in system capacity.

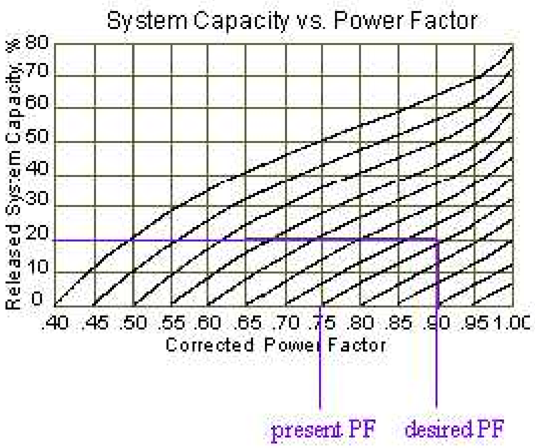

Figure 3-12 system capacity vs. power factor

4) Determine the KVAR needed to raise power factor to required level. 170.4 KVAR is required to achieve 90% power factor.

KW x Factor from Table 1 = KVAR or 400 x0.426 = 170.4 KVAR

By installing the 170.4 KVAR of capacitors, the 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.

Benefit 3 - Improve Voltage Conditions

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.

Capacitors will raise your plant voltage level, and keep it up along your feeders, right out to the last motors. Motor performance is improved and so is production.

An estimate of voltage rise from the installation of power capacitors to a factory electrical system can be made.

FORMULA:

$$\%\text{ of Voltage Rise} = \frac{\text{KVAR of Capacitors} * \%\text{ Impedance of Transformer}}{\text{KVA of Transformer}}$$

Benefit 4 - Reduce Line Losses

by supplying kilovars at the point they are needed, capacitors relieve the system of transmitting reactive current. Since the electrical current in the lines is reduced, I^2R losses decrease. Therefore, fewer kilowatt-hours need to be purchased from the utility.

FORMULA:

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

3.10.4 Installation Recommendations (Where/What Type to Install)

After careful consideration of the advantages and disadvantages of the various installation options below, 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.

OPTION A - Install directly at the single speed induction motor terminals (on the secondary of the overload relay).

ADVANTAGES:

- Can be switched on or off with the motors, eliminating the need for separate switching devices or over current protection. Also, only energized when the motor is running.
- Since KVAR is located where it is required, line losses and voltage drops are minimized; while system capacity is maximized.

DISADVANTAGES:

- Installation costs are higher when a large number of individual motors need correction.
- Overload relay settings must be changed to account for lower motor current draw.

PRODUCT:
Usually the best location for individual capacitors.

OPTION B - Install between the contactor and the overload relay.

- With this option the overload relay can be set for nameplate full load current of motor. Otherwise the same as Option A.

PRODUCT:
Usually the best location for individual capacitors.

OPTION C - Install between the upstream circuit breaker and the contactor.

ADVANTAGES:

- Larger, more cost effective capacitor banks can be installed as they supply KVAR to several motors. This is recommended for jogging motors, multi-speed motors and reversing applications.

DISADVANTAGES:

- Since capacitors are not switched with the motors, overcorrection can occur if all motors are not running.*
- Since reactive current must be carried a greater distance, there are higher line losses and larger voltage drops.

PRODUCT:
Large banks of fixed KVAR with fusing on each phase.

OPTION D - Install at the main distribution bus.

ADVANTAGES:

- Lower installation cost, since you install fewer banks in large kVAR blocks.

DISADVANTAGES:

- Overcorrection can occur under lightly loaded conditions. *
- A separate disconnect switch and over current protection is required.

PRODUCT:
Large banks of fixed KVAR with fusing on each phase.

3.10.5 How to Switch Capacitors Separately

When a group of motors are so operated that some run while others are idle, a single capacitor equipment (containing a number of individual capacitor units) can be connected to the bus to economically supply kilovars to the group. Capacitor equipments 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%

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.

3.10.6 Consider Harmonics When Applying Capacitors

System harmonics should be considered when applying power factor correction capacitors. Although capacitors do not generate harmonics, under certain conditions they can amplify existing harmonics. Harmonics are generated when non-linear loads are applied to power systems. These non-linear loads include: adjustable speed drives, programmable controllers, induction furnaces, computers, and uninterruptible power supplies. Capacitors can be used successfully with non-linear loads when harmonic resonant conditions are avoided.

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:

$$H = \sqrt{\frac{\text{KVA sc}}{\text{KVAR}}}$$

where

H = calculated system harmonic
KVAsc = short circuit power of the system
KVAR = rating of the capacitor

Harmonic values of 5, 7, 11, and 1 3 should be avoided as they correspond to the characteristic harmonics of non-linear loads. The harmonic value of 3 should also be avoided as it coincides with harmonics produced during transformer energization and/or operation of the transformer above rated voltage.

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.

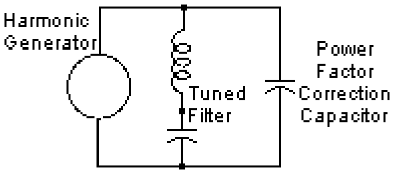

Figure 3-13 harmonic filter

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.

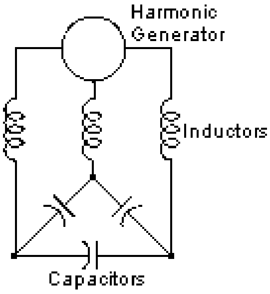

Figure 3-14 Blocking inductors

CHAPTER FOUR

4. How to calculate the power factor

4.1 calculating power factor

As was mentioned before, the angle of this "power triangle" graphically indicates the ratio between the amount of dissipated (or consumed) power and the amount of absorbed/returned power. It also happens to be the same angle as that of the circuit's impedance in polar form. When expressed as a fraction, this ratio between real power and apparent power is called the power factor for this circuit. Because real power and apparent power form the adjacent and hypotenuse sides of a right triangle, respectively, the power factor ratio is also equal to the cosine of that phase angle. Using values from the last example circuit of figure 2-16

$$\text{Power factor} = \frac{\text{Real power}}{\text{Apparent power}} = \frac{141.005\ \text{W}}{183.95\ \text{VA}} = 0.767$$

COS 39.195° = 0.767

It should be noted that power factor, like all ratio measurements, is a unit less quantity.

For the purely resistive circuit, the power factor is 1 (perfect), because the reactive power equals zero. Here, the power triangle would look like a horizontal line, because the opposite (reactive power) side would have zero length.

For the purely inductive circuit, the power factor is zero, because real power equals zero. Here, the power triangle would look like a vertical line, because the adjacent (real power) side would have zero length.

The same could be said for a purely capacitive circuit. If there are no dissipative (resistive) components in the circuit, then the real power must be equal to zero, making any power in the circuit purely reactive. The power triangle for a purely capacitive circuit would again be a vertical line (pointing down instead of up as it was for the purely inductive circuit).

Power factor can be an important aspect to consider in an AC circuit; because any power factor less than 1 means that the circuit's wiring has to carry more current than what would be necessary with zero reactance in the circuit to deliver the same amount of (real) power to the resistive load. If our last example circuit had been purely resistive, we would have been able to deliver a full 183.95 watts to the load with the same 1.533 amps of current, rather than the mere 141.005 watts that it is presently dissipating with that same current quantity. The poor power factor makes for an inefficient power delivery system.

Poor power factor can be corrected, paradoxically, by adding another load to the circuit drawing an equal and opposite amount of reactive power, to cancel out the effects of the load's inductive reactance. Inductive reactance can only be canceled by capacitive reactance, so we have to add a capacitor in parallel to our example circuit as the additional load. The effect of these two opposing reactance's in parallel is to bring the circuit's total impedance equal to its total resistance (to make the impedance phase angle equal, or at least closer, to zero).

Since we know that the (uncorrected) reactive power is 118.13 VAR (inductive), we need to calculate the correct capacitor size to produce the same quantity of (capacitive) reactive power. Since this capacitor will be directly in parallel with the source (of known voltage), we'll use the power formula which starts from voltage and reactance:

$$Q = \frac{E^2}{X} \qquad \text{………Solving for X………}$$

$$Xc = \frac{E^{2}}{Qc} = \frac{(120)^{2}}{118.13\ \mathrm{VAR}} = 121.88\ \Omega$$

$$Xc \quad = \quad \frac{1}{2\ ®\quad f\quad c}$$ ………Solving for C………

$$C = \frac{1}{2®\ f\ Xc} = \frac{1}{2®\ (50\,Hz)(121.88\,\Omega)} = 26.117\ «\ f$$

Let's use a rounded capacitor value of 26 µF and see what happens to our circuit:

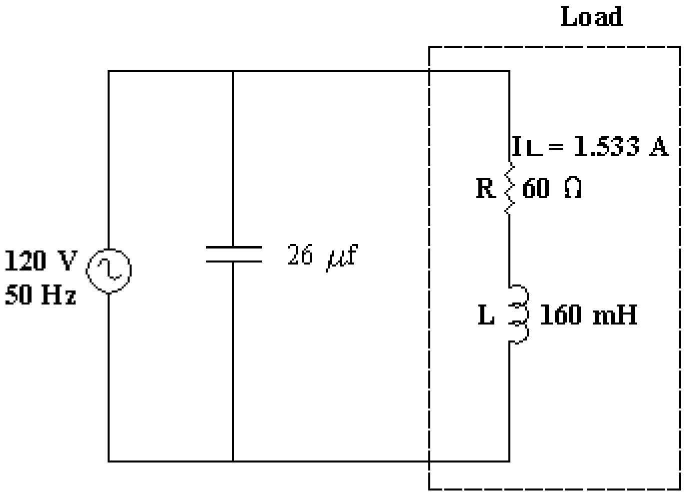

Figure 4-1 AC circuit with Resistive/reactive load with C for correction

$Z_{\text{total}} = Z_C \,//\, (Z_L - Z_R)$

$$\begin{aligned} \text{Ztotal} &= \left[(121.878\ \Omega\ \langle\text{-}90^\circ\ //\ 50.266\ \Omega\ \langle 90^\circ) - 60\Omega\ \langle 0^\circ\right] \\ &= 120.64 - \mathrm{j}\ 573.58\ \ \mathrm{m}\Omega \\ &= 120.64\ \Omega\ \langle 0.2724^\circ \end{aligned}$$

P = Real power = $I^2 * R$ = 141.005 W

S = Apparent power = $I^2 * Z$ = 183.95 VA

The power factor for the circuit, overall, has been substantially improved. The main current has been decreased from 1.41 amps to 994.7 milliamps, while the power dissipated at the load resistor remains unchanged at 119.365 watts. The power factor is much closer to being 1:

$$\begin{aligned}
\text{Power factor} &= \frac{\text{Real power}}{\text{Apparent power}} = \frac{119.365}{119.366} = 0.9999887 \\
\text{Phase angle} &= 0.272^\circ \\
\cos 0.272^\circ &= 0.9999887
\end{aligned}$$

Since the impedance angle is still a positive number, we know that the circuit, overall, is still more inductive than it is capacitive. If our power factor correction efforts had been perfectly on-target, we would have arrived at an impedance angle of exactly zero, or purely resistive. If we had added too large of a capacitor in parallel, we would have ended up with an impedance angle that was negative, indicating that the circuit was more capacitive than inductive.

It should be noted that too much capacitance in an AC circuit will result in a low power factor just as well as too much inductance. You must be careful not to over-correct when adding capacitance to an AC circuit. You must also be very careful to use the proper capacitors for the job (rated adequately for power system voltages and the occasional voltage spike from lightning strikes, for continuous AC service, and capable of handling the expected levels of current).

If a circuit is predominantly inductive, we say that its power factor is lagging (because the current wave for the circuit lags behind the applied voltage wave). Conversely, if a circuit is predominantly capacitive, we say that its power factor is leading. Thus, our example circuit started out with a power factor of 0.705 lagging, and was corrected to a power factor of 0.999 lagging.

Note:

Poor power factor in an AC circuit may be ``corrected," or re-established at a value close to 1, by adding a parallel reactance opposite the effect of the load's reactance. If the load's reactance is inductive in nature (which is almost always will be), parallel capacitance is what is needed to correct poor power factor.

4.2 Practical power factor correction

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

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

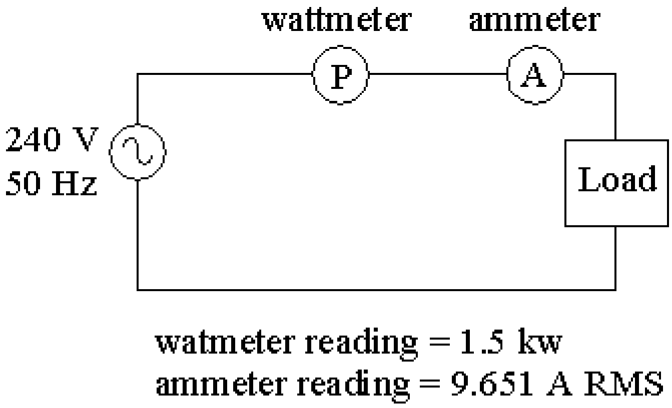

Figure 4-2 Practical power factor measuring

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

S = I * E

= (9.615 A) * (240 V)

= 2.316 KVA

As we can see, 2.316 kVA is a much larger figure than 1.5 kW, which tells us that the power factor in this circuit is rather poor (substantially less than 1). Now, we figure the power factor of this load by dividing the true power by the apparent power:

$$\text{Power factor} = \frac{P}{S} = \frac{1.5\,KW}{2.316\,KVA} = 0.65$$

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

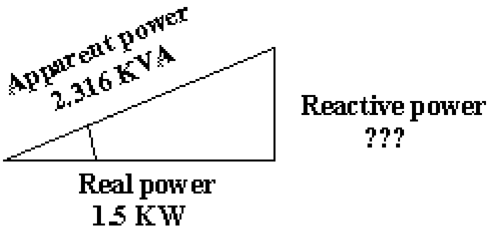

Figure 4-3 power triangle

To determine the unknown (Reactive power) triangle quantity, we use the Pythagorean Theorem "backwards," given the length of the hypotenuse (Apparent power) and the length of the adjacent side (Real power):

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

Q = 1.765 KVAR

If this load is an electric motor, or most any other industrial AC load, it will have a lagging (inductive) power factor, which means that we'll have to correct for it with a capacitor of appropriate size, wired in parallel. Now that we know the amount of reactive power (1.765 KVAR), we can calculate the size of capacitor needed to counteract its effects:

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

………Solving for X………

$$Xc = \frac{E^2}{Qc} = \frac{(240)^2}{1.765\ KVAR} = 32.635\,\Omega$$

$$Xc = \frac{1}{2\pi f c}$$

………Solving for C………

$$C = \frac{1}{2\pi Xc} = \frac{1}{2\pi (50\ Hz)\, 32.635\ \Omega} = 97.536\ \mu f$$

Rounding this answer off to 97 µF, we can place that size of capacitor in the circuit and calculate the results:

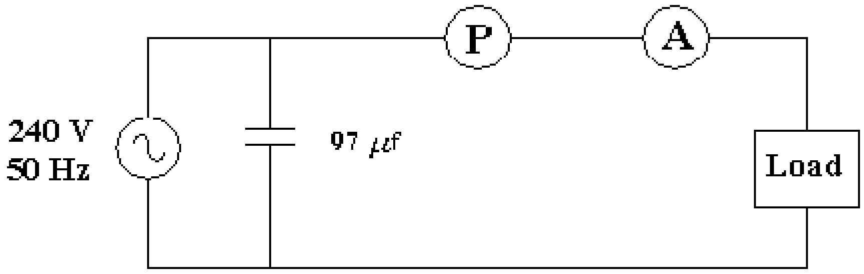

Figure 4-4 place of capacitor in the circuit

A 97 µF capacitor will have a capacitive reactance of 32.815 Ω, giving a current of 7.314 amps, and a corresponding reactive power of 1.755 kVAR (for the capacitor only). Since the capacitor's current is 180^{o} out of phase from the the load's inductive contribution to current draw, the capacitor's reactive power will directly subtract from the load's reactive power, resulting in:

Total KVAR = Inductive KVAR - Capacitive KVAR

= 1.765 KVAR - 1.755 KVAR

= 10 VAR

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

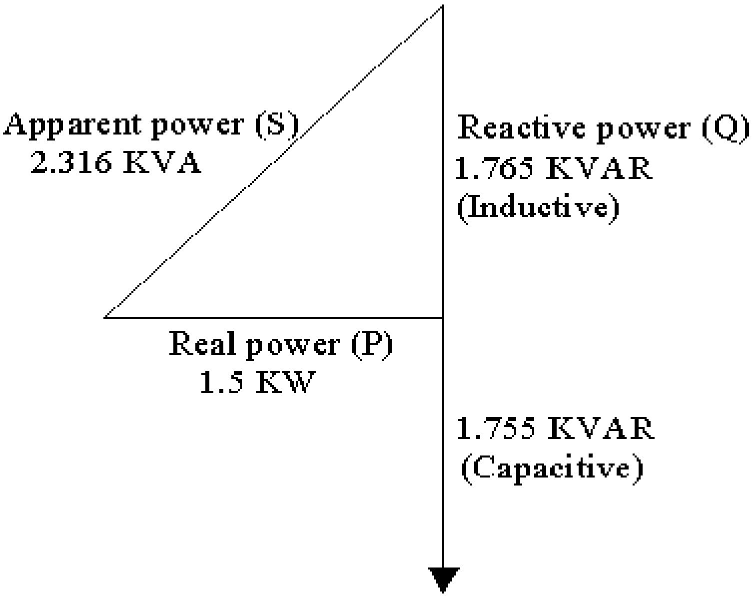

Figure 4-5 power triangle before adding capacitor

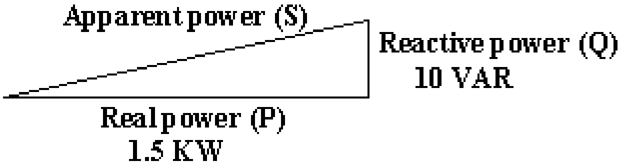

Figure 4-6 power triangle after adding capacitor

The new apparent power can be found from the real and new Reactive power values, using the standard form of the fethagorius theorem:

$$\text{Apparent power} = \sqrt{(\text{Reactive power})^2 + (\text{Real power})^2} = 1.50003\,KVA$$

This gives a corrected power factor of (1.5kW / 1.50003 kVA), or 0.999998, and a new total current of (1.50003 kVA / 240 Volts), or 6.25 amps, a substantial improvement over the uncorrected value of 9.615 amps! This lower total current will translate to less heat losses in the circuit wiring, meaning greater system efficiency (less power wasted).

4.3 Understanding Your Electric Bill:

Understanding what you pay for on your electric bill can help you reduce it. Many customers have four separate charges on their business electric bill. Some of these charges do not apply to smaller customers. Every customer has a fixed monthly basic charge and an energy charge billed in kilowatt-hours. The demand charge is based on the highest or peak use of power during the month. Large customers with many motors also have a reactive power charge.

4.3.1 Basic Charge

The Basic Charge covers services you use regardless of energy consumption: meter reading, billing, and customer service. This charge is based on the number and type of meters. In some cases, a building has multiple services, each of which has a basic charge. If separate meters are not needed for tenant billing, then combining electric services into one meter will reduce the basic charge, although this will usually require customer cost for an electrician to rewire the electric services.

4.3.2 Energy Charge

The energy charge relates to the energy you use. Energy is measured in kilowatt-hours (kWh). For billing purposes, rates are based on a separate delivery charge and energy charge. The delivery charge covers the cost of constructing and maintaining the electric distribution system. The energy charge is related to the cost of wholesale or generated electrical energy. From the customer’s point of view, the combined rates for the energy and delivery charge apply to all the electrical energy used. Two examples of energy use are shown below. In both cases, 1000 Watt-hours or one kilowatt hour (kWh) of energy is used.

Saving energy can reduce your energy bill. You achieve savings by either

(1) reducing the operating hours,
(2) reducing the amount of equipment on at any one time, or
(3) improving the equipment efficiency.

An example of an efficiency improvement is to replace the 100-Watt bulbs with 25-Watt compact fluorescent lamps. The total fluorescent energy use (kWh) would be only 25% of the incandescent lamp use. That's a savings of 75%, both in kWh and in your energy charge.

Example 1

Use one 100-Watt light bulb for 10 hours:

100 Watts x 10 hours = 1000 Watt-hours = 1 kilowatt-hour = 1 kWh

Example 2

Use ten 100-Watt light bulbs for 1 hour:

10 bulbs x 100 Watts each = 1000 Watts.

1000 Watts x 1 hour = 1000 Watt-hours = 1 kWh

4.3.3 Demand Charge

Whenever you turn on a piece of equipment, you expect to have enough power available to operate it. Because electricity isn't stored, Business customers pay a separate demand charge to cover the cost of having this capacity in reserve. Residential customers pay for this capacity through a higher residential energy rate. It's a bit like owning a car. You have to make loan and insurance payments based on the size of your car no matter how much you drive. Those are fixed costs. If you only drive down to the corner store once a week, the cost per mile for driving will be very high. Demand is measured in units of power or kilowatts (kW). A business customer is billed for the highest 15- minute period of power demand during the monthly billing period. Then the meter is reset for the next period.

Examples 3 and 4 show two different cases that have different demand charges. Operating all three motors at the same time in Example 4 creates 15 kW of demand, or three times the demand one motor creates in Example 3. This triples the

4.3.4 Demand charge.

Notice that in both cases the energy (kWh) use and the energy charge is the same. Approximate and rounded energy and demand rates are used in examples. To measure demand, electric meters record the average demand over each 15-minute period and remember the highest or peak period for the month. A short spike—such as a power surge when a motor starts up—may create a large instantaneous power use, but it will have negligible impact on demand that is averaged over 15 minutes. On the other hand, equipment that operates for longer periods at the same time as other large equipment will increase electric demand. If your operation allows, you can reduce demand charges by staggering motor or other equipment use, so that less total equipment power is on at any given time.

You can manage your demand with controls, changes in your operation, or improvements to equipment efficiency.

Example 3

Use one 5-kiloWatt piece of equipment for 300 hours in a month.
Demand = 5 kW @ $5.00/kW-month = $25.00 Demand Charge
5 kW x 300 hours = 1500 kWh. @ $0.05/kWh = $75.00 Energy Charge
Monthly Energy & Demand cost: $100.00

Example 4

Use three 5-kiloWatt pieces of equipment simultaneously for 100 hours in a month.

Demand: 3 x 5kW = 15 kW @ $5.00 = $75.00 Demand Charge
15 kW x 100 hours = 1500 kWh @ $0.05 = $75.00 Energy Charge
Monthly Energy & Demand cost: $150.00

Reactive Power (Power Factor) Charge a full technical explanation of reactive power is beyond the scope of this document. Simply put, when there is a large inductive load typically because there are many motors at a facility, reactive power must be measured to properly allocate power costs to that facility. A standard Watt-hour meter does not record reactive power. When motors or other inductive loads cause a shift between voltage and current, more current must be generated and supplied to accomplish the same electrical work.

4.4 Case study

We took al-nahda factory for iron as a case study in our project and we get the following results

Background

The total power is made up of two parts: the real power and the reactive power. The real power does the useful work and is measured in kilowatts (kW). Reactive power is measured in kilovolt- Amperes Reactive (KVAR). It is the power needed to excite the magnetic field of an induction motor or other inductive load. The two parts are vector quantities that add up to make the total power, measured in kilovolt-Amperes (KVA).

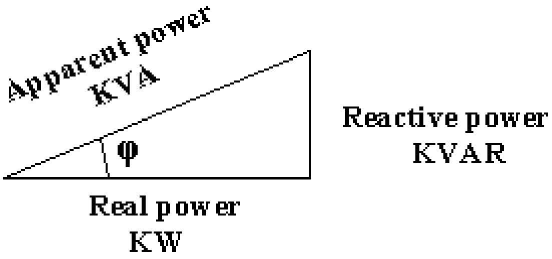

Figure 4-7 power triangle

The reactive power component does no useful work, and is not registered on a real power meter. However, it does contribute to the heating of generators, transformers, wiring, and transmission lines. Thus, it constitutes an energy loss.

Your company is charged by the amount of total power you receive from the utility. Since you cannot reduce the amount of real power you use the only way to reduce the amount of total power you receive from your utility is to reduce reactive power use.

Anticipated Savings

Since you paid for 90 KVAR of capacitance that was added to your utility company's distribution system, you are only billed for 75% (%TP) of the actual KVA that you use. This percentage of the actual KVA is billed as the monthly power charge (PC) at a rate of NIS 4.75 per KVA.

The following Power Factor Correction worksheet shows the effect of adding various amounts of capacitance (KVAR Correction) to correct the power factor. Monthly analysis is necessary because power and energy use vary from month to month. The worksheet shows dally amounts of demand (kW), kilovolt-Amperes Reactive (KVAR), kilovolt-Amperes cost (KVA$), and KVA, actual (KVAa), billed

(KVAb), and proposed (KVAp). The Proposed Cost Savings (PCS) for each month is found from

PCS = KVA$ x [KVAa - KVAp]

The Savings and Cost Summary table shows proposed KVAR correction, cost savings, implementation cost, and simple and incremental payback. We choose the optimum amount of correction based on incremental payback. The incremental payback is the ratio of the implementation cost and cost savings for each additional increment of KVAR. Once the optimum is selected, the total annual cost savings (CS) are determined, along with the simple payback. We also attempted to limit proposed power factor to around 95% to reduce the chance of overcorrecting and reducing system stability.

The best combination of cost savings and payback was found by adding 100 KVAR of capacitance. The annual cost savings would therefore be

CS = NIS2938.11 /year

Implementation Cost

Assuming an installed cost of approximately NIS20/kVAR, the implementation cost (IC) would be

IC = 100 KVAR x NIS20/ KVAR
= NIS 2000

The cost savings will pay for the implementation cost in 0.7 years.

Automatic power factor correction is also available that automatically adds the correct number of capacitors to maintain the optimum power factor as plant electric loads change. However, the cost is approximately three times as great and the payback three times as long.

Note

In general, small motors often can be corrected as a group at the motor control centers. On larger motors, installing capacitors at the motor starter. The capacitors will disconnect automatically when the motor is not operating to prevent over-correction.

If soft-start motor starters or motor load controllers are being used, the capacitors may require installation ahead of the controller. Placing capacitors between the controller and the motor may result in damage to the controller and other equipment.

There are additional benefits from improving power factor. Less total current flows in the plant wiring, motors, and other equipment. Less current means reduced power losses with resulting energy and demand savings. However, energy savings due to these power losses are typically less than 1% of plant electricity use.

Other benefits from improved power factor are that motors run cooler and that system voltage is higher. Therefore, motor efficiency, capacity and starting torque will also be slightly higher. Branch circuit capacity also is higher because more real work can be done with the same total current.

Table 4-1 data and KVAR required for correction

Present Condition			Proposed KVA				
			KVAR correction				
KVA	**KW**	**Pf**	**50 KVAR**	**75 KVAR**	**100 KVAR**	**125 KVAR**	**150 KVAR**
138.6	102.01	0.74	109.57	103.10	102.49	105.02	118.34
184.8	135.99	0.74	141.75	136.81	136.35	138.27	148.64
189	139.09	0.74	144.73	139.90	139.45	141.32	151.48
189	139.09	0.74	144.73	139.90	139.45	141.32	151.48
201.6	148.35	0.74	153.65	149.11	148.69	150.44	160.02
201.6	148.35	0.74	153.65	149.11	148.69	150.44	160.02
210	154.56	0.74	159.65	155.29	154.88	156.57	165.80
210	154.56	0.74	159.65	155.29	154.88	156.57	165.80
210	154.56	0.74	159.65	155.29	154.88	156.57	165.80
210	154.56	0.74	159.65	155.29	154.88	156.57	165.80
205.8	151.46	0.74	156.65	152.20	151.78	153.50	162.91
207.9	153.01	0.74	158.15	153.74	153.33	155.04	164.35

Table 4-2 data and prices

Present Conditions			Proposed Cost Savings				
			KVAR Correction				
KVA	**KVAR**	**KVA Charge NIS**	**50 KVAR**	**75 KVAR**	**100 KVAR**	**125 KVAR**	**150 KVAR**
138.6	106.5	658.35 NIS	137.89 NIS	159.49 NIS	171.52 NIS	159.49 NIS	96.24 NIS
184.8	142	877.80 NIS	204.49 NIS	221.03 NIS	230.14 NIS	221.03 NIS	171.76 NIS
189	145.2	897.75 NIS	210.28 NIS	226.47 NIS	235.36 NIS	226.47 NIS	178.22 NIS
189	145.2	897.75 NIS	210.28 NIS	226.47 NIS	235.36 NIS	226.47 NIS	178.22 NIS
201.6	154.9	957.60 NIS	227.76 NIS	243.00 NIS	251.32 NIS	243.00 NIS	197.51 NIS
201.6	154.9	957.60 NIS	227.76 NIS	243.00 NIS	251.32 NIS	243.00 NIS	197.51 NIS
210	161.35	997.50 NIS	239.16 NIS	253.80 NIS	261.82 NIS	253.80 NIS	209.95 NIS
210	161.35	997.50 NIS	239.16 NIS	253.80 NIS	261.82 NIS	253.80 NIS	209.95 NIS
210	161.35	997.50 NIS	239.16 NIS	253.80 NIS	261.82 NIS	253.80 NIS	209.95 NIS
210	161.35	997.50 NIS	239.16 NIS	253.80 NIS	261.82 NIS	253.80 NIS	209.95 NIS
205.8	158.15	977.55 NIS	233.46 NIS	248.40 NIS	256.60 NIS	248.40 NIS	203.73 NIS
207.9	159.75	987.53 NIS	236.31 NIS	251.10 NIS	259.21 NIS	251.10 NIS	206.86 NIS

Table 4-3 result of correction

Savings and Cost Summary					
Proposed KVAR	50 KVAR	75 KVAR	100 KVAR	125 KVAR	150 KVAR
Cost Savings CS, NIS/year	2644.9	2,834.17	2,938.11	2,834.17	2,269.84
Implementation Cost C/NIS	1000	1500	2000	2500	3000
Incremental Payback(years)	0.4	0.5	0.7	0.9	1.3

As we see from these tables, we conclude that the best value for KVAR compensation is when Q = 100 KVAR, i.e. installing capacitive unit with 100 reactive power.

CHAPTER FIVE

5. Design concept

5.1 project objectives

1. The effects of power factor on current, efficiency, voltage drop, harmonics, etc.
2. How to calculate the power factor for any plant, as case study.
3. The automatic power factor correction and its application.
4. Design an automatic power factor correction by using personal computer.

5.2 block diagram

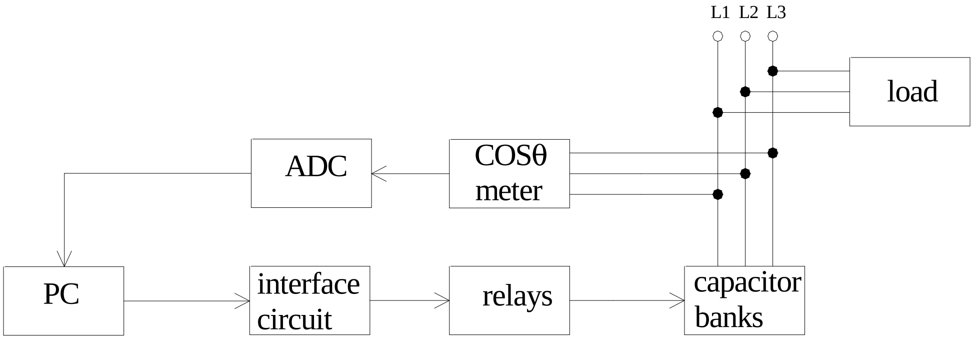

Figure 5-1 block diagram

Block diagram analyses

Control circuit

1. DC Power supply, to feed the potentiometer.
2. Potentiometer, to get the reference voltage which signs to the demand value of cos ¨ .

3. Comparator, to make comparison between the actual value of cos ¨ and the reference value of cos ¨ , and this is done by computer.
4. Amplifier, to amplify the value of Verror.
5. Logic switches, to activate and deactivate the stages of capacitor banks.

Sensor circuit

We need the following

- Cos ¨ meter

This sensor reads the actual value of PF with any change in the load state, and sends it to the comparator (to the computer), to make comparison between it with the desired value.

Note**:** Cos ¨ meter must be connected with the phase that never can be replaced, i.e. some machines are single phase and the others are three phase, so when we need just single phase machines to be in work, the power factor meter must be connected.

Power circuit

1. Three phase power supply.
2. Capacitor banks.
3. Load.

Design analyses:

In our design we use a personal computer to satisfy the following operations:

1. We store the desired value of power factor in the computer by using software program.
2. It makes comparison between the actual value and reference value of PF, which is stored in the computer

3. And it determines which bank of capacitor banks should be energized.

- In Addition to the PC, we use PF meter to determine the actual value of PF.

5.3 How to convert power factor meter into power factor sensor

For a practical AC meter movement is to redesign the movement without the inherent polarity sensitivity of the DC types. This means avoiding the use of permanent magnets. Probably the simplest design is to use a non magnetized iron vane to move the needle against spring tension, the vane being attracted toward a stationary coil of wire energized by the AC quantity to be measured.

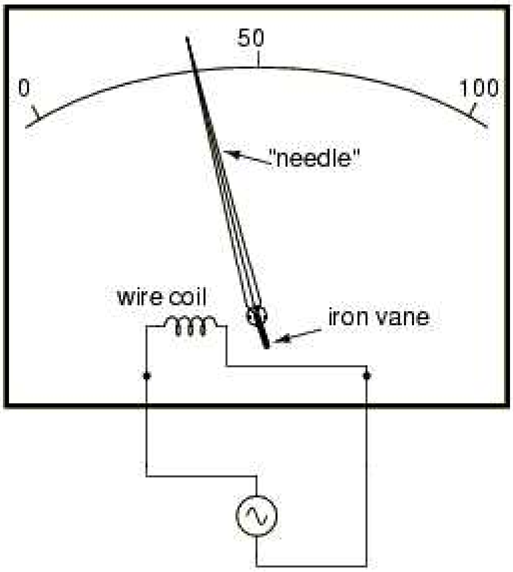

Figure 5-2 power factor meter

Electrostatic attraction between two metal plates separated by an air gap is an alternative mechanism for generating a needle-moving force proportional to applied voltage. This works just as well for AC as it does for DC, or should I say, just as poorly! The forces involved are very small, much smaller than the magnetic attraction between an energized coil and an iron vane, and as such these "electrostatic" meter movements tend to be fragile and easily disturbed by physical movement. But, for some high-voltage AC applications, the electrostatic movement is an elegant technology. If nothing else, this technology possesses the advantage of extremely high input impedance, meaning that no current need be drawn from the circuit under test. Also, electrostatic meter movements are capable of measuring very high voltages without need for range resistors or other, external apparatus.

When a sensitive meter movement needs to be re-ranged to function as an AC voltmeter, series-connected "multiplier" resistors and/or resistive voltage dividers may be employed just as in DC meter design:

We read the voltage across the coil of the iron vane as shown in figure 5-3

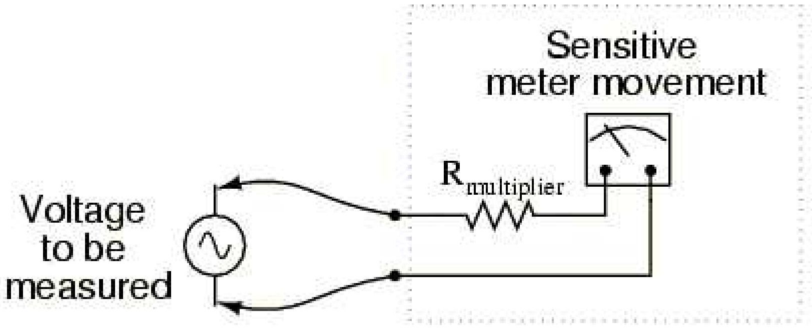

Figure 5-3 Power factor meter as sensor

5.4 How system works

By using C++ programming language, we made a software program that has the value of needed PF, take the input value of actual PF and make a comparison between both values, then give the deference value, between actual PF and needed PF, if actual PF less than needed PF the PC must actuate additional capacitor bank, then the PC take the new value of actual PF and make another comparison between a new PF and the last value of PF:

a) If the actual PF decreases, the last actuated bank of capacitor is de energized, then it take the actual value of PF and compare it with the needed value and so on, and this will be explained in chapter four.

b) If the actual Pf increases, PC compare the actual value of PF with the needed value, if the actual value is less it will energize another stage.

Note:

We must add the critical value of capacitors (the addition of KVAR mustn't increase above the value of KVAR which is caused by the inductive load).
At full load this problem is not found because the maximum value of KVAR that caused by adding capacitors is less than the value of KVAR, which is caused by the inductive load.

PC input:

There is a unique input to the PC; it is the actual value of PF, which is measured by the power factor meter from the input line of the plant, which enters analog-to-digital converter (ADC).

The A\D conversion is a quantizing process where by an analog signal is presented by equivalent binary state; this is opposite to the D\A conversion process. Analog-to- digital conversion technique. One technique involves comparing a given analog signal with the internally generated equivalent signal. This group includes successive approximation.

PC out put:

We use the parallel port to take an out put which is used to activate or deactivate the capacitor banks, the output signal which is used to actuate rely that activates contactor that actuates a stage of capacitor bank (we will use DC rely to activate AC contactor).

Using the printer port of PC, for control application using software and some interface hardware, the interface circuit with the software can be used with the printer port of any PC for controlling up to eight equipment.

The interface circuit shown in the figure is drown for only one device, being controlled by D0 bit at pin two of 25 pin parallel port. Identical circuits for the remaining data bits D1 through D7 (available at pins 3 through 9) have to be similarly wired. The use of opto-coupler ensures complete isolation of the PC from the relay driver circuitry. Lots of ways to control the hardware can be implemented using software. In C\C++ one can use the out port (portno, value) function where portno is the parallel port address (usually 378 hex for LPT1) and value is the data that is to be sent to the port. For a value =0 all the outputs (D0-D7) are off. For value =1 D0 is ON, value =2 D1 is ON, value =4, D4 is ON and so ON. e.g. if value =29 (decimal) =00011101 (binary), D0,D2,D3,D4 are ON and the rest are OFF.

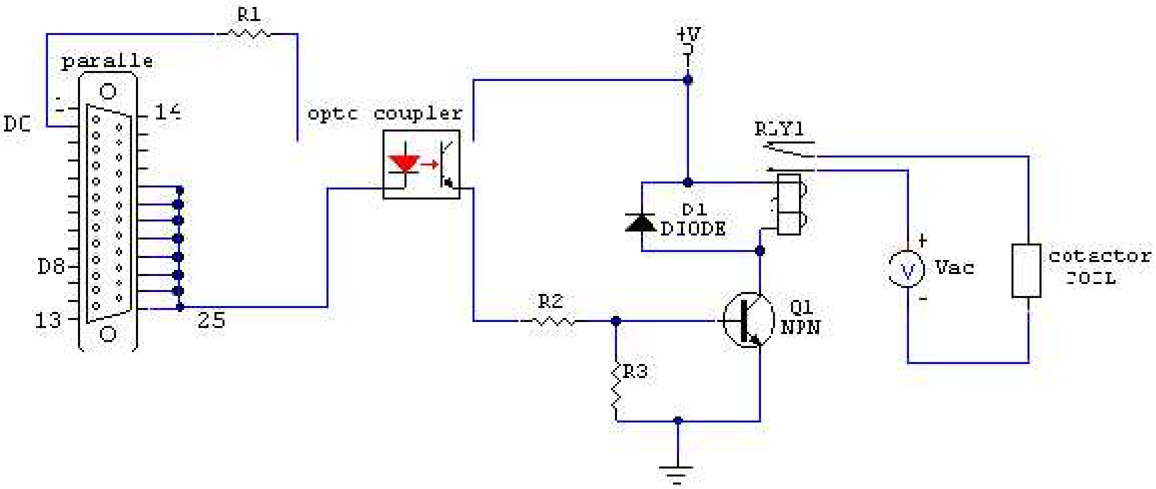

Figure 5-4 parallel port and interface circuit connection

CHAPTER SIX

6. Hardware and software system design

6.1 Compensation at low voltage (380 V)

- Fixed-valued capacitor
- Equipment providing automatic regulation, or banks that allow continuous adjustment according to requirements, as loading of the installation changes.

Note: when the installed reactive power of compensation exceeds 800 KVAR, and the load is continuous and stable, it is often found to be economically advantageous to install capacitor banks at high voltage.

Fixed capacitors

This arrangement employs one or more capacitor(s) to form a constant level of compensation. Control may be:

- Manual: by circuit breaker or load-break switch,
- Semi-automatic: by contactor,
- Direct connection to an appliance and switched with it.

These capacitors are applied:

- At the terminals of inductive devices (motors and transformers)
- At bus bars supplying numerous small motors and inductive appliance for which individual compensation would be too costly,
- In cases where the level of load is reasonably constant.

Automatic capacitor banks

This kind of equipment provides automatic control of compensation, maintaining within close limits, a selected level of power factor. Such equipment is applied at points in an installation where the active-power and/or reactive-power variations are relatively large, for example:

- At the bus bars of a general power distribution board,
- At the terminals of a heavily loaded feeder cable.

The principles and reasons, for using automatic compensation

A bank of capacitors is divided into a number of sections, each of which is controlled by a contactor. Closure of a contactor switches its section into parallel operation with other sections already in service. The size of the bank can therefore be increased or decreased in steps, by the closure and opening of the controlling contactors.

A control relay monitors the power factor of the controlled circuit(s) and is arranged to close and open appropriate contactors to maintain a reasonably constant system power factor (within the tolerance imposed by the size of each step of compensation). The cos ¨ meter for the control circuit must evidently be placed on one phase of the incoming cable that supplies the circuit(s) being controlled, as shown in figure 6-1.

By closely matching compensation to that required by the load, the possibility of producing over voltages at times of low load will be avoided, thereby preventing an over voltage condition, and possible damage to appliances and equipment.

Over voltages due to excessive reactive compensation depend partly on the value of source impedance.

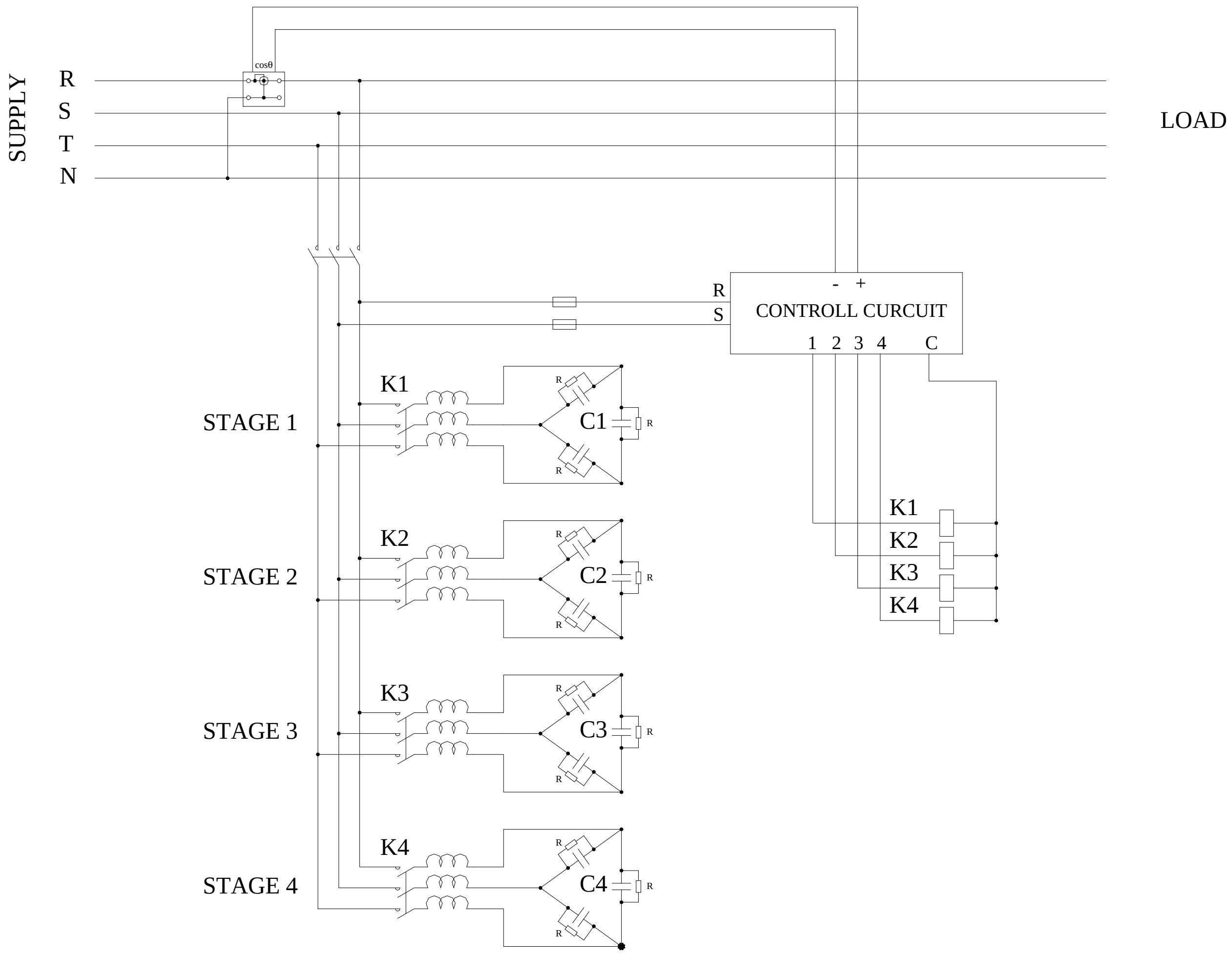

Figure 6-1: the principle of automatic-compensation control.

6.2 Power Circuit analysis

This circuit has four stages of capacitor banks (battery's), each circuit has its own contactor to activate its coil (for each phase), the coil is used for harmonic protection, each capacitor has a parallel connection of resistance to decrease the time for each capacitor discharge so these capacitors mustn't operated before discharging it.

The control circuit is a regulation controller with four stages this controller is used to activate and deactivate the capacitor bank according to value of the power factor.

System’s operation

The controller takes the value of the power factor by power factor meter, then it compares it with the value of the needed power factor, then it activates or deactivates the capacitor bank as needed.

Contactors and Protection

Only contactors designed for the switching of capacitor type loads are to be used. They should be guaranteed for a minimum of 100,000 operational cycles. The overall unit must be protected by a circuit breaker with an electronic trip circuit to allow protection grading with upstream devices.

Capacitors

The system shall utilize commercial grade capacitors; it is essential that capacitor banks in excess of 150 KVAR comprise 50 KVAR modules so that by adding or removing modules, the rating of the capacitor bank can be changed to fine tune the performance of the system. A maximum of five (5) capacitors shall be used to achieve 50 KVAR steps. Those below 150 KVAR should have 25 KVAR steps.

Low voltage capacitors shall have a minimum continuous voltage rating of 500 V_{RMS} at 50Hz. The continuous voltage and over current of the capacitors must be clearly stated on the devices. The power loss should not exceed 0.3 watts per KVAR. Capacitors shall be equipped with tunnel terminals or post terminals (quick connect terminals are not acceptable). System design should facilitate removal of a faulty module whilst allowing the balance of the capacitors to function while replacement parts are obtained.

Typically, dry capacitors have an operating life of 3 to 5 years, hybrid capacitors 6 to 8 years and oil filled 8 to 12 years depending on the manufacturer, location, operating temperatures and maintenance schedules. Any tender evaluation “weighting” should favour hybrid or oiled filled capacitors due to their superior life cycle.

The usage of static capacitors for improving a system's power factor is the most economical solution for today's industry when considering the:

- Reliability of the equipment to be installed.
- Probable electrical life span.
- Capital cost.
- Maintenance cost.
- Running cost.
- And space available.

Limitations and Risks

Several limitations and risks need to be taken into account with PFC systems. These include the following:

- Temperature – capacitor life and performance falls dramatically if the rated temperature is exceeded. For example, rated life at 50 deg C could be 17,000 hours but be cut to only 2,500 hours at 80 deg C, a drop of 85%. This makes component segregation and ventilation very important.

- Harmonics defense systems are increasingly subject to system harmonics, these can cause damage to PFC equipment**.**

- Supply Interruption – poor design can require major power disruptions during PFC repairs.

- Poor Capacitor Life – low initial cost capacitors will most likely have a shorter life and higher whole of life cost.

- System Stability – unless sufficiently small PF steps are provided with proper controls, unacceptable voltage and PF swings may well occur.

- Continuous Ratings – component life can be significantly reduced if a lower continuous current and/or voltage rating is accepted.

- Power Losses – some cheap capacitors have high losses of 2-3 watts per KVAR.

6.3 The choice between a fixed or automatically-regulated bank of capacitors

Commonly-applied rules

Where the KVAR rating of the capacitors is less than, or equal to 15% of the supply transformer rating, a fixed value of compensation is appropriate.

Above the 15% level, it is advisable to install an automatically controlled bank of capacitors.

The location of low-voltage capacitors in an installation constitutes the mode of compensation, which may be global (one location for the entire installation), partial (section-by-section), local (at each individual device), or some combination of the latter two. In principle, the ideal compensation is applied at a point of consumption and at the level required at any instant. In practice, technical and economic factors govern the choice.

6.4 Software design

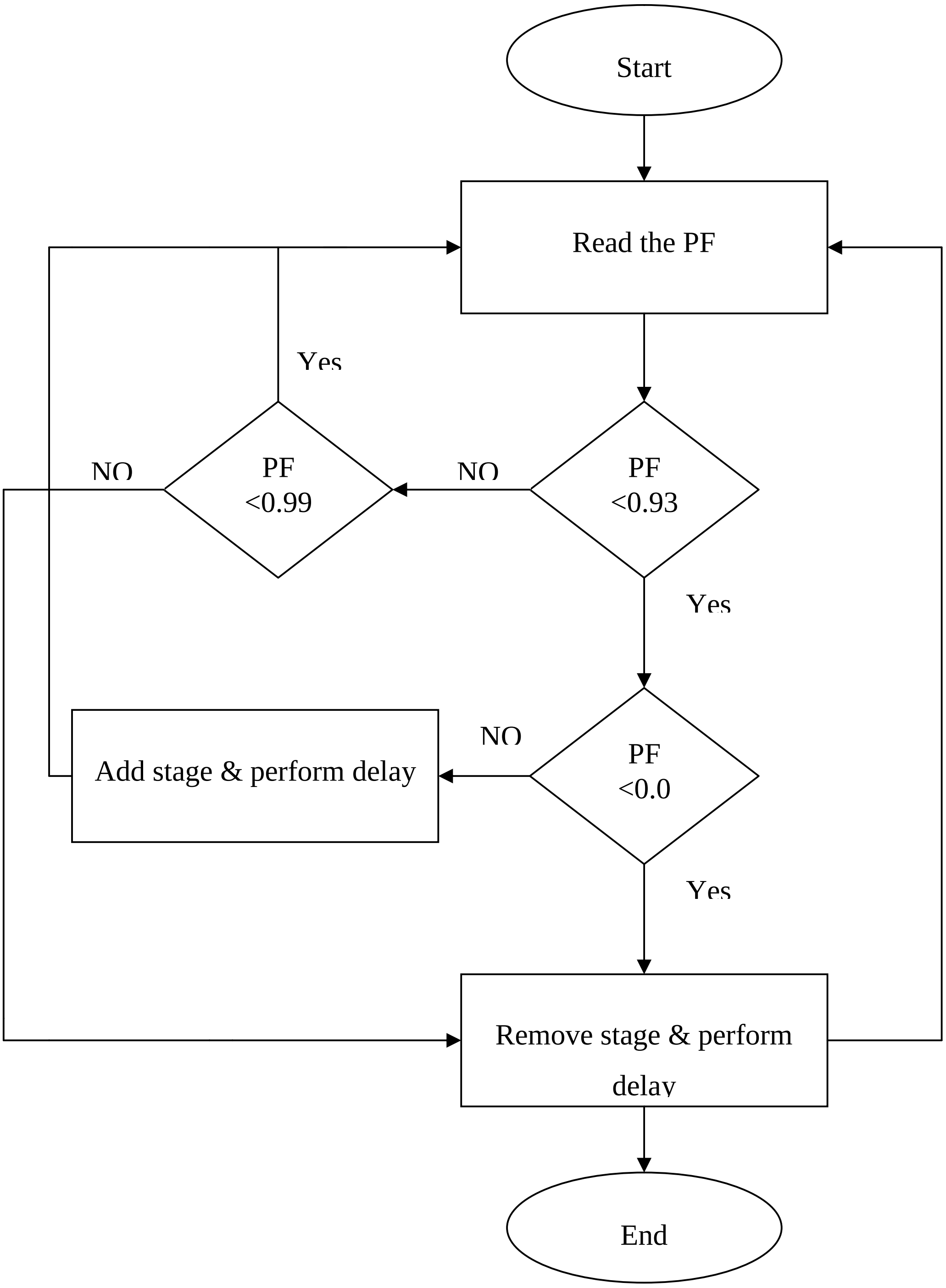

Figure 6-2 the flowchart

Flow chart analysis

1. At the first, the computer takes the value of power factor from cos ¨ meter, which measures the variation of power factor
2. The computer takes this value and compares it with the desired value of power factor.
3. If this value is less than the desired value and less than zero (i.e. leading power factor), then the controller will remove a stage, until the power factor reaches its desired value.
4. If this value is less than the desired value and greater than zero, then the controller will add a stage, until the power factor reaches its desired value.
5. If this value is greater than the desired value and less than the maximum value, then the controller will not add or remove stages, because the power factor value is acceptable.
6. If this value is greater than the desired value and greater than the maximum value, then the controller will remove a stage, until the power factor reaches its desired value.
7. After each adding or removing a stage there is a time delay, until the value of power factor is stabilized

Note:

1. We suggested the desired value of power factor to be 0.93.
2. we don’t want to let the power factor to exceed unity, i.e. the power factor mustn’t be leading

CHAPTER SEVEN

7. Conclusion

- The installation of power factor correction is a widely recognized way to reduce energy consumption.
- Significant economic or system benefit severe over-correction (P.F >1) will cause a voltage rise that can damage insulation & equipment.
- By closely matching compensation to that required by the load, the possibility of producing over voltages at times of low load will be avoided.
- The voltage rating of parallel connected capacitors is usually the same as (or a little higher than) the system voltage, but the correction in the value of P.F is small.
- The voltage rating of series connected capacitors is much higher than the supply voltage, but the correction in the value of P.F is grater.
- Individual compensation should be considered when the power of motor is significant with respect to power of the installation.
- Power factor correction equipment generates heat loads, which requires extraction to ensure the operating temperature remains within acceptable limits.
- Inductors added to the lines feeding the capacitor can be sized to block harmonic currents.
- Motors should be worked up to a maximum loading and therefore individual motors would be preferred to a single motor driving several loads where the loads are not always at a maximum.
- Motors, transformers, welding machines, induction heating coils and lighting ballasts are the major sources of lagging power factor. Factors affecting the power factor of an induction motor are size, speed and load. The larger the motor and faster its speed, the higher the full-load power factor.

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