IMPROVING THE EFFICIENCY OF POWER CONSUMPTION IN YOUR ORGANISATION BY EXAMINING POWER FACTOR CORRECTION AS A MEANS FOR MORE COST-EFFECTIVE USAGE TO CONTROL YOUR COMPANY'S ENERGY COSTS

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Abstract

This paper provides a comprehensive view into the motivation behind the installation of power factor correction equipment. A general treatment of the practical aspects of the application of reactive power compensation is given.

The paper is not intended to be a mathematical treatise, but to give a general introduction to the implementation of power factor correction and factors influencing component failure. The paper further discusses factors influencing the life-expectancy of power factor correction equipment in order to avoid their negative impact on the equipment.

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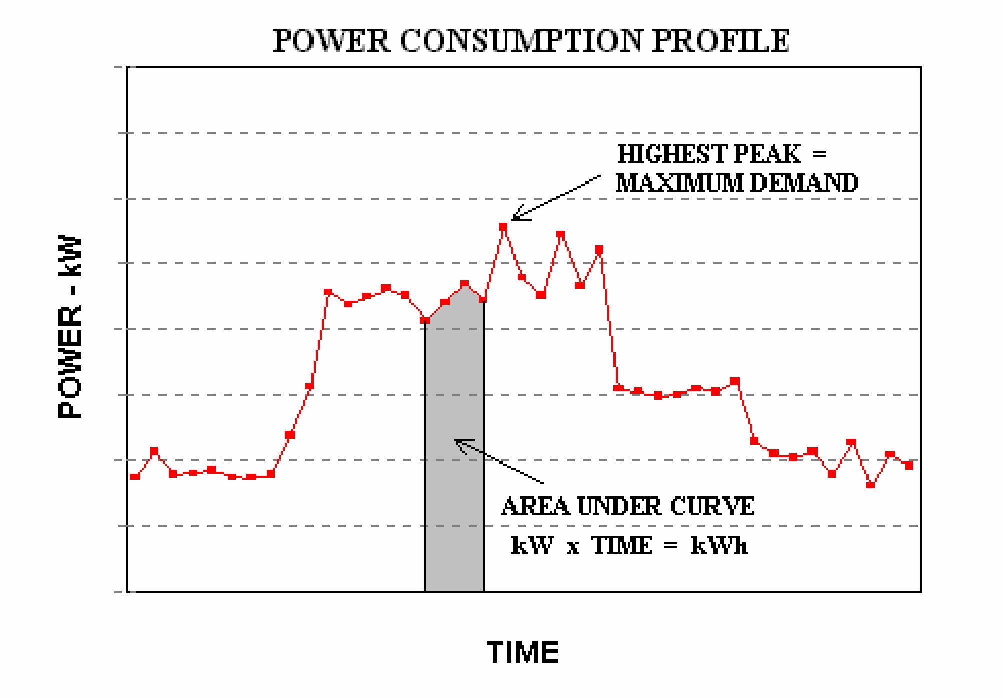
Metering Strategies

Electricity billing is generally based on two quantities - the actual power or energy used by the consumer and a maximum demand to cover the sizing of the generating plant and reticulation required to ensure that the consumer is able to run his plant under maximum operation.

To use a water flow analogy, the power or kWh consumption would be the kilolitres used by the consumer and the demand charge would be the greatest water flow drawn any time during the month. The larger the instantaneous draw required, the larger the piping the supply authority would need to install to ensure that the consumer receives the flow he requires when he requires the water.

Financially, the kWh charge covers the energy used by the consumer. The demand charge relates to the capital cost of the equipment required to generate the consumer's largest energy draw. In terms of running a plant, the demand charge relates to the number of machines which run at any one time, whereas the energy charge relates to how long each machine runs during the month.



In practice, the trend in maximum demand metering is to measure the kVA demand. :

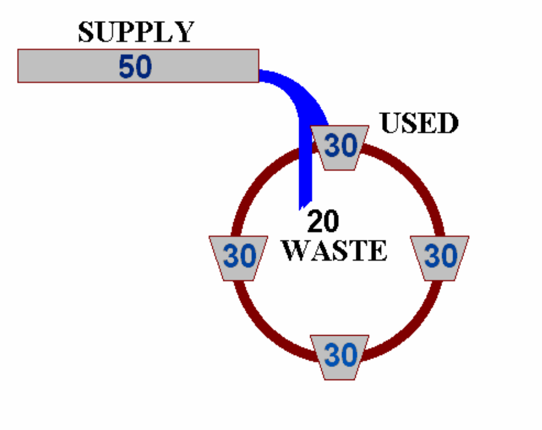
kVA = volts x current

or for a 3-phase system **:**

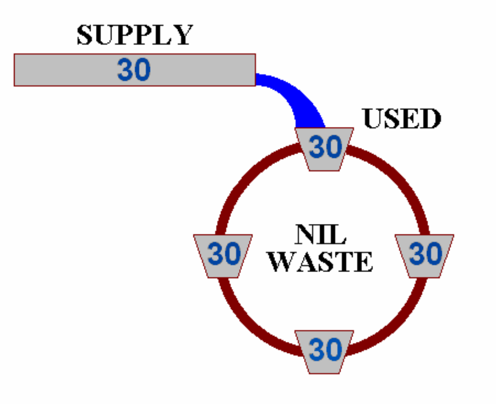
$$kVA = \sqrt{3}\, V\, I$$

Power Factor Correction

Returning to the water analogy - if the water wheel below is not in line with the water flow from the chute, water is wasted and more water is used than is needed to do the work required. Altering the timing of the wheel will result in more efficient usage of the water and less wastage.



POWER FACTOR = 30 / 50 = 0,6

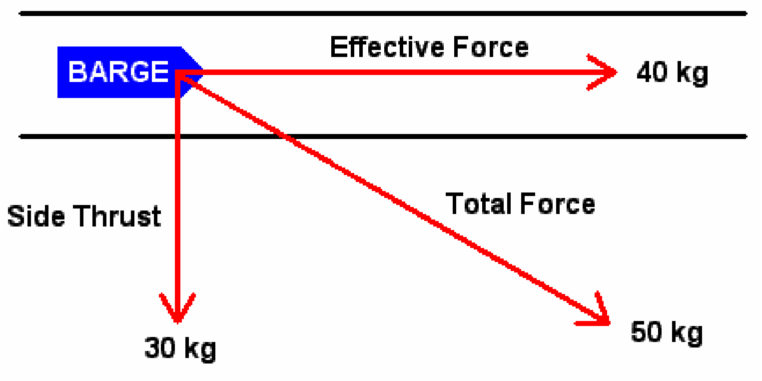


POWER FACTOR = 30 / 30 = 1,0

Improving the efficiency of the system result in lower metered charges - less water is consumed in the more efficient system.

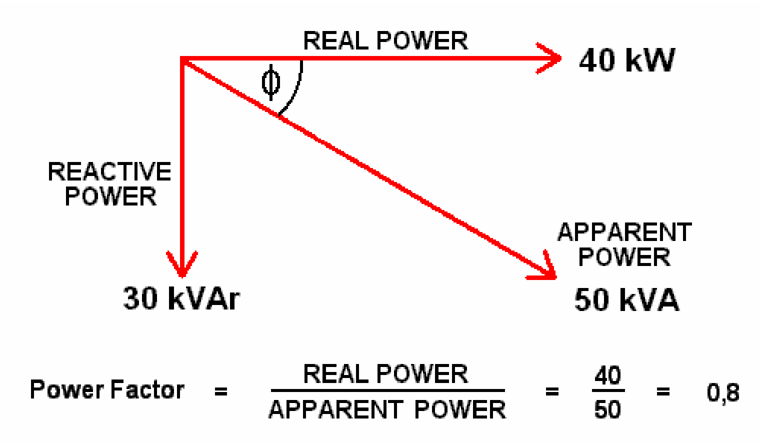
POWER FACTOR = EFFICIENCY

In order assist the concept of power factor electrically, we introduce the following barge analogy. If the barge engine breaks down and a tractor or horse is used to pull the barge, the tractor will need to drive on the bank of the canal. This results in a sidewards pull on the barge which is counteracted by the rudder. The total force needed to pull the barge is thus greater than the effective force required to move the barge forward down the canal.



$$\text{Power Factor} = \frac{\text{Effective Force}}{\text{Total Force}} = \frac{40}{50} = 0{,}8$$

Electrically the effective force is the kW power of the motor or load, the side thrust is the energy used in the magnetic field of the motor (the inductive reactive power) and the total force is equivalent to the kVA or apparent power of the motor.

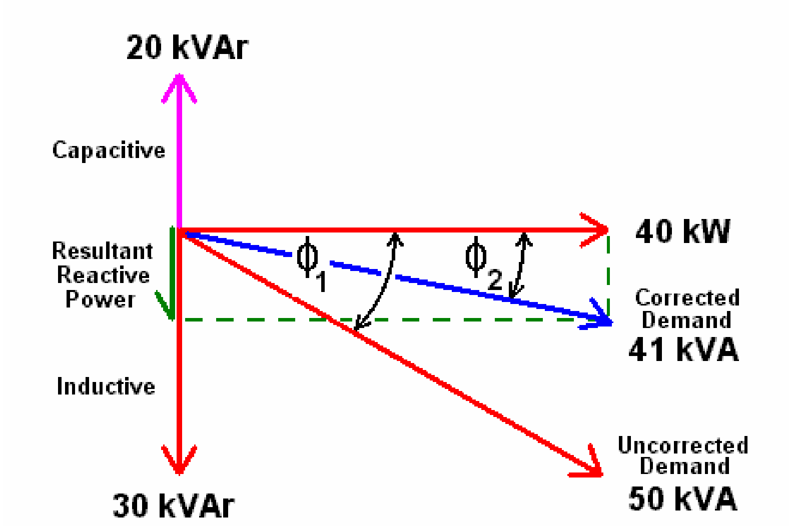


Mathematically, in terms of trigonometry :

$$kW = kVA \times \cos\varphi = \sqrt{3} \,.\, V \,.\, I \,.\, \cos\varphi$$

for a 3 - phase system.

Power factor improvement and the reduction of kVA demand



Adding 20 kVAr capacitive reactance to the above electric motor, we reduce the reactive power to 10 kVAr and the apparent power to 41 kW.

The power factor becomes : **40 kW / 41 kVA = 0,98**

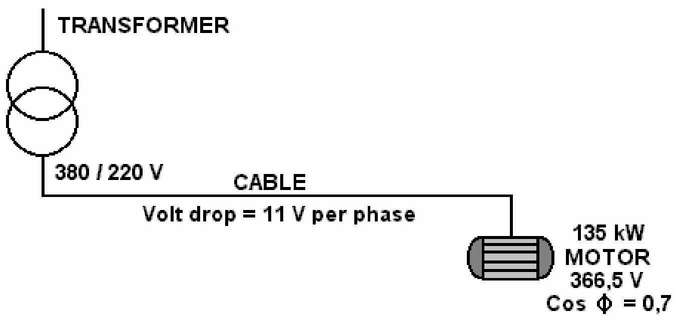
The saving in maximum demand = **50 kVA - 41 kVA = 9 kVA or 18 % of Maximum Demand**

Power factor improvement and reduction in I^2R losses

Mathematically : **kVA = V . I**

From this formula, we can see that a reduction in kVA results in a proportionate reduction in current, at a constant system voltage.

We consider the following system comprising a transformer, a cable and an induction motor :



		No Capacitor	With Capacitor
Power factor	:	0,7	0,95
Volt drop	:	11,00 V	7,98 V
Cable losses	:	10,03 kW	5,27 kW
Current	:	303,9 A	220,3 A
kVA reduction	:	200,0 kVA	145,0 kVA

Before the installation of the power factor correction capacitor, the voltage drop on the cable was measured as 11 volts.

The uncorrected system may be analysed as follows :

Motor current = **kW / (√3 . V . Cos φ)** = **<u>303,9 A</u>**

Cable resistance = **Volt drop / Current = 11 / 303,9 = <u>0,0362 Ω per phase</u>**

Cable Loss = **$i^2R \cdot 3$ = $303{,}9^2 \cdot 0.0362 \cdot 3$ = <u>10.03 kW</u>**
kVA demand = **√3 . V . I = <u>200 kVA</u>**

To solve the corrected system, we use the constant kW load of the motor :

kW = √3 . V . I . cos φ or I is inversely proportional to cos φ

The cable losses are **i^2R** so it can be seen that the losses are inversely proportional to Power Factor^2.

Losses = **10,03 kW . $0{,}7^2 / 0{,}95^2$ = 5,45 kW or 1817 W per phase**
Volt drop = **√ W . R = √ 1817 . 0,0362 = 8,11 V**

This is an initial estimate. Solving the circuit using trigonometry gives a volt drop of 7,96 V and the other parameters are as indicated in the figure above.

Monetary savings due to power factor correction

Assuming the motor in the previous cable loss calculation runs 50 % of the time, the monetary savings on the electricity account would be :

kWh : **4,76 kW * 10 c / kWh * 0,5 hr**

= 23,8 c / hr

= R 171,36 / Month

kVA : **55 kVA * R 35,00 / Month**

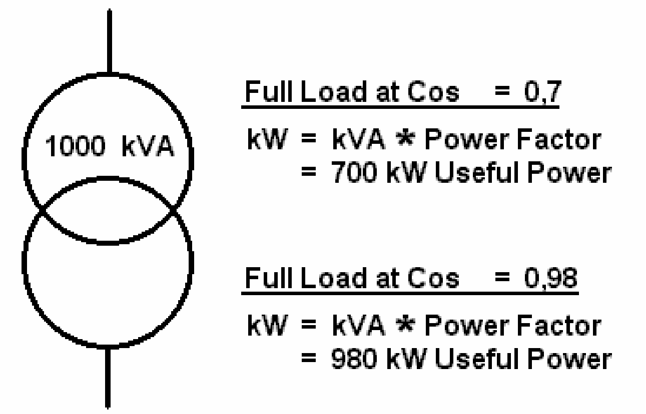
= R 1 935,00 / Month

From these figures it can be seen that by far the greater saving is due to the reduction in kVA demand.

In a similar way, power factor correction capacitors reduce the kW losses in transformers and the supply network due to the reduction in current caused by the application of power factor correction.

Other benefits of power factor correction

Increased utilisation of transformer capacity



Full Load at Cos = 0,7

kW = kVA * Power Factor
= 700 kW Useful Power

Full Load at Cos = 0,98

kW = kVA * Power Factor
= 980 kW Useful Power

Although power factor correction allows for increased utilisation of transformer capacity, it should be noted that the removing the power factor correction panel from service may result in tripping of the supply circuit breaker.

Improved voltage regulation of the supply transformer

Due to the transformer internal impedance, improving the power factor results in reduced voltage drop across the transformer windings, thereby improving the voltage regulation of the transformer.

Benefits of power factor correction

As discussed in the previous sections, implementation of power factor correction :

- Reduces Maximum Demand charges
- Reduces kW losses in cables and transformers
- Increases transformer capacity
- Improves transformer voltage regulation

POWER FACTOR CORRECTION SAVES MONEY ON ELECTRICITY CHARGES

Causes of poor power factor

Equipment which generally causes a bad power factor is :

- Induction motors
- Power transformers and voltage regulators
- Welding Machines
- Induction Furnaces
- Reactor / Choke coils and magnet systems
- Rectifiers
- Flourescent and Discharge lighting

Generally, the magnetising currents of electrical equipment as in motor field windings, transformers chokes and magnets do not form part of the useful power of the equipment. It is this inductive reactive power which is compensated for by the application of power factor correction capacitors.

Application of power factor correction

Power factor correction may be applied in a number of different ways, each suited to specific applications :

1) **Fixed Capacitor Banks**

   Where a small amount of power factor correction is required :

   - Limited to 10 % of the transformer rating. The transformer no-load reactance is typically in the region of 5 % of the transformer kVA rating.
   - Can be cost effective as only the protective circuit breaker is used to switch the capacitor bank..
   - Voltage rise at reduced transformer loading should be considered in the selection of the capacitors.
   - The presence of Harmonics may require special consideration.

2) Individual Motor Correction

Application of the power factor correction at the motor starter.

Advantages :

- Maximum reduction of kW losses in cables and switchgear.
- Reduction of voltage drop in cables.
- Improved voltage and starting torque.
- No control gear required.

Disadvantages :

- The higher cost per kVAr for smaller capacitors.
- High labour installation costs.
- Often installed and forgotten.
- Limited to a target power factor of Cos $\varphi = 0{,}95$.
- Does not allow for diversity of the load. Both primary and secondary or standby motors need to be corrected.

Care must be taken to install the power factor correction capacitors on the load side of the line contactor in Direct-on-line and Star-Delta starters. Incorrect installation in series with the motor windings can result in a situation of partial resonance at the fundamental frequency which could lead to high voltages causing motor and / or capacitor failure.

Over correction of motors can result in over-exitation of the motor windings on disconnection from the supply. Again this may lead to high voltage and the subsequent failure of equipment.

3) Automatic Power Factor Correction Panels

Automatic power factor correction panels involve several capacitor banks which are individually switched with load variation. The target power factor is maintained over a wide range of load conditions.

- Can be cost effective against fixed banks or individual motor correction for divers loads or a large number of small motors.
- The panels are easily monitored and maintained.
- The newer computerised reactive power controllers incorporate alarms, temperature and harmonic sensing.

4) Medium and high voltage power factor correction

Correction at medium and high voltages becomes cost effective for large capacitor banks, typically larger than 1 MVAr.

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Power factor correction components : Factors influencing the life expectancy

The following general information will provide information concerning the factors which lead to deterioration of power factor correction panels and the associated equipment.

Capacitors

Low voltage three phase capacitors are usually internally delta connected. The larger capacitor units comprise several capacitor cells making up the total rated kVAr. The latest trend is to internally fuse each capacitor element and some manufacturers include an internal over-pressure disconnect device to prevent fire or explosion in the event of element failure.

Capacitors are static, with no moving parts. They will operate for many years without trouble provided the operating conditions fall within the design specifications of the capacitors regarding Temperature, Voltage and Current.

Capacitors comprise two parallel metallic films separated by an insulating dielectric. Early power factor correction capacitors comprised an aluminium film separated by an oil impregnated paper. High voltage capacitors are still manufactured in this way today. The capacitance of a capacitor is inversely proportional to the square of the distance between the plates. In the interests of cost and being able to fit a larger amount of capacitance in a smaller space, the modern trend is towards metallised film capacitors. In these capacitors, a zinc film is vacuum deposited on a polypropylene film.

With the thickness of the polypropylene film being of the order of 6 - 8 microns thick, metallised film capacitors are extremely sensitive to voltage fluctuations. This is discussed further below.

TEMPERATURE

Most metallised film capacitors dissipate approximately 0,5 Watts / kVAr of heat. This causes the capacitor units to become quite warm over a period of time. Inoperative units can therefore be quite easily detected as they are cold to the touch. Further checks should be carried out as detailed under the Annual / Biannual Service paragraph.

Capacitors subject to the IEC-831 specification are rated according to temperature class categories. A class D capacitor is subject to a maximum ambient temperature of 55 EC. The maximum allowable average over 24 hours is 45 EC and the maximum allowable average over one year is 35 EC. In South Africa within enclosed switchboards, it is quite easy to exceed these specifications.

Exceeding the rated temperature of a capacitor element can drastically reduce its life expectancy. A 7 EC temperature rise can reduce the capacitor life expectancy to 30 %. Cooling of the capacitor elements is essential if the rated temperature of the elements is exceeded.

CURRENT

Capacitors are subject to excess currents due to over-voltages and power system harmonics. The IEC-831 specification allows 30 % over-current through the capacitor elements.

Excess capacitors current leads to higher losses and localised over-heating of the capacitor elements. It is therefore possible for an element to fail at less than the rated over-current due to excessive heating.

VOLTAGE

Due to the thinness of the dielectric film in metallised film capacitors, the capacitors are extremely sensitive to voltage variations. Capacitors are susceptible to failure due to surges, overvoltages and spikes.

The IEC-831 specification allows 10 % over-voltage for a maximum of 8 hours out of 24. With increasing over-voltage, the allowable duration reduces to 30 % over-voltage for a maximum of 1 minute in 24 hours.

With power system harmonics, although the rms voltage may be within the specification, the peak voltage across the capacitors may equal the sum of the peak voltage of the fundamental and the voltage harmonics. This may lead to excessive overloading of the capacitor.

Switched capacitors are further subject to a switching over-voltage. Excessive switching of the capacitors will also lead to reduced life expectancy.

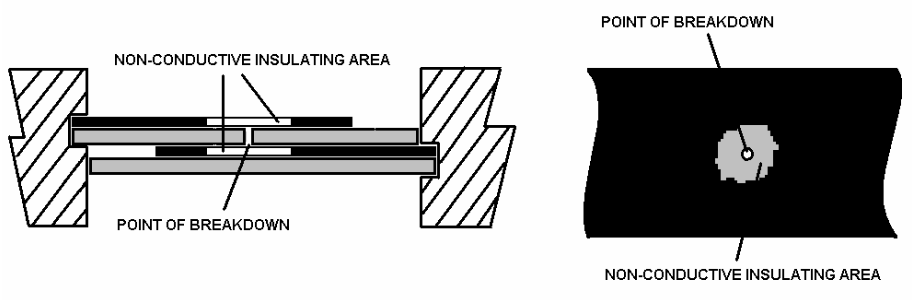
NOTE

Although the IEC-831 specification allows for voltage, temperature and current overloading of capacitor elements, the elements are not expected to be subject to maximum overload conditions in all three areas.

DISCHARGING THE CAPACITORS

Capacitors are fitted with fixed discharge resistors which are designed to reduce the voltage to 50 V within a period of 1 minute. Switching the capacitors before they have fully discharged may lead to excessively high voltages across the contactors and increased switching transients.

SELF HEALING CAPACITORS



A further property of zinc impregnated film capacitors is that they are essentially “self healing”. Should breakdown of the dielectric occur, the increased fault current through the capacitor dielectric vaporises the zinc and clears the internal fault.

Each “self healing” incident generates a small amount of hydrocarbon gas which remains in the capacitor element. Should enough small “self healing” incidents or a fault which is unable to clear occur, the capacitor element may explode and / or catch fire.

In order to prevent explosions and / or fire some manufacturers include an over-pressure disconnect device in the capacitor elements. Should the internal pressure in the element exceed the threshold of the device, the element is removed from service.

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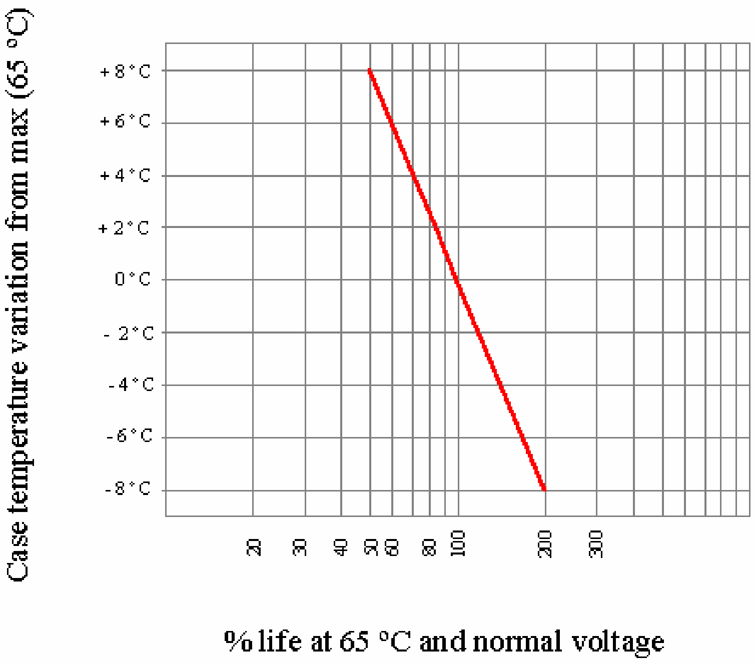
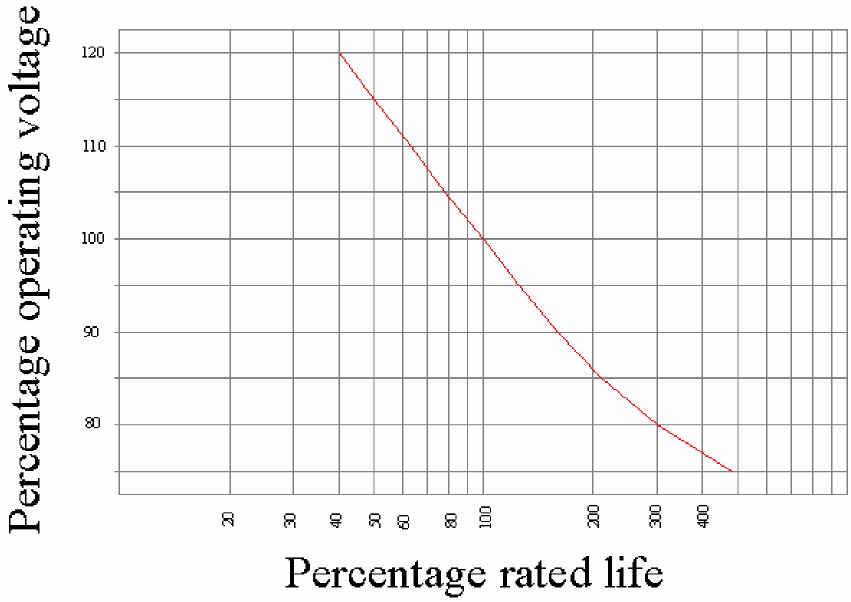


Maximum recommended case temperature

From the above figure it can be seen that an 8 degree centigrade temperature rise can half the life expectancy of the capacitors. Temperature is one of the most detrimental influences on capacitor life expectancy.



Maximum recommended operating voltage

A 15 % permanent overvoltage can reduce life expectancy of the capacitors to half.

Contactors

Contactors for power factor correction duty are generally subject to different selection criteria from other applications. Contactor manufacturers will have a capacitor rating for the contactor or may have special capacitor switching contactors. Some units incorporate methods for limiting capacitor inrush current.

On closing a contactor, a capacitor essential presents a short-circuit to the supply until the capacitor becomes charged. Contactors are thus subject to high transient inrush currents. Frequent switching can lead to deterioration and failure of the contactors.

Dusty environments will cause the contactors to become noisy. The iron circuit pole faces of the contactor need to be kept clean for quiet operation. Contactor coils have a range of voltage operation - generally - 15 % to + 10 %. The contactor draws a closing current which reduces once the iron circuit of the contactor closes. Should low voltage or a mechanical reason prevent the iron circuit from closing, the higher closing current will lead to failure of the contactor coil.

Reactive Power Relays

The reactive power controllers are electronic apparatus requiring absolutely no site maintenance. After commissioning of the power factor correction panel, the settings on the relay should not require any further adjustment.

Reactive power relays are used to switch automatic power factor correction panels. All relays incorporate a switching delay to allow the capacitors to discharge before re-energising the contactors.

All reactive power relays measure the reactive power of the supply. The settings on the controller allow the unit to compare the reactive power of the capacitors banks with that of the system and make a switching decision.

The reactive power controller is the brains behind the power factor correction equipment. Should a reactive power relay not operate for a period of 30 minutes, the entire monthly saving due to the power factor correction panel may be lost. Generally the cost of a new controller is less than the lost monthly saving.

The reactive power controller is probably the single most important item in the power factor correction panel. Should the unit fail, we would recommend further testing and possible replacement.

HRC Fuses & Bases

HRC fuses are installed for the purpose of short-circuit protection of the capacitors and contactors. Since failure of the HRC fuse is usually due to capacitor overload or failure - the fuses are there to protect the contactor.

The rating of the fuses is generally between 1,6 to 1,8 times the capacitor current rating. The size of the fuse should not exceed the contactor manufacturers recommended maximum rating to prevent permanent damage to the contactor.

HRC FUSES MUST NEVER BE REPLACED OR EXTRACTED LIVE !!

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HAND-OFF-AUTO Selector Switches

These switches are installed to give control of the equipment in the event of a reactive power controller failure.

Care should be taken when installing these switches, since :

i) The hand switching overrides the built-in safety delay in the controller. The capacitors may be manually re-energised before they have completely discharged.

ii) Unless the capacitors are manually energised immediately (before 15 - 30 minutes), the saving due to the power factor correction will have been lost for the current billing month.

iii) Leaving large banks of capacitors energised at low loads can lead to excessive voltage rise on the main busbars. This is generally why an automatic panel was required in the first place.

Should Hand-Off-Auto switches be installed on your system, pause a minimum of 10 seconds before re-closing the switch. A longer delay may be necessary depending on the contactors and discharge device fitted to the system. As a reference, a reactive power controller usually has a delay of approximately 50 seconds before re-energising the same contactor.

Main Supply circuit breaker / isolator

A main supply circuit breaker should be installed to supply the power factor correction equipment. A circuit breaker is required to protect the cable feeding the power factor correction panel, or where the cross-sectional area of the power factor correction panel busbars is less than that of the main switchboard busbars. A circuit breaker prevents tripping the entire installation should a busbar fault or short circuit occur in the power factor correction panel.

An isolator should be installed in addition to a circuit breaker in the event of the power factor correction panel being out of sight of the main supply circuit breaker. Should the main supply circuit breaker be fitted with a padlockable isolation device, the isolator in the power factor correction panel may not be required.

A circuit breaker and / or isolator should not be used to switch off a power factor correction panel with all the capacitors energised. The power factor correction capacitors will disconnect momentarily after the main circuit has been interrupted. The subsequent voltage surge can lead to restrike through the isolator / circuit breaker. Furthermore, the surge can lead to either blowing of the control circuit fuses or the reactive power controller (or both).

It is generally good practise to manually step out the capacitor banks before operating a circuit interrupting device.

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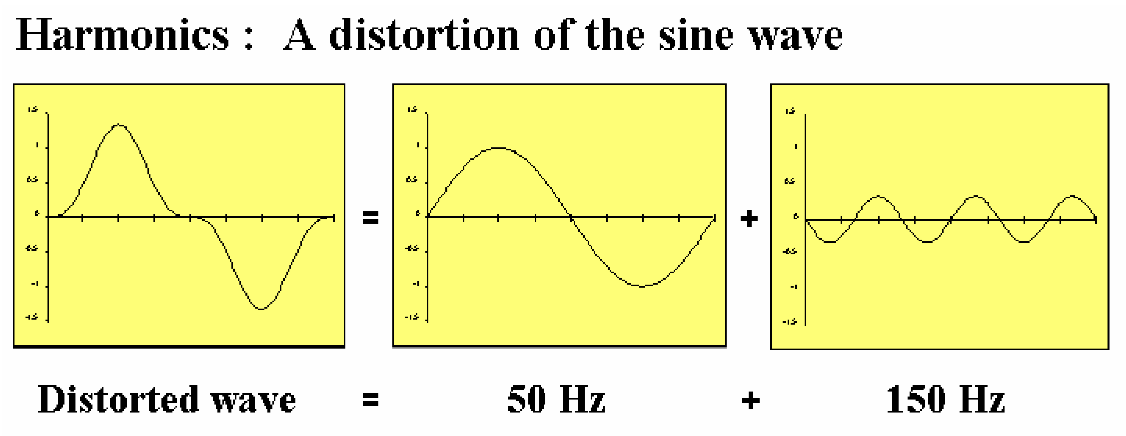
Power system harmonics

Blown capacitor fuses and capacitor banks are generally one of the first signs of power system harmonics.

Current harmonics generally lead to elevated current levels in the system. Higher currents may cause excessive heating of equipment which can lead to early ageing and failure of electrical equipment.

Voltage harmonics, particularly in the presence of power factor correction capacitors, lead to an increase in the peak voltage of the voltage waveform. This can cause to voltage overstressing of insulation and capacitor dielectrics, leading to premature ageing and breakdown.



Harmonic Generators

The following are some equipment which generate harmonics :

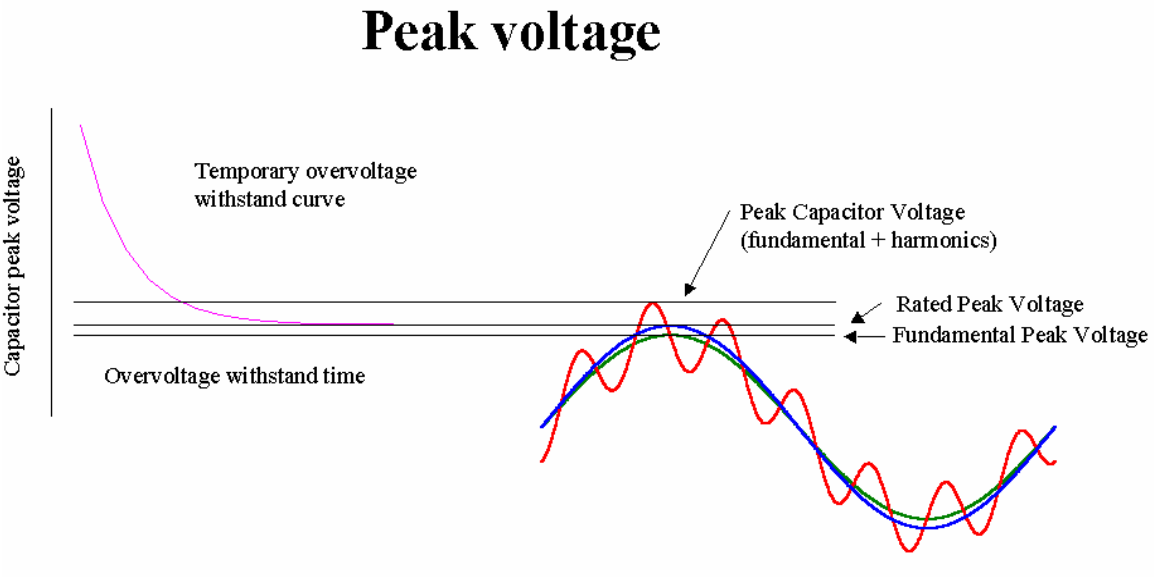
- Variable speed drives
- Thyristor controlled equipment
- Static converters (UPS systems)
- Arc furnaces
- Welding machines
- Flourescent and discharge lighting
- Saturated reactors

Harmonic effects on capacitors

As mentioned earlier blown capacitor banks and fuses are often the first sign of abnormally high harmonic levels. The capacitive impedance is inversely proportional to frequency. High order harmonic voltages can lead to high levels of harmonic current in capacitor systems.

Effects of harmonics on capacitors are :

- Abnormally high current levels
- Increase in the peak voltage of the voltage waveform - breakdown of capacitor dielectric
- Increased operating temperature of capacitors



As shown in the above figure, the harmonic voltages are additive to the peak voltage of the voltage waveform. An rms measurement of the voltage may show very little voltage rise, whereas excessive peak voltage may lead to capacitor dielectric breakdown.

Recommended harmonic limits

The recommended limit for voltage THD in South Africa is 8 %. The internationally accepted limit for low voltage systems is 5 %. This limit of 5 % is the acceptable limit for computer and data processing power supplies. Microprocessor and computerised equipment (including PLC=s) may experience problems if the total harmonic distortion exceeds this level.

Power factor correction capacitors are extremely susceptible to power system harmonics. Blown capacitor banks and fuses are often the first signs of high harmonic levels in industry.

The capacitor manufacturers have recommended that standard voltage power factor correction capacitors be used at voltage THD of up to 2 %. Between 2 and 5 % voltage THD, capacitors of a higher voltage rating may be used. Above 5 % voltage THD, harmonic filters are required.

Harmonic solutions

Practical methods of counteracting the effects of harmonics are :

- Over rating the capacitor voltage to allow for the peak voltage rise at moderate harmonic levels.
- Countering the effects of resonance with detuning reactors.
- Reducing the power system harmonics on the network by installing passive harmonic filters.
- Protection of the power factor correction capacitors with harmonic protection relays and alarms.

Conclusion

Capacitors are often misunderstood in their application and are often blamed for power quality problems. As discussed in this paper, failure of power factor correction systems is often the symptom of power quality problems and not the cause.

The presence of increasing levels of power system harmonics due to the trend to the greater control provided by solid state equipment such as converters, variable speed drives and soft starters has lead to the need for increased care in the installation of power factor correction equipment so as to prevent early failure of the equipment.

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