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. The paper further discusses the influence of power factor correction equipment on power quality in order to avoid the negative impact on the equipment.

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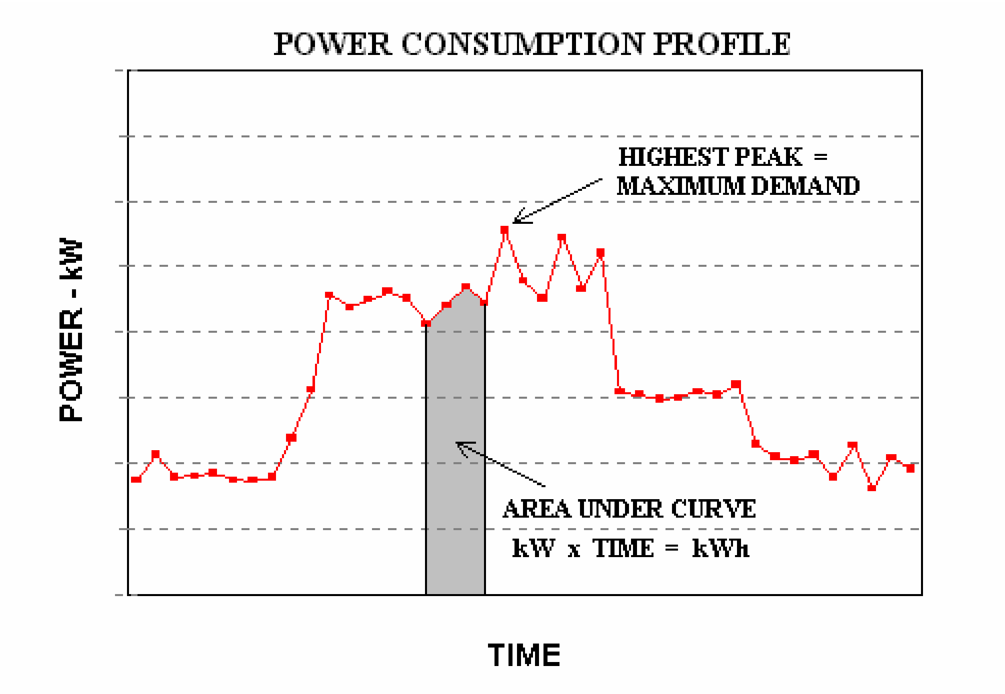
Metering Strategies

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. :

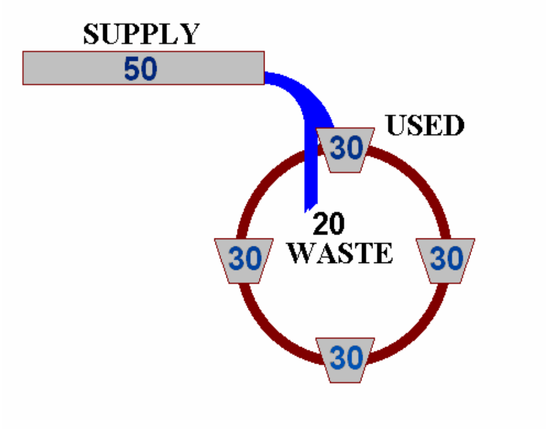
kVA = volts x current

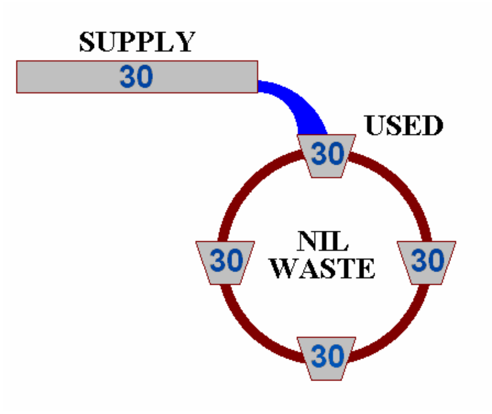
or for a 3-phase system **:**

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

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.





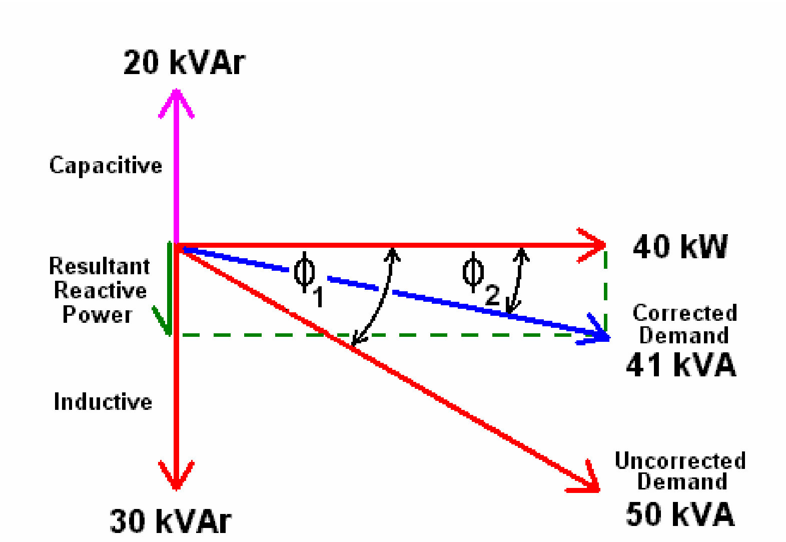
POWER FACTOR = 30 / 50 = 0,6 **POWER FACTOR = 30 / 30 = 1,0**

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

POWER FACTOR = EFFICIENCY

Power factor improvement and the reduction of kVA demand

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.



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**

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.

Benefits of power factor correction

Implementation of power factor correction benefits the consumer in the following ways :

- Reduces Maximum Demand charges
- Reduces kW losses in cables and transformers – less voltage drop in long cable runs
- In certain applications may result in kWh savings due to decreased kW losses
- Increases transformer capacity – greater utilisation of existing transformer capacity and electrical switchgear
- Improves transformer voltage regulation
- Improvement of motor starting torque as a result of improved voltage at motor terminals
- Shunt capacitors do not increase system fault level
- Reduction in required generating capacity results in reduced utilisation of expendable resources to generate power and hence lower the negative impact on the environment.
- Consideration in ISO requirements for eco-friendly operation of plants and factory environs

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.

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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. The reduced cost per kVAr of MV and HV capacitor banks is offset against the increased costs of the switchgear.

POWER FACTOR CORRECTION AND POWER QUALITY

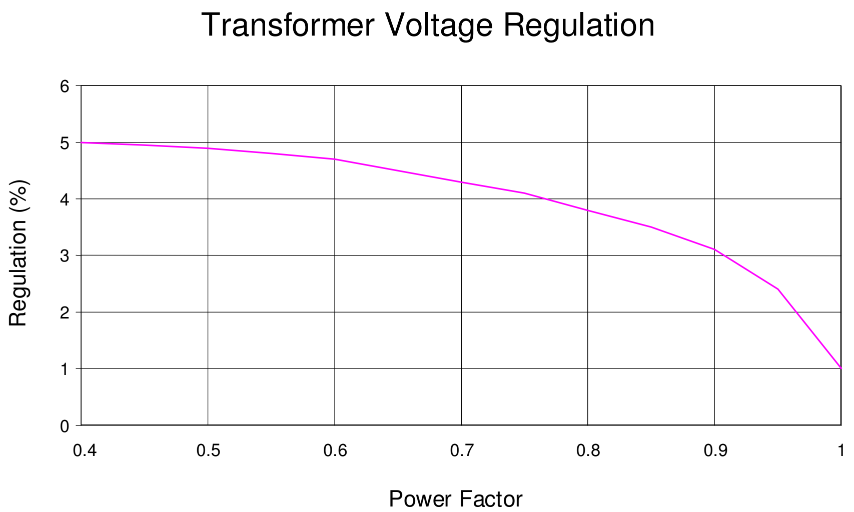
The addition of power factor correction capacitors to predominantly inductive networks leads to the formation of complex RLC systems. Series and Parallel resonance points need to be considered in the application of large capacitor banks. Transients caused by switching and discharging capacitors banks need to be considered in order to limit their adverse effects on equipment connected to the supply networks. Correct application of capacitors can assist in reducing voltage flicker and improve voltage regulation in power systems.

1) Voltage Regulation

Power factor correction effects voltage regulation in the following areas:

Power Transformers

Voltage regulation of power transformers improves as the power factor of the load approaches unity. Permanently connecting capacitor banks across the transformer secondary terminals produces a rise in both full-load and no-load voltage, but does not alter voltage regulation. Improved regulation can only be achieved by automatically switching in capacitor banks as the load increases.



Voltage Rise

Capacitors connected across transformer terminals causes a voltage rise at low loads. Should the short circuit capacity, in kVA be greater than 100 times the transformer rating, the following simplified expression may be used to determine the voltage rise :

$$\text{Percentage voltage rise} = \frac{Q}{P} \times \text{Percentage } X_T$$

Where

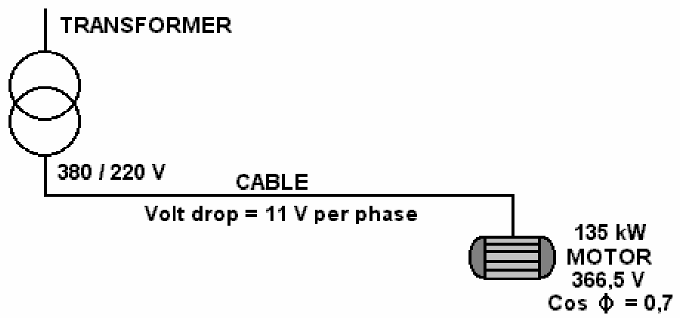
Q	=	capacitor rating in kVAr
P	=	transformer power in kVA
Percentage X_T	=	percentage transformer reactance

Using this formula, 600 kVAr of capacitors on a 1000 kVA transformer with 5 % reactance would result in a 3 % voltage rise.

This would generally be considerably less than the voltage rise on the system due to reduced loading of the network during off-peak periods.

Voltage drop in Cables

By installing individual motor correction at the motor terminals of motors at the end of long cable runs, the current in the cable is reduced, which results in reduced kW losses and voltage drop over the length of the cable.



		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

The reduction in voltage drop is directly proportional to the improvement in power factor.

Over-compensation of Motors and Alternators

When a power factor correction capacitor is directly connected across the motor terminals, it is possible for the motor windings to form a closed loop. Should the connected capacitor exceed the no-load kVAr rating of the motor, it possible for self-excitation of the motor to occur. In these circumstances, the voltage across the terminals could rise to sufficiently high enough levels to cause damage to control gear and /or the motor insulation.

Should the motor be re-energised during this period of self-excitation, there is a risk of a violent electrical transient occurring and producing mechanical shock. This has been known to fracture shaft couplings, gear boxes or cause distortion of cores or motor windings.

With correct application, the voltage at the motor terminals will decay on disconnection due to sub-synchronous speed.

Power factor correction is not usually applied to industrial alternators, since they are generally rated at an operating power factor of 0,8. Correcting closer to unity will not attain further capacity from the prime mover.

Industrial alternators are particularly sensitive to leading power factors. Operating an alternator on a purely capacitive load can lead to practical voltage increases of up to 33,3 %.

Application of Power Capacitors to High-Voltage Transmission Lines

Shunt Capacitors

The addition of shunt capacitors on electric supply systems provides the following advantages:

- They reduce the transmission of inductive kVAr from the load to the generating source
- Reduce overloading of circuits and/or release load carrying capacity
- Release spare generating capacity on the generators
- Reduce system i^2R losses
- Improve voltage regulation

The load end of the transmission lines should not become too leading at low load as this can lead to excessively high voltage levels on the receiving end. The resulting over-saturation of the magnetic cores of the transformers may lead to elevated harmonic levels in the system.

Series Capacitors

In applications where only improvement in voltage regulation is required, series capacitors are instlled to reduce the reactive power losses in the transmission lines. As the reactive power component is automatically cancelled by the voltage appearing across the capacitor, series capacitors are essentially self-regulating. NO improvement of the load power factor is obtained.

Series capacitors are used in the following applications:

- Improvement of voltage regulation
- Reduction of rapid voltage fluctuations (voltage flicker)
- Resistance welders
- Control of load sharing between parallel feeders

The application of series capacitors is not as predictable as shunt capacitors and requires careful study in their installation.

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Voltage Flicker

Series capacitor circuit

In fluorescent lighting installations, the installation of the capacitor at the end of the line in the circuit assists starting and suppresses interference. The capacitor impedance is twice that of the ballast or choke. This results in a leading power factor at the incoming terminal of the circuit. In twin-tube circuits, only one lamp is fitted with a series capacitor giving an average power factor of the circuit of unity. The phase shift caused by the capacitor further assists in reducing the visible flicker in the fitting, as the voltages across the two lamps are out of phase.

2) Voltage Transients

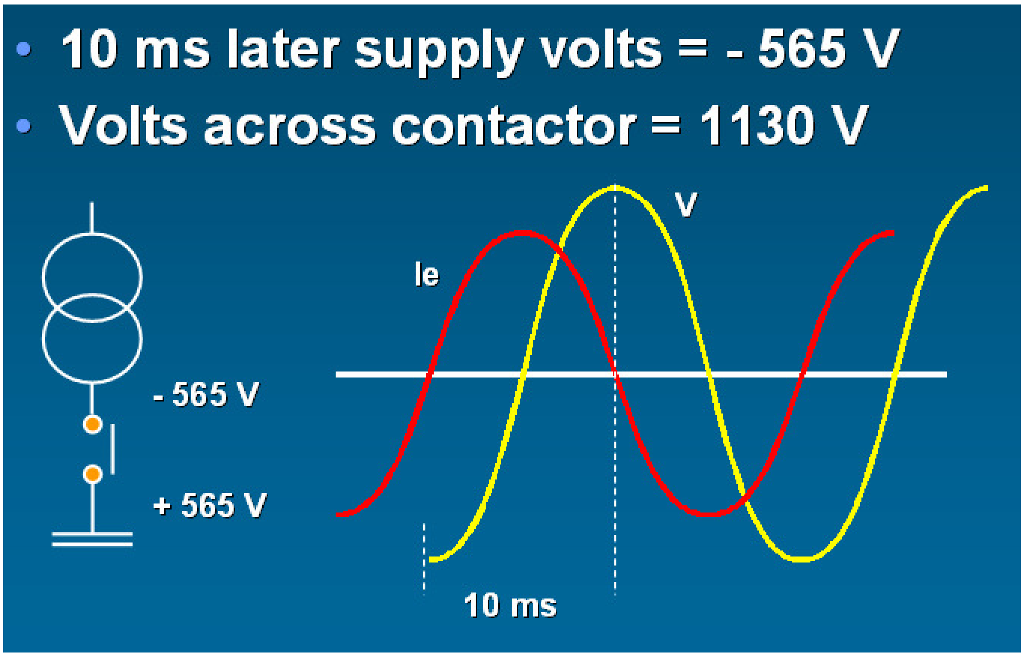
Capacitor Energising Transients

On energising power factor correction capacitors, a high transient current flows for a short period. In the case of a single capacitor bank, the inrush rarely exceed s20 times the nominal r.m.s. current of the capacitor at a frequency which may approach 1 kHz.

On switching parallel capacitor banks, the capacitors which are already energised discharge into the incoming capacitor bank, which presents a virtual short circuit to the energised banks. Inrush currents of up to 200 times greater that the nominal values at frequencies of up to 20 kHz can occur.

In order to limit inrush currents, the impedance between the capacitor banks need to be increased. In LV systems, a few turns of an air-cored coil may be used. In MV and HV systems, inrush limiting reactors are used. A further feature for limiting inrush in LV capacitor banks is to install capacitor contactors fitted with inrush limiting resistors. These resistors are connected in series with the capacitors through early-make contacts. This allows the capacitor banks to charge partially before the main contacts close – thereby assisting in limiting the inrush current.

Re-striking of Switchgear



When a capacitor is disconnected from the supply, the circuit is interrupted at current zero. At this point, the residual voltage across the capacitor is at maximum of the system value and decays slowly. 10 milliseconds later, the voltage on the supply has reversed, placing double the peak voltage across the opening contacts.

Should the contacts not have separated sufficiently, re-strike of the arc could occur. Resulting high voltages and subsequent re-strikes can lead to damage and failure of the equipment.

Capacitor Filtering and Surge Protection

The impedance of a capacitor banks is inversely proportional to the frequency. This means that capacitors supply a low impedance path to high frequency transients and harmonics. Capacitors connected to the power network do provide a filtering effect which "smooths" the voltage waveform. Care needs to be exercised to ensure that inductances in the circuit do not lead to resonance with power factor correction capacitors.

Shunt capacitors provide one form of surge protection and will modify the shape of a surge wave by reducing the steepness of the wave front. Capacitors do not limit the amplitude of the surge appreciably and combinations of capacitors and other components have been adopted in surge arrestor systems.

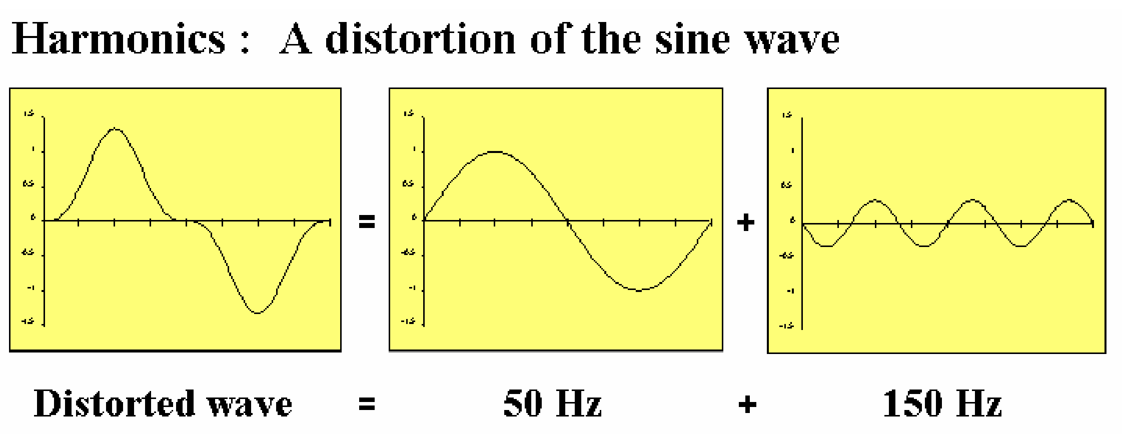
The design of surge arrestor systems is a specialist field beyond the scope of this paper.

3) 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 :

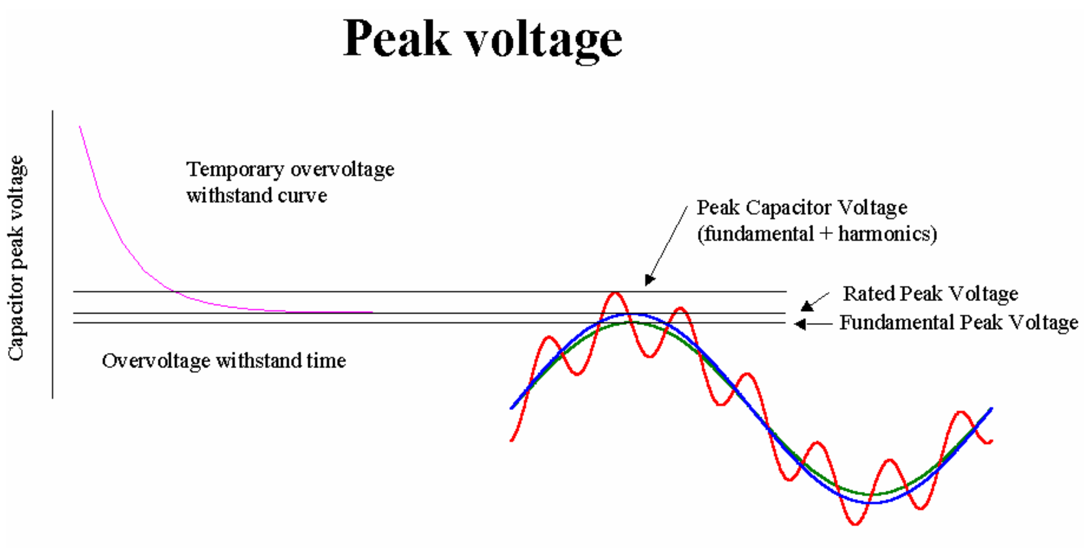
- Variable speed drives
- Thyristor controlled equipment
- Static converters (UPS systems)
- Arc furnaces
- Welding machines
- Flourescent and discharge lighting
- Saturated reactors

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



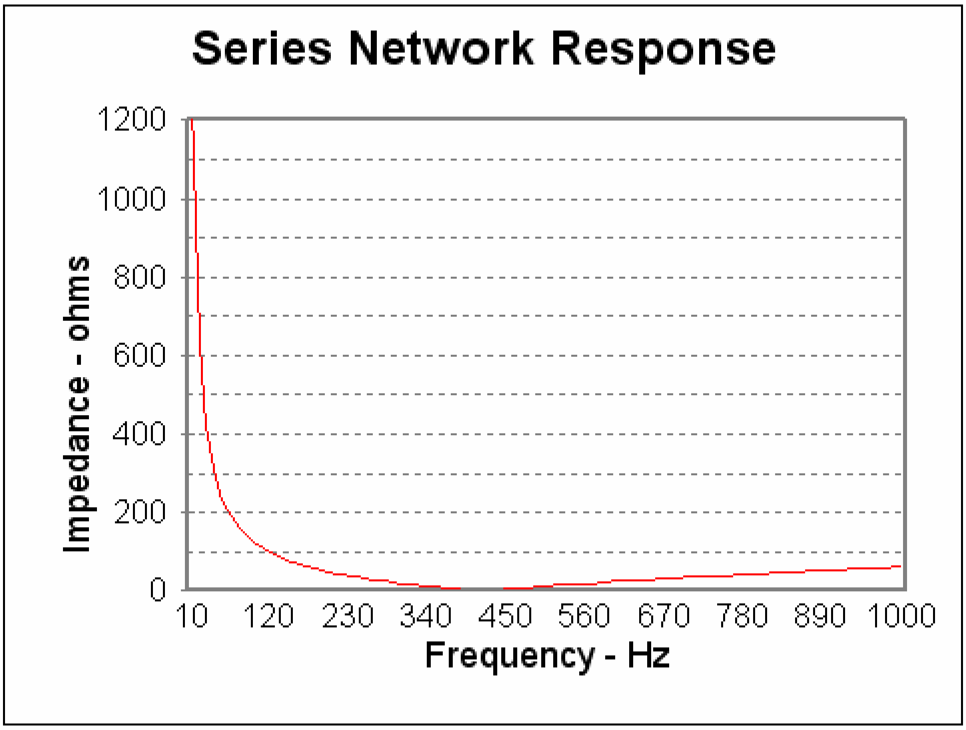
As shown in the above figure, the harmonic voltages are additive to the peak voltage of the voltage waveform. An rms measurement of the voltage may show very little voltage rise, whereas excessive peak voltage may lead to capacitor dielectric breakdown.

Series Resonance

The installation of large capacitor banks on the LV switchboard busbars form a tuned circuit with the supply transformer. Partial resonance with any one of the power system harmonics prevalent on the MV network can lead to elevated levels of harmonic pollution in the network.

The existence of large capacitor banks on the LV side of transformers lowers the impedance of the consumer as seen from the supply network. This can lead to elevated levels of harmonic current flowing into the consumer's load. These harmonic currents will manifest themselves as harmonic voltages on the LV busbars.

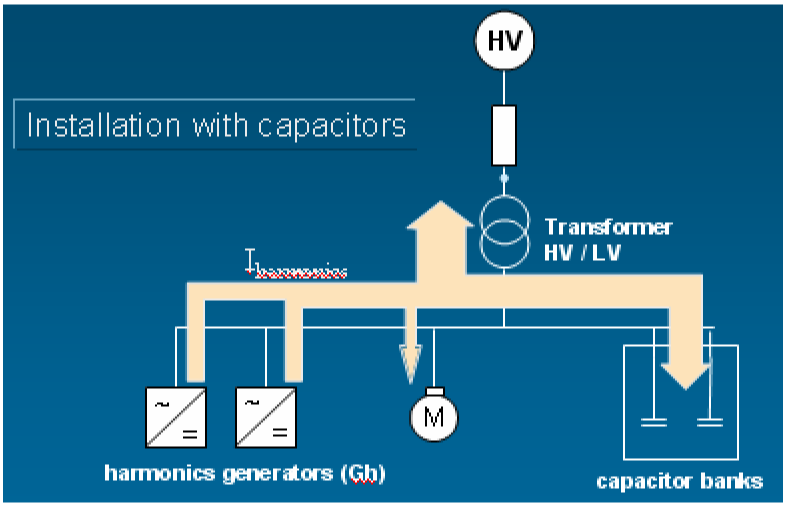
In practice, installing a capacitor bank of 50 % of the transformer kVA rating has lead to a raising of the harmonic levels by approximately 1 %. Generally the predominant amplification of harmonics occurs in the region of the fifth harmonic.



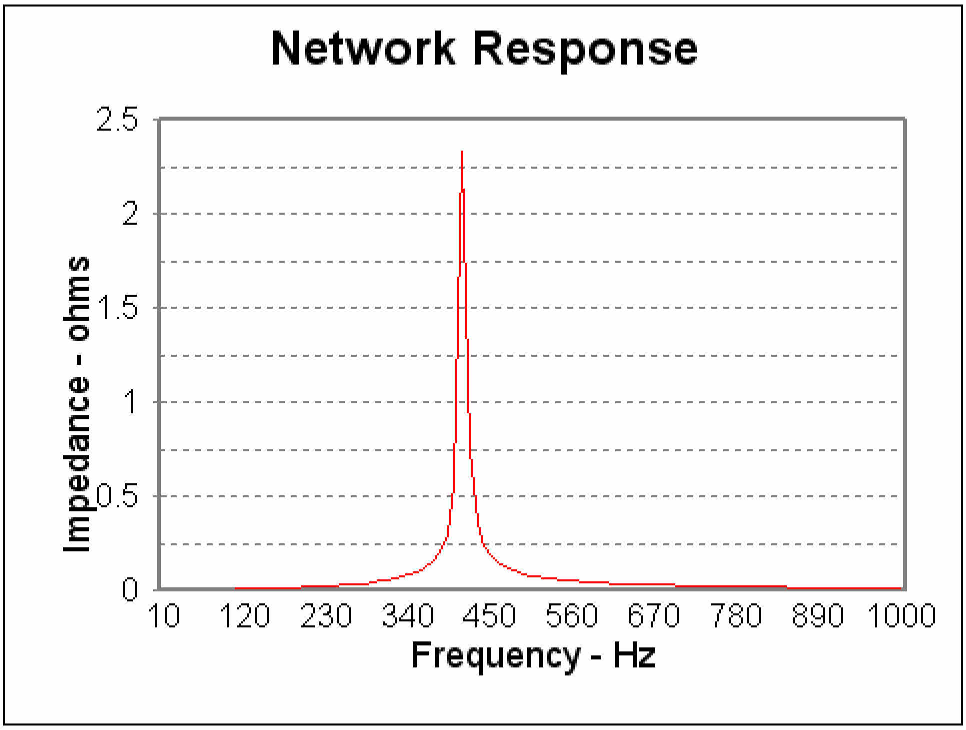
From the above figure, the lowering of the network impedance as seen from the MV busbars will result in amplification of 5 th and 7 th harmonic currents in the LV network.

Parallel Resonance

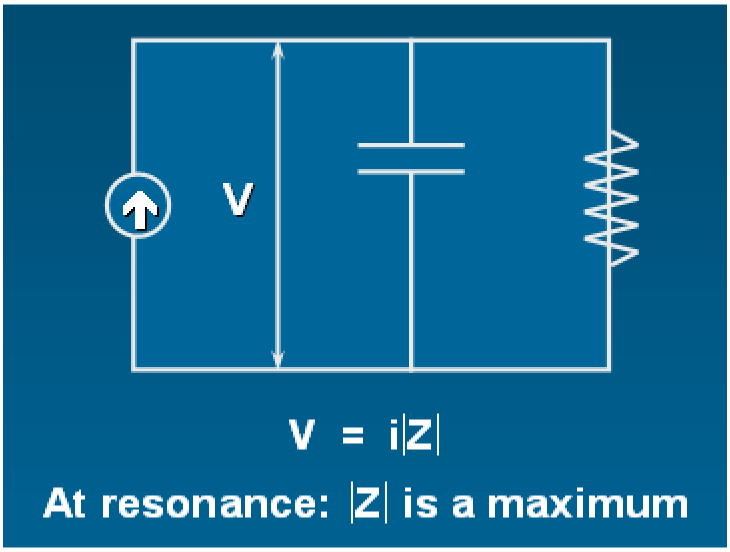
The addition of power factor correction capacitors to the LV terminals of a transformer which has harmonic generating load also results in the formation of a parallel RLC network.



The parallel network impedance is shown in the graph below:



At the resonant frequency, V = I x |Z| ie The Harmonic Voltage is a maximum at the resonant frequency

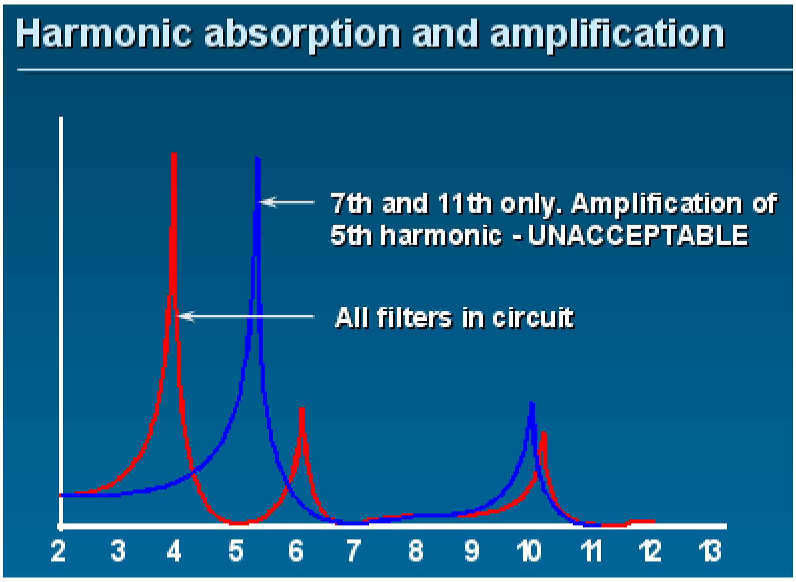


Since the capacitor current is given by :

$i = 2 \pi f C V$ It can be seen that the capacitor current will be high at the resonant frequency.

This harmonic current can be up to 20 times greater than the harmonic currents originally present in the LV power network. The amplified harmonic current circulates between the capacitors and the transformer windings.

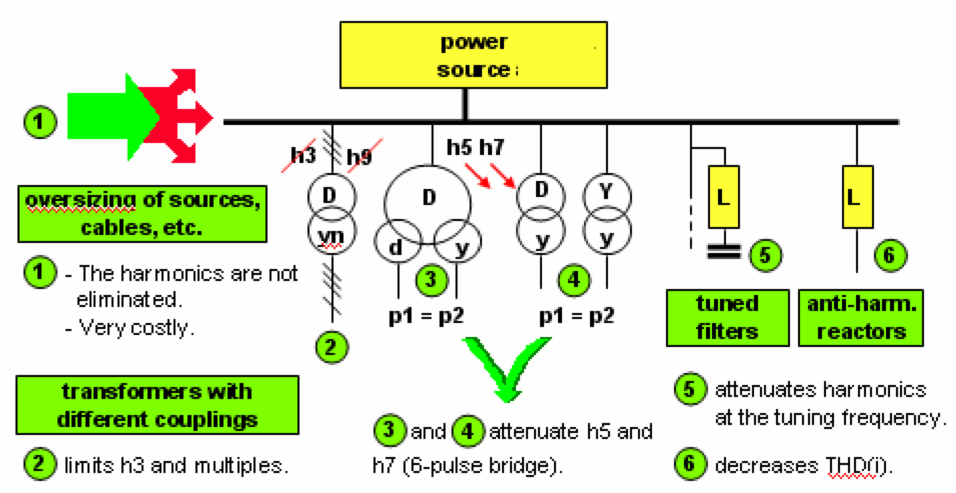
With the application on passive harmonic filters and plain capacitors, further resonant points are created in the network which can lead to unwanted amplification of existing power system harmonics. Care should be taken in switching tuned shunt filters to ensure that the filter banks are switched in the correct sequence to alleviate harmonic amplification through resonance.



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 or anti-harmonic 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.
- Installation of active harmonic filters.



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 and amplification of power quality problems.

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