Power Factor Correction
The Basics

Introduction

Power Factor Correction is the common name for what may more accurately be described as Reactive Power Compensation.

Most three phase electrical loads draw not only active power (kW, the part that does useful work), from the supply, but also reactive power (kVAr, essential, but 'Wattless' power); examples of these loads would be induction motors, motor drives (both AC and DC) , switch-mode power supplies, and most forms of lighting.

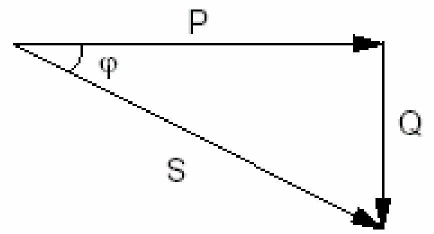
To make a very crude example of an induction motor, the active power is what comes out of the shaft and does work, whilst the reactive power is what is used by the coils of the stator to create the magnetic field. This magnetic field is essential for the operation of the motor, but does no actual work, only permitting the transfer of power from the stator to the rotor.

The total demand on the supply for a load of this type is called the apparent power, and is the vector sum of both the active and reactive components of power.

The 'power factor' of a load is the ratio of active power to apparent power, kW to kVA, sometimes referred to as Cos (ϕ).

When a load draws reactive power from the supply, its power factor is said to be lagging, when the reactive power is exported to the supply, its power factor is said to be leading. This is a reference to the phase of the load current with respect to the supply voltage.

This is the 'Displacement Power Factor' or DPF, more commonly known as just the 'Power Factor' and only takes into consideration the frequency components of voltage and current.



$P = V_{RMS} \,.\, I_{RMS} \cos\varphi$:	In-Phase or Real Power
$Q = V_{RMS} \,.\, I_{RMS} \sin\varphi$:	Reactive or Quadrative Power
$S = V_{RMS} \,.\, I_{RMS}$:	Total Apparent Power

There is another 'Power Factor' known as the 'True Power Factor' which takes into account the effect that harmonic distortion may have on the voltage and current waveforms of a load.

It is calculated as:

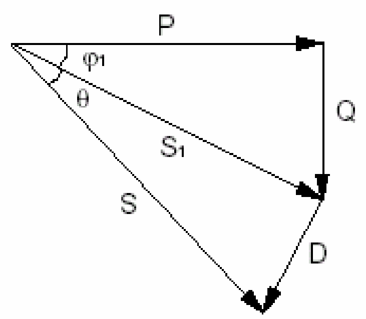
True Power Factor $= (\text{Displacement Power Factor} \times I_{frequency})/I_{RMS}$

$= \text{active power}/(V_{RMS} \times I_{RMS})$

For a linear load on a non-distorted supply, the displacement power factor and true power factor have the same value.

The greater the proportion of harmonic content in the current waveform of a given load, the greater the difference between the true and displacement power factors, and the worse the true power factor will be.

For example, a typical six pulse PWM, (pulse width modulator) voltage-source inverter drive would have a displacement power factor of approx. 0.96 lagging, but a true power factor of 0.89 lagging.



P = Real Power

$= V_{RMS} \cdot I_{RMS} \cdot \cos \varphi$

Q = Reactive Power

$= V_{RMS} \cdot I_{RMS} \cdot \sin \varphi$

S_1 = Apparent Fundamental Power

$= V_{RMS} \cdot I_{1RMS}$

D = Distortion Power

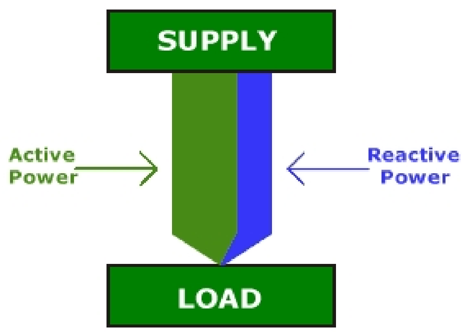
$= V_{RMS} \cdot \sqrt{\sum_{n=2}^{\infty} I^2_{nRMS}}$

S = TOTAL APPARENT POWER

$= V_{RMS} \cdot I_{RMS\,(total)}$

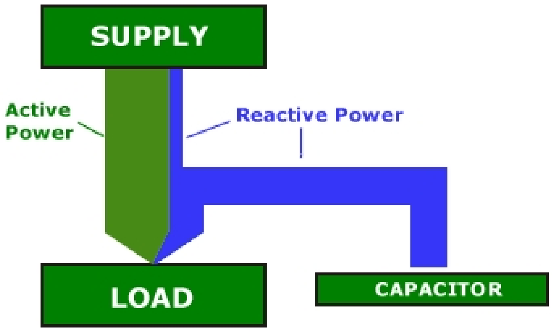
When seeking to improve the power factor of a load, what is actually being done is to supply a proportion of the reactive power demand of this load locally. This results in a greater proportion of active current being drawn from the supply.

With no power factor correction equipment installed, the supply is required to provide the total active and reactive power demand of the load.



A Typical Inductive Load

With a capacitor installed electrically adjacent to a load, the supply is required only to provide the active power demand, and a smaller proportion of the reactive power demand.



The Effect of a Capacitor on an Inductive Load

This reduces the burden on the supply for a given load, and is usually the source of most beneficial effects associated with power factor correction.

The term ‘correction’ itself can be misleading, ‘improvement’ is often a better way to indicate what is or desired to be achieved.

Calculating Capacitor Ratings

To calculate the ‘size’, or more correctly, the ‘reactive power output’ of the capacitor which is required to improve the power factor of a given load, then the active and reactive components of the load must be known, together with the level of improvement in power factor which is required; typically this would be given as the active component of a load and its ‘natural’ or ‘uncorrected’ power factor. The first of many approximations and assumptions is required at this point, as the power factor of a composite load comprising many smaller loads is rarely constant, and an average or worst-case value must be taken.

When sizing a capacitor for the power factor improvement of a single motor, it is important that the figure used for power is the input power to the motor, and not its rated shaft output. This common error results in capacitors being undersized for the application, generally speaking, the smaller and slower a motor, the worse its power factor.

The method of calculation depends on the values available, but would typically be as follows:

Calculation for a Composite Load

Capacitor power required = active load x $[\mathrm{Tan}(\phi_1)-\mathrm{Tan}(\phi_2)]$
(Where $\mathrm{Cos}(\phi_1)$ and $\mathrm{Cos}(\phi_2)$ are the uncorrected and target power factors respectively).

If the active load is given in kW, then the capacitor power will be in kVAr.

The actual angles ϕ_1 and ϕ_2 are rarely even noted, and the actual calculation performed is most commonly:

$$kVAr(C) = kW \times [Tan(Cos^{-1}(\phi_1))-Tan(Cos^{-1}(\phi_2))]$$

The value $[Tan(Cos^{-1}(\phi_1))-Tan(Cos^{-1}(\phi_2))]$ is sometimes referred to as the ‘multiplying factor’.

Calculation for a Single Load

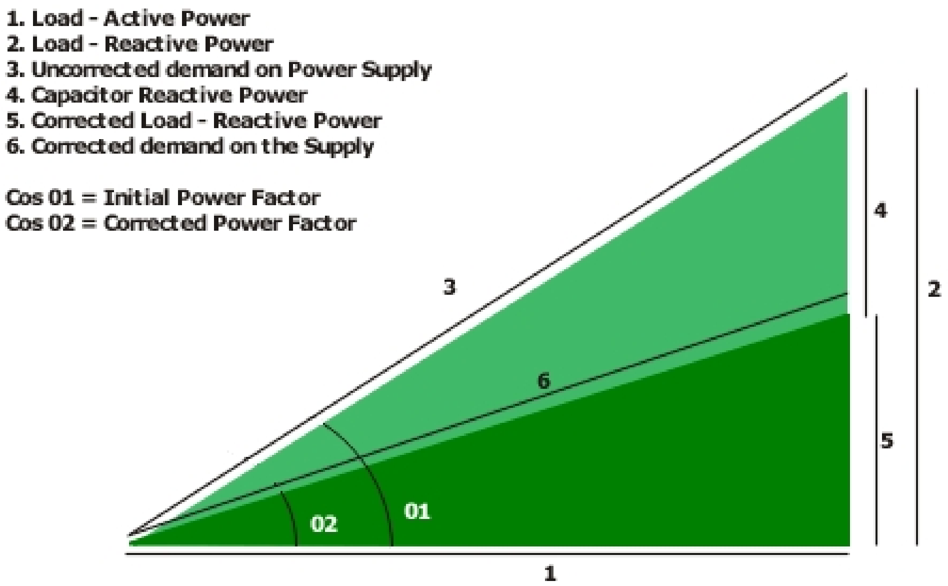
The formula

$$kVAr(C) = kW \times [Tan(Cos^{-1}(\phi_1))-Tan(Cos^{-1}(\phi_2))]$$

is still true for this situation, but it must be noted that in this case, the figure used for kW must be the input power to the motor, not the rated shaft output. The most common ‘work-around’ for this is to use the formula which gives the correct result.

$$kVAr(C) = (shaft\ kW/efficiency) \times [Tan(Cos^{-1}(\phi_1))-Tan(Cos^{-1}(\phi_2))]$$

These, and many alternative methods of calculation, can be confirmed and determined from the load vector diagram including the effect of the capacitor.



Power Factor Correction - Vector Diagram

Implementation of Power Factor Correction Capacitors

The most common methods of implementation of the capacitors required are:

Individual Power Factor Correction

In this case, a single capacitor is sized and connected electrically adjacent to a single load, usually a motor or lighting unit

Group Power Factor Correction

In this case, a single capacitor is sized and connected electrically adjacent to a group of individual loads sharing the same duty cycle, which can be treated as a single, composite load.

Automatic or Centralized Power Factor Correction

In this case, a number of capacitors are used, the total output of all the capacitors meeting the requirements for reactive power compensation at the full load condition, but divided into smaller steps or sections to enable more accurate control of the reactive power demand at partial load conditions. In this case, a reactive power control relay is used. These relays monitor the load current and supply voltages, and use the phase difference between these quantities to calculate the reactive power demand of the load, which is then compared to the reactive power outputs of the capacitors connected. This is then compared to a preset target power factor, and signals are sent to contactors to switch capacitor sections in and out as appropriate.

The method of implementation best suited to a particular installation varies according to the installation, and may include a combination of two or more of the methods above. For the same capacitor reactive power, a single capacitor is cheaper than a capacitor requiring fuse gear and a means of isolation, which is in turn cheaper then an automatic bank. However, if individual correction would mean the use of a large number of capacitors, then an automatic bank may prove the cheaper option, particularly where there is significant diversity of load. In this case, it may only be necessary to install, say, 200kVAr as an automatic bank, whereas the combined total of all individual capacitors may be in excess of 300kVAr.

Again, very generally, 11kV capacitors are cheaper than 415V capacitors of the same rating. However, the switchgear, fuse gear and contactors which may be required are more expensive, and for capacitor systems up to many hundreds of kVAr it is almost always more Cost effective to implement the capacitors at low voltage.

Benefits of Power Factor Correction

The benefits of power factor correction are far more diverse than the financially dominated electricity tariff savings which are usually the only benefit given any consideration.

Physical Benefits of Power Factor Correction

The reduction in demand on the supply from the installation of Power Factor Correction equipment results in:

- 'Spare' supply capacity which may be used to connect additional load without the necessity of network reinforcement
- Reduced losses and hence reduced heating in transformers, cables and switchgear, increasing reliability, useful service life, and reducing servicing costs
- Reduction in reactive power demand from the supply improves voltage regulation, as to a first approximation, the voltage drop in a supply network is proportional to the reactive power supplied by that network ($\Delta V \cong QX$, where ΔV is the voltage drop, Q the reactive power demand, and X the system reactance)
- An increase in Power Quality, as the presence of a large capacitor bank gives significant attenuation of mains borne voltage spikes, and can also reduce the effects of short duration dips or notches in the supply voltage
- Reduction in distribution system losses means that fewer kWh are required from the electricity generators, resulting in lower carbon dioxide emissions

Contractual benefits of Power Factor Correction

- Most contracts for the supply of electricity stipulate a minimum power factor for the load to be connected, though this is often ignored by both supplier and consumer until problems occur, at which point the solution is more costly than would have been the case had the situation been addressed initially
- Engineering Recommendation G5/4, (relates to planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom), is now enforceable legislation. The use of detuned capacitor banks has the effect of absorbing a proportion of any harmonic currents produced by the load, and can often result in compliance with G5/4 without the need for further harmonic reduction equipment.
- Engineering Recommendation P28, (relates to planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the United Kingdom), details limits on 'Voltage Flicker'. As the majority of flicker is caused by voltage drop due to sudden reactive power demand, the installation of power factor correction capacitors can reduce the levels of flicker to within acceptable limits without the need for supply reinforcement.
- Organizations having or seeking approval under ISO14001 (Environmental Management) can easily show increased electrical efficiencies and reduction in carbon emissions by implementing an appropriate Power Factor Correction scheme.

Financial Benefits of Power Factor Correction

- Reduction in kVA required to supply a given kW load means that initial capital expenditure can be reduced, as the primary distribution network components (transformers, switchgear etc.) can be reduced in rating and hence Cost.
- Reduction in losses in distribution equipment due to reduced demand on the supply is reflected in the kWh usage for the site. Whilst this reduction in kWh

consumption may at first appear to be small, it can amount to between 1% and 3% of the total consumption, with the associated savings in electricity charges.

- The tariff under which charges are made for electricity may include items which relate directly or indirectly to poor power factor. These are usually specific to the consumer, and hence generalizations are difficult. Items falling into this category which may be affected include Authorized Supply Capacity, Metered Monthly Maximum Demand, and Reactive Unit charges.

Whilst at present, many consumers may not be charged for items relating to poor power factors, this is likely to change in the near future in almost all countries around the world as focus is directed towards reduction in companies carbon footprint and directives are issued regarding global warming.

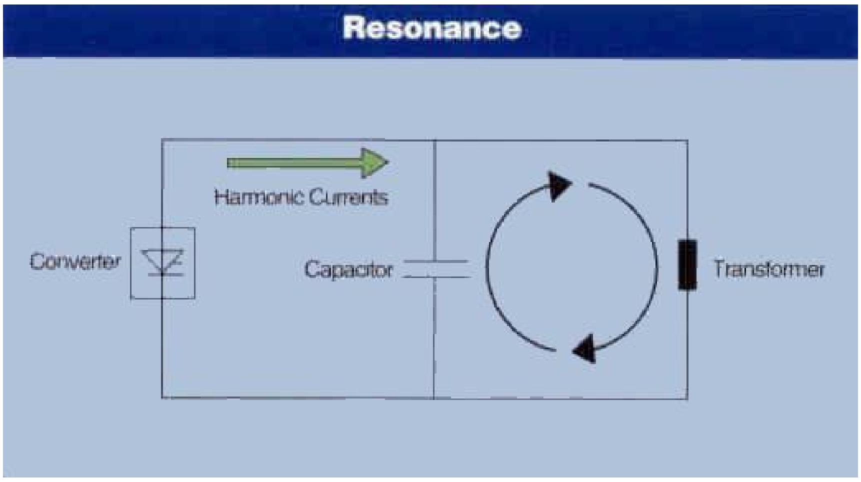
The following quote is taken from a current UK Government Consultation Document produced by OFGEN "'Power Factor' is the share of network capacity that can be used as actual, or active, power. The residual is called reactive power and is needed to energize electric and magnetic fields in certain types of network and customer equipment. The transport of reactive power reduces available network capacity and causes additional network losses, however, equipment exists that corrects for low power factors and therefore increases available capacity. This has the benefits of reducing losses, deferring the need for network reinforcement and improving voltage quality. Power factor correcting equipment can be installed both on customers' premises and on the network itself …… It is important that charging arrangements reflect the costs that low power factors impose on the networks. Competition in supply would then mean that it would be in suppliers' interest to give the appropriate signals to their customers, we, (the Government), would therefore expect suppliers to include charges for low power factors for large customers as part of a revised charging methodology … "

Power Factor Correction Capacitors and Harmonic Distortion

A complete study of this topic is beyond the scope of this document, however, detailed below is a summary of the main points often giving cause for concern and requiring consideration.

An increasing number of loads draw not only sinusoidal currents from the supply, but currents at multiples of the supply frequency, known as harmonics, examples of such loads include AC and DC variable speed motor drives, 'soft-start' motor starters, (during ramp up), rectifiers, battery chargers, switch-mode power supplies (almost all IT equipment), some ozone generators and most lighting including high-efficiency light fittings. These harmonic currents flow in the supply network, and the effect they have depends on their magnitude and the nature of the supply network.

When the network consists of a supply transformer and power factor correction capacitors, these two components form a parallel resonant circuit. If the resonant frequency of this circuit is close to the frequency of a harmonic current produced by the load, then this current is amplified, sometimes to many times the level of current produced by the load.



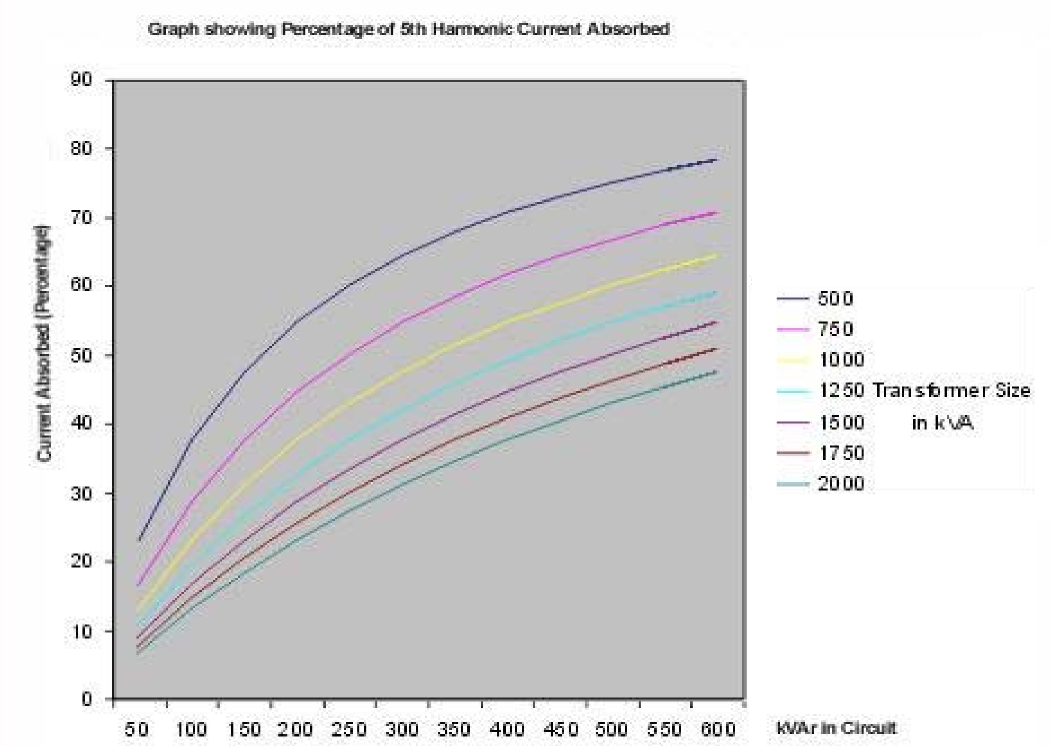
The phenomena associated with high levels of harmonic distortion are many, varied, and without exception, undesirable, they include:

- Nuisance tripping of circuit breakers and other protective devices
- Premature (sometimes catastrophic) failure of capacitors
- Overheating (and occasionally burning) of cables and other conductors
- Ageing of insulating materials due to elevated temperatures
- Poor operation or failure of relays, monitoring devices and other sensitive loads
- Increased losses due to harmonic currents

In order to avoid these phenomena, a ‘detuned’ or ‘reactor-connected’ capacitor bank is used. This includes a reactor connected in series with each capacitor, selected so as to tune the capacitor circuit to a frequency lower than that of the lowest harmonic current present on the network. This has the effect of making the impedance of the capacitor circuit inductive at harmonic frequencies, hence there is no capacitance to form the parallel resonant circuit, hence there is no resonance. The detuned capacitor system remains capacitive at the supply frequency, thus supplying the reactive power required for power factor improvement.

In addition to preventing harmonic amplification and resonance, the use of detuned capacitor systems actually has the effect of diverting (or filtering) a proportion of harmonic currents from the supply, by providing a low impedance path for them to flow in. The amount of harmonic current absorbed by a capacitor network depends on many factors, and is best calculated on a per-instance basis.

The graph below shows the percentage of 5^{th} harmonic current absorbed by a capacitor bank (detuned to 210Hz) of a given rating, when installed on a low voltage network supplied from a given transformer rating.



For example, the connection of a capacitor bank of 200kVAr to a low voltage network fed from a typical 1000 kVA transformer would have the effect of absorbing approx. 37% of the 5^{th} harmonic current produced by the load.

In cases where only a moderate proportion of the load is harmonic-generating, a detuned capacitor system can reduce the levels of distortion to acceptable limits without the need for further harmonic reduction equipment.

Conclusion

The use of capacitors to supply the reactive power demands of a load results in many benefits, many times not considered but providing generally not only benefits in terms of supply condition but also financial, (direct and indirect). In addition to the direct financial benefits dictated by the tariff under which charges are made for electricity, other physical, financial, contractual and environmental benefits result from the improvement of power factor. The use of detuned capacitor systems on networks subject to harmonic distortion not only avoids any of the undesirable effects associated with high levels of harmonic distortion, but actually reduces the levels of distortion on the network.

Example calculation

A typical load comprising:

A 1000kVA 11kV:415V distribution transformer, 4.75% impedance, full load copper losses 11.8kW

10 metres of cable from transformer to L.V. distribution board, 2 x 400mm2 per phase, resistance 0.064 Ohms/km per cable

A 1600A 3-pole withdrawable air circuit breaker, conductor losses 265W per pole at full load

An inverter load of three110kW 6 pulse inverters with typical characteristics (95% efficiency, input power factor 0.936 lagging, harmonic currents of I_5 = 33.5%, I_7 = 12%, I_{11} = 7.8%, I_{13} = 5.2%)

A conventional motor load of 360kW at an average power factor of 0.8 lagging

- The total load characteristics are 708kW, 401kVAr inductive, and 814kVA at a power factor of 0.87 lagging. This requires 195kVAr of capacitors to improve the power factor to 0.96 lagging, the standard rating used would be 200kVAr.
- The load characteristics with 200kVAr of capacitors installed are improved to 708kW, 201kVAr inductive, and 736kVA at a power factor of 0.96 lagging.
- The harmonic currents flowing in the supply, with and without the 200kVAr of detuned capacitance in circuit, are

Harmonic Number	Without capacitors	With 200kVAr detuned to 210Hz
5	172.8A	107.3A
7	61.8A	47.6A
11	40.2A	32.9A
13	26.7A	22.0A
RMS total	189.8A	123.9A

Including the harmonic currents in the total load figures, the uncorrected load is 814kVA (50Hz) and 1148A RMS, while the 'corrected' load is 736kVA (50Hz) and 1,031A RMS.

- Copper losses in the transformer are reduced from 8.031kW to 6.479kW
- Losses in the cables are reduced from 1.265kW to 1.020kW
- Losses in the A.C.B. are reduced from 0.409kW to 0.330kW
- Total reduction in losses in these network components alone is 1.876kW

Benefits achieved from the installation of 200kVAr of detuned capacitors

- if the site operates on average for 70% of the time at the load conditions stated, then the reduction in losses is

  0.7 x 24 x 365 x 1.876 = 11,504kW/h per annum

  at a typical cost of electricity of £0.05 per kW/h, this corresponds to a saving of £575 per annum

- Taking a generalized figure of 0.43kg of carbon dioxide per kWh generated, this reduction in losses corresponds to an annual reduction in carbon dioxide of:

  11,504 x 0.43 = 4,947kg

  or approx 5 tonnes per annum, taking into account only the distribution system components 'on-site'.

- Reduction in maximum demand of 78kVA (from 814kVA to 736kVA), if charged at a typical figure of £0.94 per kVA per month, would result in savings in maximum demand charges of:

  0.94 x 78 x 12 = £880 per annum

- Reduction in maximum demand could lead to reduced availability charges, 814kVA could be charged at an availability of 850kVA, 736kVA could be charged at an availability of 750kVA, this reduction of 100kVA, if charged at a typical rate of £0.94 per kVA, (typical for the UK), would result in savings of:

  100 x 0.94 x 12 = £1,128 per annum

- The 5^{th} harmonic current at the 11kV side of the transformer is reduced from 6.519A to 4.048A. The reference limit given in G5/4 for such a load is 3.9A, with a permitted tolerance of 10% or 0.5A, hence the 5^{th} harmonic current is reduced to a value within acceptable limits.

If the tariff is such that all savings may be realized, then the total savings would total some £2,583 per annum.

This calculation assumes a loss-less capacitor system, (a theoretical ideal). Taking into account typical capacitor system losses for this type of equipment of approx. 2W/kVAr, the savings that may be realized due to reduced losses are reduced to £452 per annum.

The savings due to reduction of demand and availability remain unchanged.

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