



Power Factor Correction and Power Quality Issues

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1. INTRODUCTION

Motors and other inductive equipment in a plant require two kinds of electric power. One type is working power, measured by the term kilowatt (kW). This is what actually powers the equipment and performs useful work. Secondly, inductive equipment needs magnetising power to produce the flux necessary for the operation of inductive devices. The unit of measurement of magnetising or reactive power is term as kilovar (kVAR). The working power (kW) and reactive power (kVAR) together make up apparent power, which is measured in kilovolt-amperes (kVA).

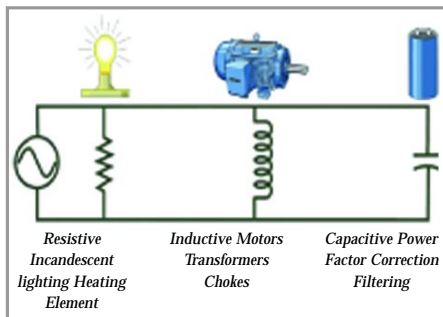


Figure 1: Types of loads

Power utility companies will provide a limited amount of reactive power (kVAR) at no cost, however, customers with high reactive power loads are charged for the additional power. Power factor penalties (or power factor surcharges) will be inflicted to the customers if their average power factors are less than 0.85 lagging.

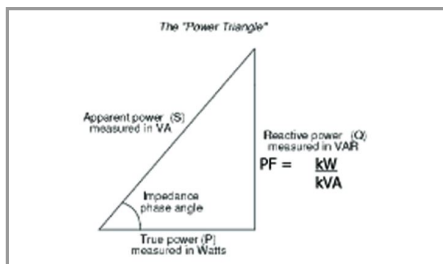


Figure 2: A Power Triangle

There are many commercial and industrial customers in Malaysia having

average power factors as low as 0.7 or 0.6 or even less. These power factor values are accessible in the monthly electricity bills. The typical electricity bill for a customer with low power factor comprises of:

$$\begin{aligned} &\text{Electricity bill (RM)} \\ &= \text{Energy Consumption (kWh)} \\ &+ \text{Power Factor Penalty} \end{aligned} \quad (1)$$

In essence, power factor is an indication of the cost effectiveness of the customer's electricity purchase. If the customer has a low power factor, he may be paying more than necessary for his electricity consumption.

2. WHAT IS POWER FACTOR?

Power factor is the ratio of the active (or useable) power measured in kilowatts (kW), to the total (active and reactive) power measured in kilovolt amperes (kVA), which includes the reactive power being used (kVAR). Power factor is commonly referred to in percent, with 100% being a perfect power factor, also called unity. At unity power factor, the $kVA = kW$, therefore the utility company does not supply any reactive power. See Figure 2.

3. WHAT CAUSES POWER FACTOR TO BE LOW?

A poor power factor can be the result of either a significant phase difference between the voltage and current at the load terminals, or it can be due to a high harmonic content or distorted or discontinuous current waveform.

Poor load current phase angle is generally the result of an inductive load such as an induction motor, power transformer, lighting ballasts, welding equipment or induction furnace. A distorted current waveform can also be the result of a rectifier, variable speed drive, switched mode power supply, discharge lighting or other electronic load.

4. WHY IS POWER FACTOR IMPORTANT?

Power factors in industrial plants are usually lagging due to the inductive nature of induction motors, transformers, welding equipment, ballasts, lighting, induction heating furnaces, etc. This lagging power factor has two costly disadvantages for the power user. Firstly, 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.

Secondly, it reduces the load handling capability of the industrial plants electrical distribution system which means that the industrial power user must spend more on distribution lines and transformers to get a given amount of useful power through his plant.

All current will cause losses in the supply and distribution system. A load with a power factor of 1.0 results in the most efficient loading of the supply and a load with a power factor of 0.5 will result in much higher losses in the supply system.

5. POWER FACTOR CORRECTION OVERVIEW

Industrial customers and commercial customers (except domestic and street lighting tariffs) need to implement power factor correction to reduce electricity bills, transformer loading, reduce losses and to improve voltage regulation.

Power factor correction is achieved by the addition of capacitors in parallel

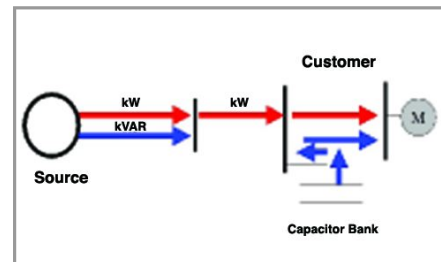


Figure 3: The concept of power factor correction

with the connected motor circuits and can be applied at the starter, or applied at the switchboard or distribution panel. The resulting capacitive current is leading current and is used to cancel the lagging inductive current flowing from the supply.

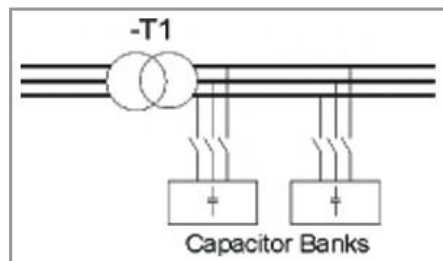


Figure 4: Capacitors at the distribution panel (1)

On the spot delivery of magnetising current provided by capacitors means that kilovars do not have to be sent all the way from the utility system to the customer's. This relieves both the customer and the utility of the cost of carrying this extra kilovar load.



Figure 5: A low voltage capacitor bank at the distribution panel (2)

It is important to note that a poor power factor due to an inductive load can be improved by the addition of power factor correction, but a poor power factor due to a distorted current waveform requires a change in equipment design or expensive harmonic filters to gain an appreciable improvement.

Many inverters are quoted as having a power factor of better than 0.95 when in reality, the true power factor is between 0.5 and 0.75. The figure of 0.95 is based on the cosine of the angle between the voltage and current but does not take into account that the current waveform is discontinuous and therefore contributes to increased losses on the supply.

6. INDUSTRIES WITH LOW POWER FACTORS BENEFIT MORE FROM POWER FACTOR CORRECTION

Low power factor results when motors are operated at less than full load. This often occurs in cycle processes such as those using circular saws, ball mills, conveyors, compressors, grinders, punch presses, etc – where motors are sized for the heavier load. Examples of situations where low power factors (from 0.3 to 0.5) occur include a surface grinder performing a light cut, unloaded air compressor and a circular saw spinning without cutting.

The following industries typically also exhibit low power factors (PF):

Industry	Uncorrected PF
Saw Mills	0.45 to 0.6
Plastic (esp Extruder)	0.55 to 0.7
Machine tools	0.6 to 0.7
Plating, textile	0.65 to 0.75
Hospitals, granaries	0.7 to 0.8

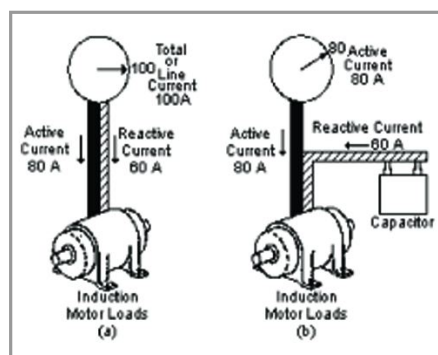


Figure 6: Benefits obtained from Power Factor Correction

Including power capacitors in one's new construction and expansion plans can reduce the size of transformers, busses, switches etc, and bring one's project in at a lower cost.

Note: Raising the power factor from 0.7 to 0.9, releases 0.32 kVA per kW. On a 400 kW load, 128 kVA are released.

7. CALCULATION OF KVAR REQUIREMENT TO REDUCE ELECTRIC BILLS

An average power factor is calculated for each month using data recorded by an energy meter installed at the customer's premises. The energy meter records the kW-hours (kWh) and kVar-hours

(kVARh) consumption. The kVAR and kWh values are then used to calculate the average power factor for the billing period. The following equation is used to calculate average power factor for customers:

$$\text{Average Power Factor} = \text{PF}_{\text{avg}} = \frac{\text{kWh}}{\sqrt{\text{kWh}^2 + \text{kVARh}^2}} = \cos \theta \quad (2)$$

If assumed an energy meter has recorded kWh values of 123,345.24 and kVarh values of 87,453.23, the average power factor is 0.82. Referring this value to the Tariff, the customer will be imposed a power factor penalty, as the value is less than the allowable power factor value of 0.85.

The size of capacitor needed to improve the power factor can be determined using this equation:

$$\text{KVAR} = \text{kW} \times (\text{Tangent } \theta_1 - \text{Tangent } \theta_2) \quad (3)$$

θ_1 – The original power factor angle

$\theta_2 = \cos^{-1}(\text{power Factor Value})$

θ_2 – The proposed power factor angle

kW – Maximum Demand (Loads)

8. HARMONIC DISTORTION ISSUES

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

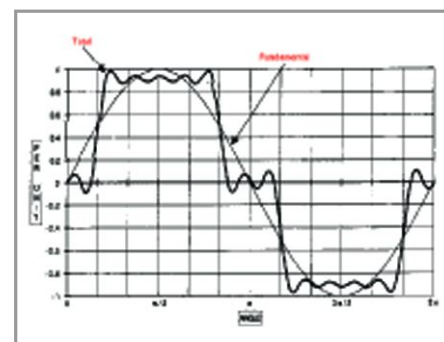


Figure 7: Typical Harmonic waveforms

furnaces, computers, and uninterruptible power supplies.

Harmonics on the supply cause a higher current to flow in the capacitors. This is because the impedance of the capacitors goes down as the frequency goes up. This increase in current flow through the capacitor will result in additional heating of the capacitor and reduce its life.

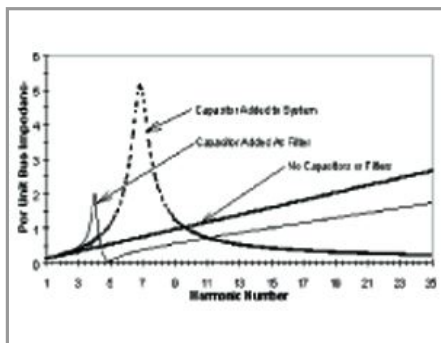


Figure 8: Resonance condition

9. RESONANCE CONCERNS

Capacitive power factor correction connected to a supply causes resonance between the supply and the capacitors. If the fault current of the supply is very high, the effect of the resonance will be minimal, however in a rural installation where the supply is very inductive and can be high impedance, the resonance can be very severe resulting in major damage to plant and equipment.

Voltage surges and transients of several times the supply voltage are not uncommon in rural areas with weak supplies, especially when the load on the supply is low.

As with any resonant system, a transient or sudden change in current will result in the resonant circuit ringing, generating a high voltage. The magnitude of the voltage is dependant on the 'Q' of the circuit, which in turn is a function of the circuit loading. One of the problems with supply resonance is that the 'reaction' is often well remove from the 'stimulus' unlike a pure voltage drop problem due to an overloaded supply. This makes fault finding very difficult and often damaging surges and transients on the supply are treated as 'just one of those things'.

If this resonance occurs at a characteristic frequency of a harmonic

producing load, the harmonic distortion could become severe. The following equation can be used to determine the frequency at which the resonance will occur.

$$f_r = \text{Resonant frequency} \\ = \sqrt{(kVAsc/kVAR)} \times 50$$

kVAsc=Short circuit kVA
at the capacitor location

kVAR=kVAR of capacitor bank

10. THE HARMONIC SOLUTION

Harmonic values of 5, 7, 9, and 11 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 energisation and/or operation of the transformer above rated voltage.

Harmonic voltages can be reduced by the use of a harmonic compensator, which is essentially a large inverter that cancels out the harmonics. This is however an expensive option.

Passive harmonic filters comprising of resistors, inductors and capacitors can also be used to reduce harmonic

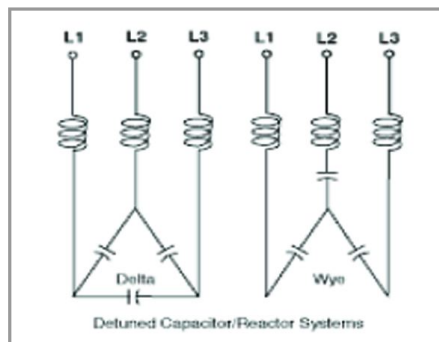


Figure 9: Capacitors with filter reactors

Table 1: Common reactor sizes for tuning the circuit

Tuned index at Harmonic	Tuned frequency	Reactor value in %
3	150	11.11%
5	250	4.00%
7	350	2.04%
9	450	1.23%
11	550	0.83%
13	650	0.59%

voltages. This is a general and an inexpensive solution.

In order to reduce the damage caused

to the capacitors by the harmonic currents, it is becoming common today to install detuning reactors in series with the power factor correction capacitors. These reactors are designed to make the correction circuit inductive to the higher frequency harmonics. Typically, a reactor would be designed to create a resonant circuit with the capacitors above the third

Table 2: Common reactor sizes for detuning the circuit

Tuned index at Harmonic	Detuned frequency	Reactor value in %
2.77	138.5	13.03%
3.78	189	7.00%
4.06	203	6.07%
4.4	220	5.17%
4.7	235	4.53%
4.8	240	4.34%
4.2	210	5.67%

harmonic, but sometimes it is below. (Never tuned to a harmonic frequency!)

SWITCHING SURGE ANALYSIS

Shunt capacitor bank switching transients are often a concern for utility and industrial engineers that are planning to apply capacitors at the distribution voltage level. Their primary area of concern is typically with how the capacitor switching transients will affect power quality for nearby industrial and commercial loads.

Switching surges occur during most switching operations. They occur during the transition when the system is changing from one steady state operating condition to another (this occurs during energisation and de-energisation of all equipment). The magnitude of the switching transient depends upon switching time and the resistive,

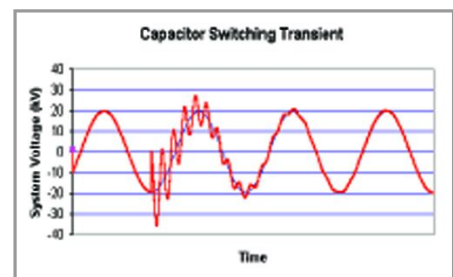


Figure 10: Capacitors switching surges

capacitive, and inductive characteristics of the system.

Capacitor switching and miss-operation of switches due to re-strike and

pre-strike generally cause the more severe switching surges.

Some of the commonly used techniques to mitigate the problem are to use:

- synchronous closing
- inrush reactor and
- detuning reactor

11. CAUTION FOR A SOFT STARTER SCHEME

Static Power Factor correction capacitors must not be connected to the output of a solid-state soft starter. When a solid-state soft starter is used, the capacitors must be controlled by a separate contactor, and switched in when the soft starter output voltage has reached line voltage. Many soft starters provide a “top of ramp” or “bypass contactor control” which can be used to



Figure 11: A Soft Starter

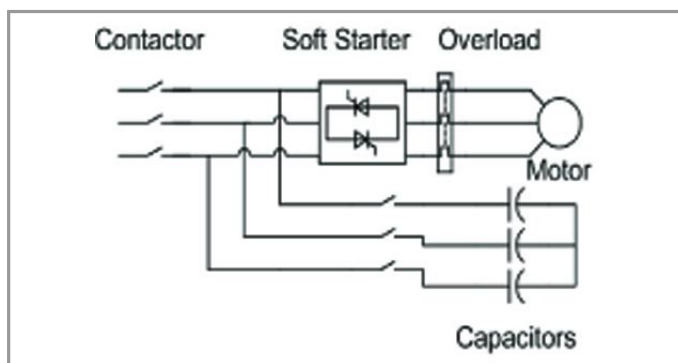


Figure 12: Typical connection for a soft-starter scheme

control the power factor correction capacitors.

The connection of capacitors close to the input of the soft starter can also result in damage to the soft starter if an isolation contactor is not used. The capacitors tend to cause transients to be amplified, resulting in higher voltage impulses applied to the SCRs of the Soft Starter, and the energy behind the impulses is much greater due to the energy storage of the capacitors.

Switching capacitors, Automatic bank correction etc, will cause voltage transients and these transients can damage the SCRs of Soft Starters if they are in the Off state without an input contactor. The energy is proportional to the amount of capacitance being switched. It is better to switch lots of