# Controlling the Impact of Power Factor and Harmonics on Energy Efficiency

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# Summary

# Executive summary

A Power Factor Correction (PFC) and harmonics mitigation plan will always improve the energy efficiency of electrical installations. Much like bumps and holes in a road impede the progress of an automobile, distorted voltage in AC distribution systems negatively impacts operations and drives up expenses. This paper analyzes PFC and harmonics problem areas and offers practical approaches for improvements.

# Introduction

Design engineers and facility managers are now required to pay more attention to saving energy and improving the availability of clean electricity at their work sites. This paper is written to assist electrical installation designers in identifying out-of-phase and voltage distortion problem areas. In addition, various harmonics mitigation and PFC solutions are discussed. The goal is to leverage existing and new technologies to decrease OPEX and to improve energy efficiency within the site's power infrastructure.

# Controlling the Impact of Power Factor and Harmonics on Energy Efficiency

# Identifying and analyzing problem areas

In AC distribution systems, the maximum active power is transmitted to a load when voltage and current are in phase and undistorted.

When voltage and current are phase-shifted, the instantaneous power P = V x I is negative when the signal signs are opposite. The average power is then reduced compared to the situation where the signals are in phase. The relevant parameter is the Displacement Power Factor (DPF) which is the cosine of the phase angle φ between voltage and current (cos φ).

When a current is distorted, the instantaneous power fluctuates significantly. The average power is then reduced compared to a situation where the current is undistorted. The current distortion means that harmonics are present, generated by non-linear loads. The Total Harmonic Distortion (THD) is the usual parameter to evaluate the distortion of current ($THD_i$) or voltage ($THD_u$). Therefore, low DPF and harmonics mean that the power transfer to the load is not maximized for a given value of r.m.s. (root-mean-square) current. In other words, the current circulating in the electrical circuits is higher than what is strictly necessary for transmitting the active power to the machines.

The Power Factor (PF) has been introduced to assess this phenomenon.

For illustration, **Figure 1** presents voltage and current wave forms for different situations, but with the same active power P transmitted to the load. With DPF = 0.7 or THDi = 100 %, the r.m.s. current is increased by more than 40 % for the same active power.

As the power losses in the circuits are proportional to the square of the r.m.s. current, the power losses in the two non-ideal situations are doubled. These additional power losses mean more $CO_2$ emission, premature ageing, higher electricity cost, and higher equipment cost.

Another major consequence of harmonics is the deterioration of the supply voltage quality. The circulation of harmonic currents through the system impedance creates voltage harmonics resulting in voltage distortion. The negative impact may remain un-noticed, with adverse economic results.

Power Factor Correction and proper harmonic mitigation can contribute to improved operations within companies in several ways:

- reduced overloading on the electrical system thereby releasing useable capacity
- reduced system losses and demand power
- reduced risks of outage
- extended equipment lifetime.

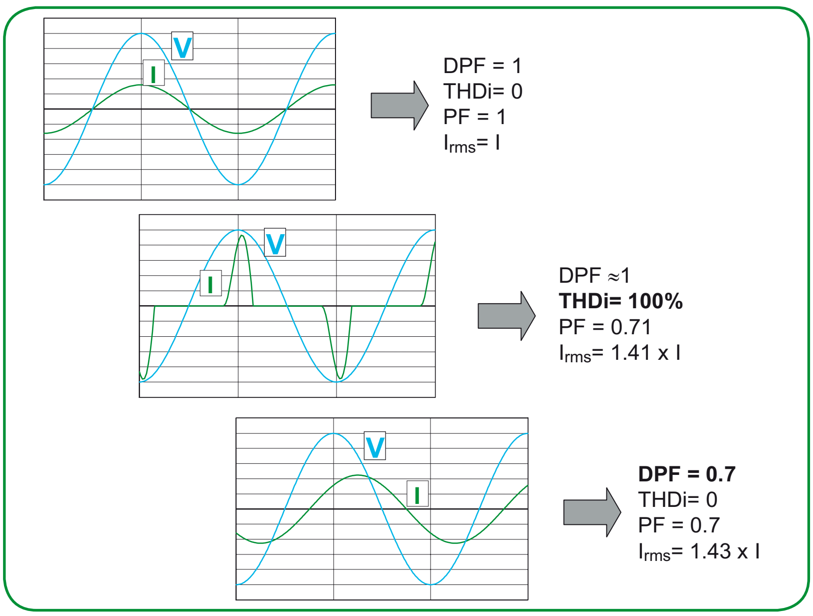


Figure 1
Sample situations impacting power factor.

# Harmonic mitigation and PFC solutions

Numerous approaches can be deployed to address harmonics and power factor issues in a facility. The following section illustrates some of the main categories of options.

## Capacitor banks

Capacitor banks (see **Figure 2**) improve Power Factor Correction and help to avoid reactive energy penalties charged by the utility. Capacitor bank equipment may be connected at the following levels of the facility's power infrastructure installation: medium voltage (MV) substation, low voltage (LV) main switchboard, LV secondary switchboard, and machine terminals.

Figure 2 – Example of low voltage capacitor banks.

When capacitor banks are installed in the presence of harmonics, two parameters shall be considered:
$G_h$: total power of the non-linear loads,
$S_n$: rated power of the supply transformer.

Different types of equipment must be selected depending on the level of the network harmonic emission. The selection is based on the value of the $G_h/S_n$ ratio, as illustrated in **Figure 3**:

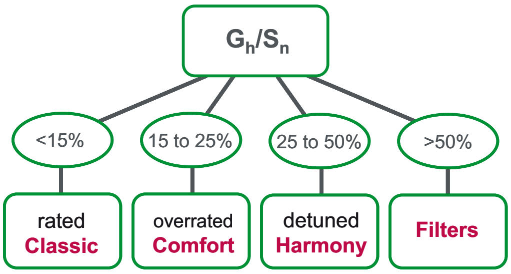


Figure 3 – Selection criteria.

The following points should be considered when selecting capacitors:
Overrated capacitors must be selected when $G_h/S_n$ exceeds 15 % because harmonic currents will be responsible for increased stress.
When $G_h/S_n$ exceeds 25 %, a series reactor is necessary to protect the capacitors against harmonic currents. This is called a detuned reactor because capacitors and the reactor are set up in a resonant circuit configuration, not tuned to the frequency of any harmonic order.

Passive filters are implemented when Power Factor Correction is requested with a high level of existing harmonic distortion. These filters consist of reactors and capacitors set up in a resonant circuit configuration, and are tuned to the frequency of the harmonic order to be eliminated. A system may be composed of a number of filters to eliminate several harmonic orders.

## Active filters

Active filters are systems employing power electronics which provide the harmonic currents required by nonlinear loads thereby avoiding distortion on the power system.

The active filter injects, in opposite phase, the harmonics drawn by the load, such that the line current remains sinusoidal.

## Hybrid filters

Hybrid filters are systems that include a passive filter and an active filter in a single unit. They combine the advantages of both technologies and provide an optimum cost / performance ratio.

Figure 4 - Examples of active and hybrid filters.

## Electronic compensators

Active or hybrid filters are also capable of compensating for low values or fluctuations of the Displacement Power Factor.

In this mode of operation, they are also known as "Static Var Compensators" (SVC) or "Hybrid Var Compensators" (HVC).

## Solutions that support Variable Speed Drives (VFD)

AC-Line or DC-link chokes are commonly used with drives up to about 500kW unit power. When a large number of drives are present within an installation, the use of AC-Line or DC-link chokes for each individual drive is recommended. This measure increases the lifetime of the drives and enables use of cost effective mitigation solutions, such as active filters, for example, at the time of installation (see **Figure 5**).

C-less technology applies to Variable Speed Drives and offers a reduced current distortion compared to traditional technology. Combined with an advanced control algorithm, this solution is suitable for applications with low over-torque requirements like centrifugal pumps, fans and HVAC machines.

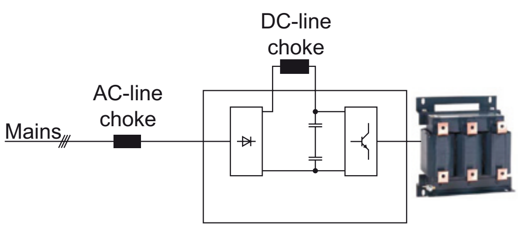


Figure 5 – Chokes for drives.

A multi-pulse arrangement is often used for drives above 400 kW, but could also be a reasonable solution for smaller power ratings (see **Figure 6**). A precondition is a dedicated transformer directly supplied from the MV network. The use of a 3-winding transformer providing a 12-pulse supply for the drive is considered standard. This limits the harmonic emission and, in most cases, no further mitigation is necessary. Multi-pulse solutions are the most efficient in terms of power losses and compliance to standards is simplified.

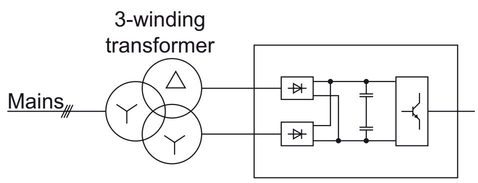


Figure 6 - Multi-pulse arrangement.

An Active Front End (AFE) is the best performing solution concerning harmonic mitigation with drives, limiting the THDi below 5 % (see **Figure 7**). All the applicable standard requirements can be met. No detailed system evaluation is necessary, making this solution the easiest to implement. In addition to harmonic mitigation, power regeneration and power factor correction are inherent.

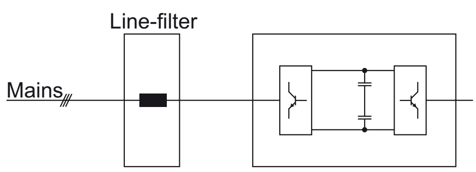


Figure 7 - Active Front End configuration.

# Designing for energy efficiency

In the domain of electrical installations, energy efficiency is defined as follows:

- energy savings: reduction in energy consumption
- energy cost optimization: reduction in the cost of energy paid to the utility
- availability and reliability: reduction in the risk of outage, and efficient equipment operation.

PFC and harmonic mitigation impacts all 3 aspects of energy efficiency in the following ways:

- Reduction of the power losses in transformers, cables, switchgear, motors, capacitors
- Reduction of the demand power (in MVA), resulting in lower electrical bills
- Optimization of total system capacity, without risk of overload, nuisance tripping or premature ageing of equipment.

## Parameters to be considered

In order to better manage harmonics, the following parameters should be considered:

**Network parameters**

It is important to understand the characteristics of the power network in order to be able to accommodate conditions at the Point of Common Coupling (PCC)–this is the point where the installation is connected to the utility network, and where other utility customers may be connected. The system size (known by power or impedance) and topology both have an influence on the resulting harmonic distortion.

**Industry**

Applicable standards vary depending upon the environmental characteristics of industry specific facilities. Relevant standards in residential, commercial or light industry sectors are generally applicable to pieces of equipment. Standards in heavy industry sectors, on the other hand, are applicable to global installations and not at the individual component level. Thus, central mitigation is generally more cost effective in heavy industry sectors.

**Applicable harmonic standard**

Once industry and network parameters are determined, the applicable standards should be enforced. Exceeding the standard requirements, however, will result in a higher investment than is needed. On the other hand, application of excessively relaxed standards can result in higher energy and maintenance costs, as well as disturbances on the mains.

**Project drivers**

Whenever an investment is necessary, it is important to set a priority concerning the project drivers. A solution optimized for a low Capex may result in higher Opex and vice versa. Performance specifications for a solution will also impact both Capex and Opex.

**Applicable reactive energy penalties**

The contractual arrangements with energy suppliers can also influence the design of the installation. If penalties for exceeding reactive energy limits are in place, the implementation of Power Factor Correction capacitors should be considered. However, if harmonic current generators and capacitor banks are present, current and voltage distortions may be amplified (resonance phenomenon). This has a significant impact on the resulting harmonic distortion. Thus, a simultaneous review of both PFC and harmonic mitigation should be considered and additional precautionary measures may need to be taken.

**Ratio of non-linear load power to total load power**

The higher the share of non-linear loads compared to the total load power of an installation, the higher the necessity for evaluation of harmonics.

# Harmonic mitigation of Variable Speed Drives (VSD)

The installation of Variable Speed Drives (see Figure 8) should take into account the following considerations:

- if the motor driven by the VSD is newly installed, the availability of power from the supply system should be checked
- the Power Factor Correction has to be revised, as no significant reactive energy is requested anymore by the VSD driven motor
- the impact of harmonics has to be analysed, both in terms of possible disturbances and compliance to standards.

Figure 9
Variable Speed Drives in a pumping station

## Steps for deploying a solution

The evaluation and selection of a suitable harmonics mitigation solution should include the following three steps:

**1. Select the relevant harmonic emission limit (equipment or installation standard)**

This step identifies the applicable standards. The standards can apply to specific equipment or to a global installation. As the limits applicable at the installation level are generally more restrictive, applying these limits at the equipment level is not cost effective.

**2. If harmonic mitigation is needed or advisable, consider equipment mitigation first**

For drives totalling a power load of up to 100 kW:

- this power usually represents less than ~20 % of the transformer rated power. The standard solution is to use AC-Line or DC-link chokes.

For total drives power from about 100 kW up to about 1,000 kW:

- in this power range, it is advisable to have the transformer power equal to at least 2.5 times the drives load. The standard solution is to use AC-Line or DC-link chokes.

For drives whose power load ranges from 100 kW to 1,000 kW:

- in this power range, drives are usually equipped with a dedicated transformer directly supplied from the MV network. A 3-winding transformer is commonly used, providing a 12-pulse supply for the drives. This limits the harmonic emission and, in most cases, no further mitigation is necessary. In addition, multi pulse solutions are the most efficient in terms of power losses. This allows for easy compliance to the most stringent standards.

**3. Check impact on existing equipment of installation**

When a new non-linear load is connected to an existing installation, it has to be determined if it influences the other components already connected on the same network. This is relevant for capacitors and active filters in particular. Below are some examples of common scenarios:

- if capacitors are already present in the installation (Power Factor Correction or passive harmonic filter), there is a risk of overload and resonance introduced by the additional harmonic currents. Usually the supplier of the PFC or passive filter is able to evaluate the situation and should be contacted first.
- if passive or hybrid filters are present, the installed filter can be kept unchanged if it is oversized and can match the new current requirements. Otherwise, the passive element must be redesigned, as it is not possible to connect another element in parallel with exactly the same frequency tuning.
- if an active filter is present, non-linear loads must always be equipped with line chokes. This will significantly reduce the harmonic current emission and thus the necessary current rating of the active filter. No risk is introduced by the additional harmonic currents as the active filters are usually protected against overload. However, the cancellation of harmonic currents may not be totally effective, and the global performance may be deteriorated. Usually the network designer is able to evaluate the situation and should be contacted first.

# Conclusion

Power Factor and harmonics, because of their impact on energy efficiency, are important issues to consider for the management of electrical installations. Multiple approaches are analyzed and explained so that performance of electrical systems can be optimized.

Solutions for Power Factor Correction and harmonic mitigation have been presented in a practical way, answering basic questions frequently asked by electrical installation designers.

Power Factor Correction and harmonics mitigation both provide immediate benefits in terms of reduced power losses and reduced electricity bills. In addition, both of these best practices encourage the use of total system capacity in electrical installations thereby increasing payback on investment.

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