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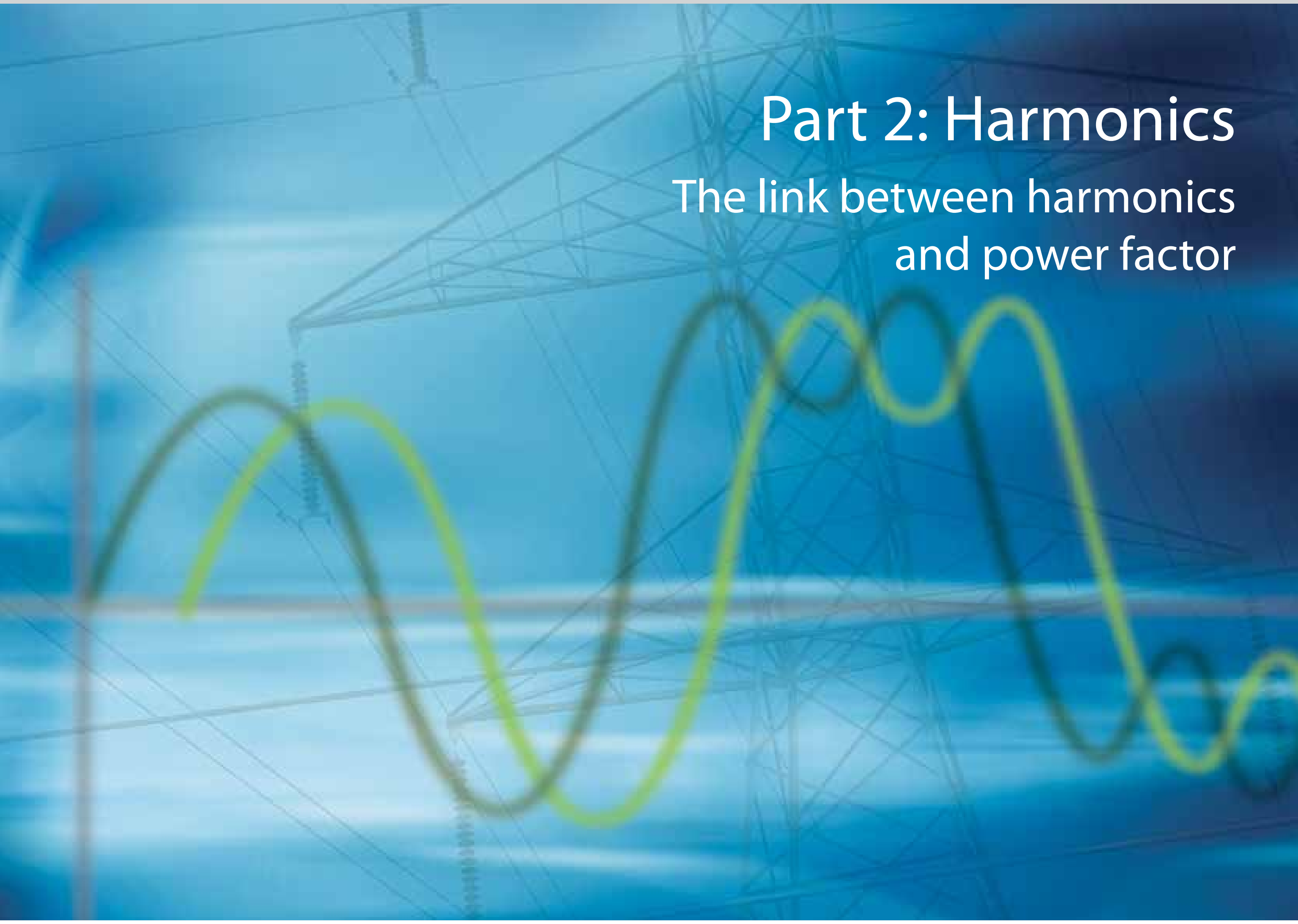
Technical News

Industrial Electrical and Automation Products, Systems and Solutions

Part 2: Harmonics

The link between harmonics and power factor



Written by Justin Charlot
Product Manager – Power Quality

INTRODUCTION

A significant shift between linear inductive loads to non-linear loads is taking place. The benefits of these non-linear loads in terms of overall efficiency, flexibility and control have contributed to the growth in this market. Direct online (DOL) motors and soft starters are being replaced with variable speed drives, incandescent lights replaced by fluorescent and LED lighting, and the sustained growth in the automation industry has resulted in more data centres, switched mode power supplies and UPS systems being installed.

The generation of harmonics by these non-linear loads and the problems they cause is discussed in detail in the previous NHP Technical News Edition (Issue #64 – Harmonics: Part 1 - Where they come from, the problems they cause and how to reduce their effects).

One very important aspect of this shift is the impact harmonics is having on power factor. In this edition, we explain the link between harmonics and power factor and what this means for power factor correction and harmonic mitigation solutions.

The electrical power (apparent power) that is delivered through the power mains by an electricity supplier is comprised of active power (kW), which actually does the work, as well as reactive power (kVAr) and distortion power.

Reactive power is the power required to produce a magnetic field to enable real work to be done. This reactive power is necessary to operate equipment that requires a magnetic field to function. For example, linear inductive loads such as induction motors require a combination of active power (kW) from the supply and reactive power (kVAr) to maintain the electromagnetic field required by the windings.

Only real power (kW) is delivered at the fundamental frequency i.e. 50Hz. Since non-linear loads draw current at the fundamental frequency as well as harmonic frequencies, the current drawn at harmonic frequencies contribute to the overall power consumption or apparent power (kVA). Distortion power is the result of current harmonics drawn from the network by non-linear loads. Examples of non-linear loads include equipment that operates via a rectifier circuit such as variable speed drives, switched mode power supplies, UPS systems, data centres and electronic ballasts used in fluorescent lighting.

Power factor refers to the ratio of real power to apparent power or

$$\frac{\text{Real Power (kW)}}{\text{Apparent Power (kVA)}}$$

The power factor is desired to be kept as close to unity as possible. As the power factor decreases, the apparent power draw increases. As a result the size of the transformer and installation power wiring may need to be increased to allow for the increase in current.

Many supply authorities charge for the base load (kW) and a maximum demand tariff. If this tariff is measured in kVA, then improving the power factor will reduce power costs. It is important to note that total or true power factor is influenced by two factors; displacement power factor and distortion power factor.

DISPLACEMENT POWER FACTOR

Displacement power factor is defined as the ratio between apparent power (at the fundamental frequency) and real power. Or, in other words $PF_{displacement} = \cos(\theta)$, where θ is the phase shift between voltage and current at the fundamental frequency (refer to Figure 2). Therefore, inductive loads such as induction motors will affect the displacement power factor. When the load is inductive, the inductance tends to oppose the flow of current, storing energy then releasing it later in the cycle. The current waveform lags behind the voltage waveform. When the load is capacitive, the opposite occurs, and the current waveform leads the voltage waveform. So, lagging versus leading is another way of saying the net reactance is either inductive or capacitive.

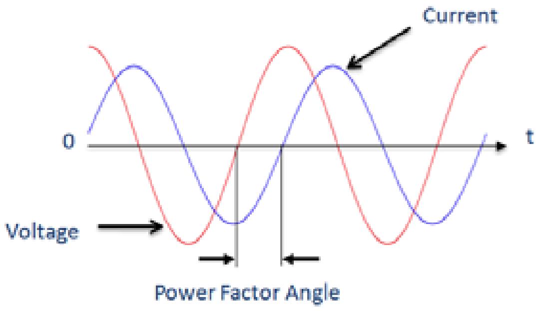


Figure 2: Phase shift between voltage and current at the fundamental frequency

DISTORTION POWER FACTOR

Distortion power factor is the ratio between the current at the fundamental frequency and the total current. As shown in the following derivation, distortion power factor can be shown to be a function of total harmonic current distortion (THID):

$$i.e. \quad PF_{Distortion} = \frac{I_{\text{Fundamental}}}{I_{\text{Total}}}$$

$$where \quad I_{Total} = \sqrt{I^2_{Fundamental} + I^2_{Harmonic}}$$

$$As \quad THID = \frac{I_{Harmonic}}{I_{Fundamental}} \times 100$$

$$PF_{Distortion} = \sqrt{\frac{1}{1 + THID^2}}$$

Equation 1: Distortion Power Factor [1]

As evident in Equation 1, distortion power factor can be improved by reducing the current harmonic distortion. There are many different ways of mitigating harmonics, which will be application dependent. For example, passive harmonic filters (PHF) are specifically designed to mitigate harmonics produced by a 6 pulse variable speed drive (VSD), while active harmonic filters (AHF) can compensate any type of non-linear load connected to a three phase power network.

TOTAL POWER FACTOR

The relationship between displacement power factor and distortion power factor is further highlighted in Figure 3:

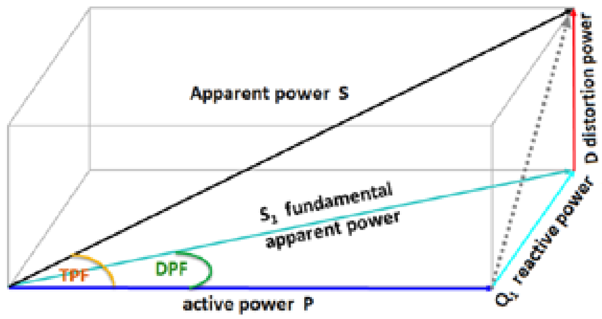


Figure 3: Total Power Factor

Therefore: $S^2 = P^2 + Q_1^2 + D^2$ and $Q^2 = Q_1^2 + D^2$

Therefore what we can decipher from Figure 3 is that displacement and distortion power factor contributes to the total power factor. To improve total power factor means that both the total harmonic current distortion and reactive power at the fundamental must be compensated.

Prime examples of how different equipment influence total power factor are illustrated below:

Direct online (DOL) motors are an inductive source with a typical total power factor of around 0.8-0.85i. The harmonic content is low to non-existent for a DOL motor, and hence the total power factor of 0.85i is influenced primarily by the displacement power factor of the load. To improve the total power factor, we must improve the displacement power factor. Power factor correction systems consisting of capacitor banks provide an alternative reactive power source. Hence, the introduction of power factor correction improves the displacement power factor and total power factor.

A 6 pulse variable speed drive (VSD) exhibits good displacement power factor, typically around 0.95i. However, VSDs produce harmonics, which influence the total power factor and as a consequence, the total power factor of a 6 pulse VSD may actually be around 0.87i. This means that a traditional power factor correction system is not a suitable solution to correct the total power factor since the VSD already has good displacement power factor. Rather, we must mitigate the harmonics produced by the VSD. There are a few common methods available to mitigate the harmonics associated with a 6 pulse VSD. These include:

- AC line choke / DC link choke
- Passive Harmonic Filter (PHF)
- Active Harmonic Filter (AHF)

Therefore, by mitigating the harmonics produced by the VSD, we are improving the distortion power factor component and consequently improving the total power factor.

TRADITIONAL POWER FACTOR CORRECTION SYSTEMS

Traditional Power Factor Correction Systems consisting of capacitor banks (refer to Figure 4) are designed to improve lagging (or inductive) displacement power factor by providing an alternative source of reactive power and reducing the amount of reactive power sourced from the electricity supplier. There is no escaping the fact that the inductive loads require reactive power but you can choose where the bulk of the reactive power is sourced from.

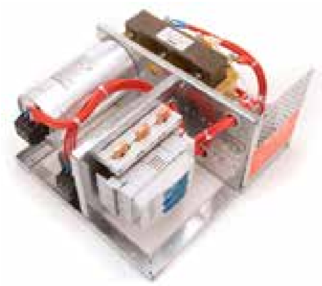


Figure 4: Capacitor bank used in traditional PFC systems

The impedance of the capacitor decreases as the frequency increases, as highlighted by Equation 2.

$$X_c = \frac{j}{2\pi fC}$$

Equation 2

where:

X_C is the capacitor reactance (kVAr)

f is the system frequency (Hz)

C is the capacitance of the capacitor (µH)

Hence, harmonics lead to a higher capacitor current, which can result in premature depletion of capacitors.

The implementation of a detuned arrangement, where a reactor is connected in series with the capacitor is designed to force the resonant frequency of the network below the frequency of the lowest harmonic present, hence ensuring no resonant circuit and amplification of harmonic current. The reactor also serves the purpose of limiting inrush current, preventing interference with supply authority signals and blocking harmonics from the capacitor, which as previously mentioned prevents premature depletion of the capacitor.

Figure 5 showcases the overall impedance of a capacitor bank. The impedance is capacitive at the fundamental frequency. As the frequency increases the nett impedance curve moves towards inductive. At a given frequency, the overall reactance is 0 and this is the series resonant point, also referred to as the tuning frequency of the capacitor bank. This tuning frequency should be selected to be below the lowest order harmonic present on the network. The standard tuning frequency is 189 Hz. Above 189Hz the reactance of the capacitor bank is inductive.

The impedance of the inductor increases as the frequency increases as highlighted by Equation 3 hence a tuning frequency of 189Hz serves the purpose of "blocking" the 5th order harmonics and above.

$$X_L = 2\pi fL$$

Equation 3

Where X_L is the inductive reactance (kVAr)

f is the system frequency (Hz)

L is the inductance (mH)

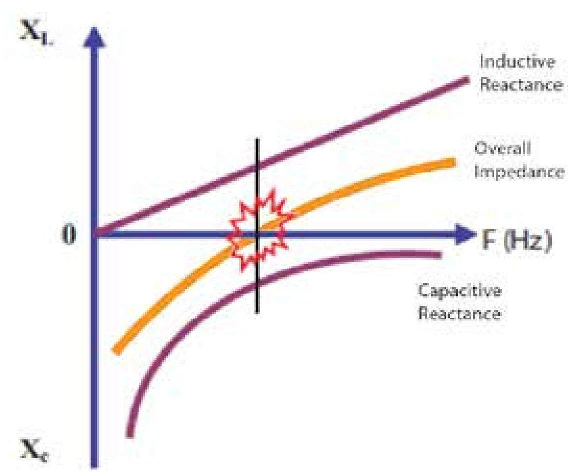


Figure 5: Impedance curve of a traditional capacitor bank vs. inductive and capacitive impedance curves

As the capacitor depletes (normal course of action over a period of time), the tuning frequency moves. In Figure 5, this tuning frequency will move towards the 5th harmonic and hence, the importance of maintenance of a PFC system. Some PFC systems are now available with a detuned arrangement at 134Hz – i.e. designed to block 3rd harmonics and above.

All of the above points bring to a head a few very important points regarding harmonics and traditional Power Factor Correction Systems

1. The PFC system is not designed to reduce harmonic current distortion.

2. The PFC system is not immune to the adverse effects of harmonic distortion simply because it has reactors installed on each step. A high presence of current harmonic distortion will contribute to premature capacitor failure with or without harmonic blocking reactors installed. Hence, following a power audit, NHP advises whether a harmonic mitigation solution is required prior to the installation of a PFC system to ensure the safe and reliable operation of the Power Factor Correction System.

ADVANCED PFC SOLUTIONS

More advanced PFC technologies in the form of active harmonic filters are now readily available on the market. The Schaffner ECOsine Active harmonic filter (as pictured in Figure 6) can perform both power factor correction and harmonic mitigation simultaneously and therefore improve both components of total power factor – displacement power factor and distortion power factor. Hybrid solutions consisting of both traditional power factor correction systems and harmonic filters is a solution where both poor displacement power factor and high level of harmonic distortion is required to be addressed.

HYBRID PFC AND HARMONICS SOLUTION

A hybrid solution will consist of both a traditional PFC system to address displacement power factor and a harmonic mitigation solution which will vary depending upon the non-linear loads installed (i.e. line chokes, PHFs, AHFs etc.). A hybrid solution will usually be a cost effective solution when both poor displacement power factor and high level of harmonics are an issue due to the combination of linear and non-linear loads installed on the network. There are important installation considerations, including the location of the PFC, AHF and external CTs. Ideally, the AHF would be compensating non-linear loads downstream of the PFC system (refer to Figure 7).

Figure 6: Schaffner ECOsine™ active harmonic filters can perform dynamic reactive power compensation

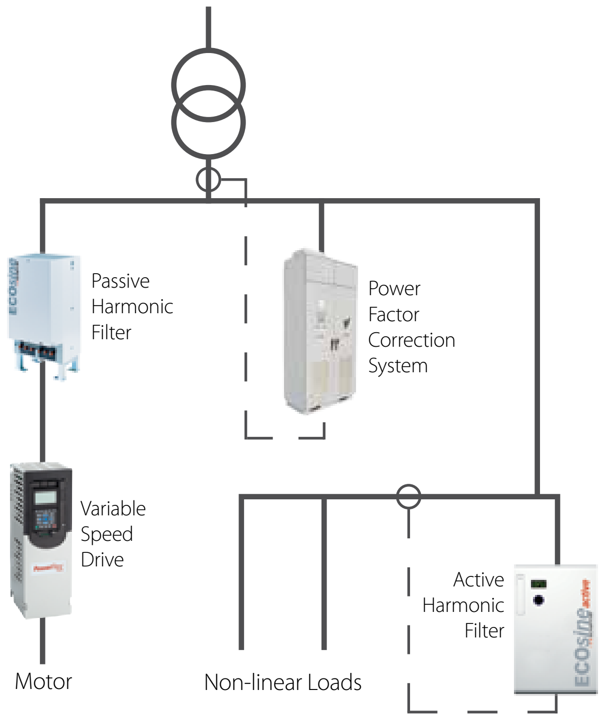


Figure 7: An example of a hybrid PFC and harmonics solution

Scan the QR code to download the Harmonic Filtering Brochure.

CASE STUDY - WASTE WATER TREATMENT PLANT

In this case study, NHP had conducted a site power audit at a waste water treatment facility. The objective behind this site audit was to assess the possibility of installing a PFC system to further improve the end users power factor and reduce kVA tariffs.

The data shown in Figure 8 shows displacement power factor (Average DPF) consistently around 0.99 to 1.0 and harmonic distortion power factor (HDPF) averaging around 0.93. Total power factor ranged around 0.88 to 0.94 and the total current harmonic distortion (THID) on-site ranged between 25-40% under load conditions (refer to Figure 9).

There are a few events captured during this recording period which highlight the relationship between distortion power factor and the corresponding THDI level and displacement power factor. At approximately 1:48pm, the THDI% level dropped and this is reflected in an improvement in distortion power factor. However total power factor remained the same?

This is due to a change in displacement power factor, which had dropped during this same period. This indicates the operation of linear inductive load(s) and possibly a reduction in the operation of non-linear load(s). This also appears to be the case early in the recording between 00:00 – 1:00am, however there was minimal load operating at this time (refer to Figure 8).

For the majority of the recording period, total power factor was influenced primarily by the distortion power factor. In this instance, a traditional power factor correction system is not ideally suited for this application due to the high levels of current harmonic distortion and inherent good displacement power factor averaging 0.99 for the majority of the recording. A harmonic mitigation solution would reduce THID levels and improve the distortion power factor, hence improving total power factor and reducing kVA tariffs and improving power quality on-site.

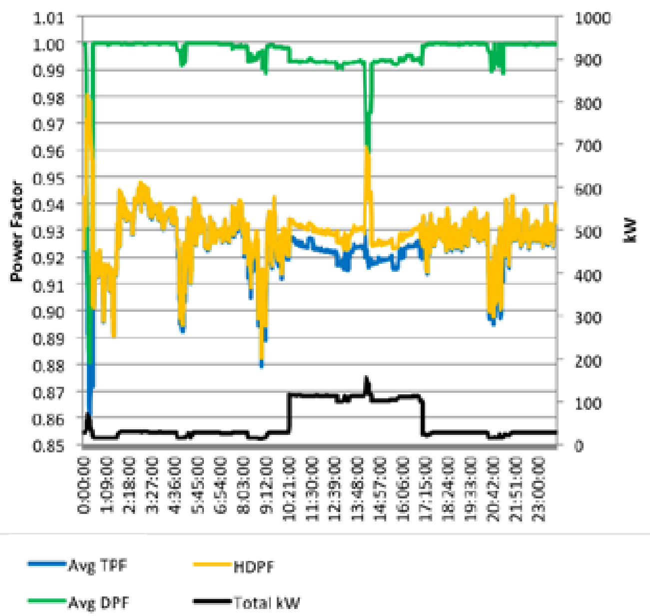


Figure 8: Power Factor (Displacement, Distortion and Total) and kW load

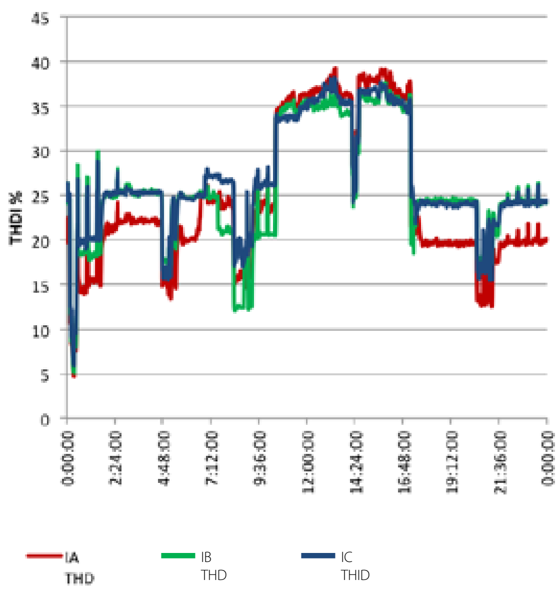


Figure 9: Harmonic Current distortion

SUMMARY

The link between power factor and harmonics is commonly neglected and/or misunderstood but is fast becoming a topical issue that impacts the application of traditional power factor correction systems. With the growing presence of non-linear loads on the network, distortion power factor is an important aspect when considering solutions to improve power quality, facility capacity and tariff billing.

The value of a power quality audit is increasingly more valuable as additional information such as distortion power factor along with current and voltage harmonic levels, displacement and total power factor and other power, voltage and current measurements, assist greatly in identifying the most appropriate solution.

Traditional power factor correction systems are not typically designed to improve distortion power factor and advanced harmonic solutions, which also incorporate reactive power compensation is emerging more frequently in the global market.

Scan the QR code to view the Power Factor Concept explained with a live demonstration

Scan the QR code to view a live demonstration of the Schaffner ECOsine Active Harmonic Filter

SOURCES

[1] Harmonics and how they relate to power factor, Grady W. M, Gilleskie, R. J, San Diego, CA November 1993

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