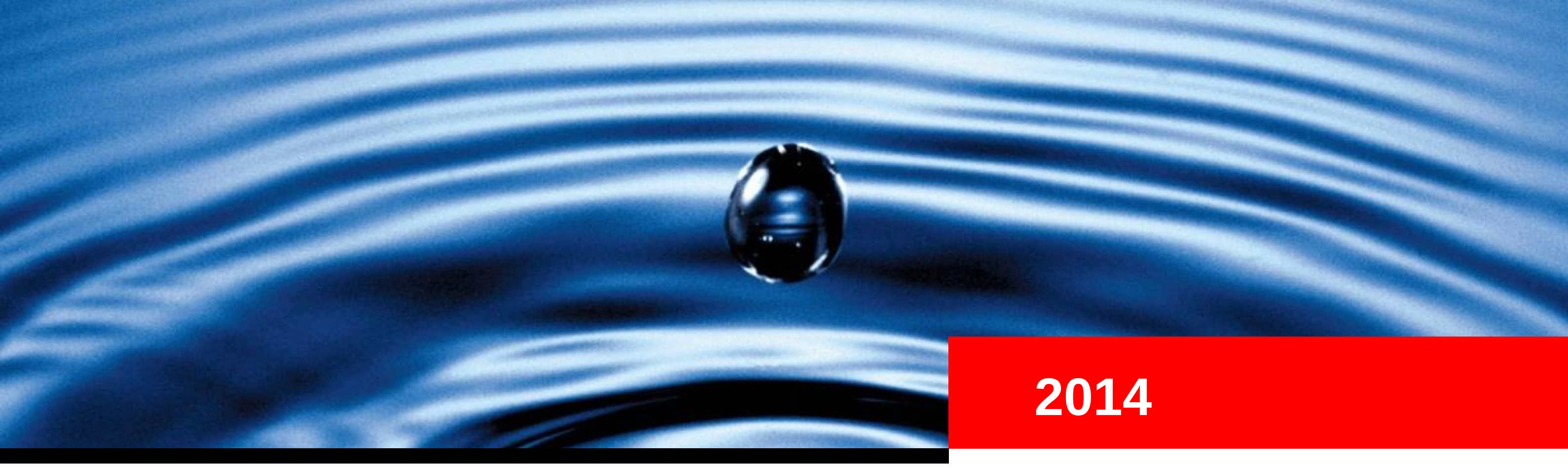

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Six tough topics about harmonic distortion and Power Quality indices in electric power systems

SCHAFFNER
energy efficiency and reliability

A white paper of the Schaffner Group

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CHAPTER 1

Basics of the harmonic theory

Introduction

The electricity supply would, ideally, show a perfect sinusoidal voltage at every point of the power network. In reality it is almost impossible to accomplish such desirable conditions. Voltage and current waveforms deviate massively from a sinusoidal. These waveform deviations are described by the use of waveform distortion and usually called harmonic distortion.

Even if harmonic distortion is a quite old phenomenon it today presents one of the main concerns for public utilities, distribution system operators as well as their end customers. Already in the first years of operation of power distribution networks, there were first disturbances. In the beginning they came from mercury vapor rectifiers that were used in industrial environments. The major concern at this time was the effect that harmonic distortion had for the electric machines itself. Another well-known issue was interference in the telephone lines. But in general it can be said that harmonic distortion in former times did not have the same dangerous potential like it has today. Especially machines have been designed much more conservative and the distribution networks have not been on their limit loads.

Starting a few years ago there is a clear and strong worldwide tendency towards energy efficiency realized by the increasing use of power electronics. This equipment along with power networks on the edge increases the voltage distortion and will continue rising. As this creates a lot of issues and problems the topics in this white paper are most important to know.

Basics

The term "harmonics" originated in physical eigenvalue problems, meaning waves whose frequencies are integer multiples of one another. One example for such waves is the frequencies of the harmonics on stringed musical instruments. The notion of harmonics in the electrical meaning became known in the second half of the 20th century. Like surfers, most electrical devices are looking for the perfect wave. For alternating current, perfection is defined by a sinusoidal wave in which electrical voltage changes smoothly from positive polarity to negative and back again 50 (50Hz) or 60 (60Hz) times per second. Anyway to use the notion of wave though in connection with harmonics is not completely correct. A wave extends in time and space, whereas the oscillations observed here, do only expand in time. Thus a harmonic component in an AC power system is defined as a sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple (the so called order of harmonic) of the fundamental frequency of the system:

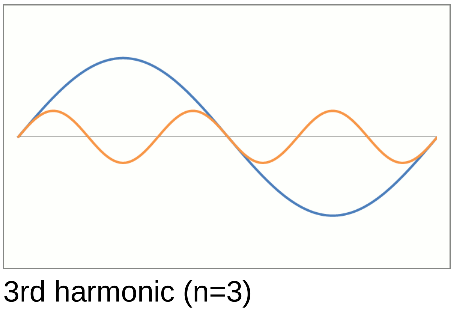
$$f_h = n * fundamental\ frequency$$

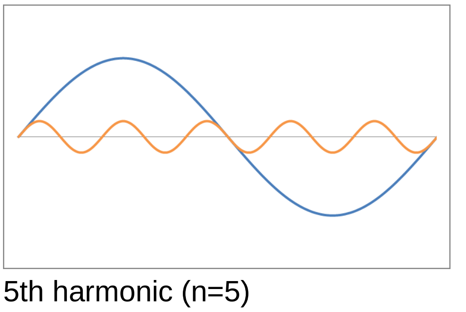
f_h..harmonic order, n..integer, fundamental frequency is either 50 or 60 Hz

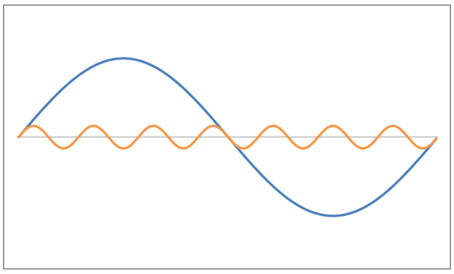
Harmonic order f_h	Freq. (Hz) in 50Hz networks	Freq. (Hz) in 60Hz networks
1	50	60
3	150	180
5	250	300
7	350	420
11	550	660
13	650	780
n	50*n	60*n

Table 1 - harmonic frequencies

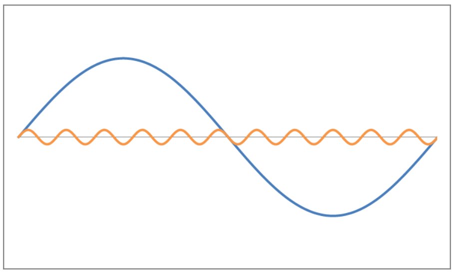
Figure 1 shows an ideal 50-Hz waveform with frequencies three (3rd harmonic), five (5th harmonic), seven (7th harmonic) and eleven (11th harmonic) times the fundamental frequency.


3rd harmonic (n=3)


5th harmonic (n=5)



7th harmonic (n=7)



11th harmonic (n=11)

Figure 1 – Harmonic frequencies

Composition and Decomposition of distorted waveforms

Figure 2 shows a distorted waveform. A distorted waveform in general can be obtained by the superposition of sinusoidal waveforms of various frequencies and amplitudes. That means it can be “composed” from harmonic components. The example in figure 2 is the result of the summation of a sine wave with multiple harmonics.

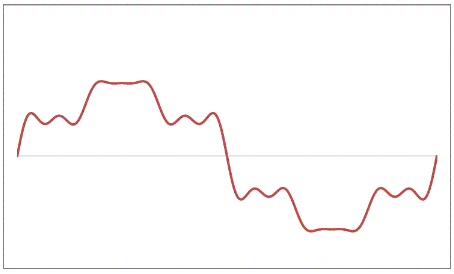


Figure 2 – Distorted waveform

If any distorted waveform can be composed from harmonic components, any periodic waveform can also be decomposed into a sinusoid at fundamental frequency and a number of sinusoids at harmonic frequencies. The French mathematician Jean Baptiste Fourier was the first to demonstrate this technique. That’s why we call it today Fourier transformation. Depending on the kind of the waveform coefficients may or may not exist. If we consider figure 1.2 as an example, the decomposition would result in the fundamental which is super positioned by the 5th, 7th, 11th, and 13th harmonic:

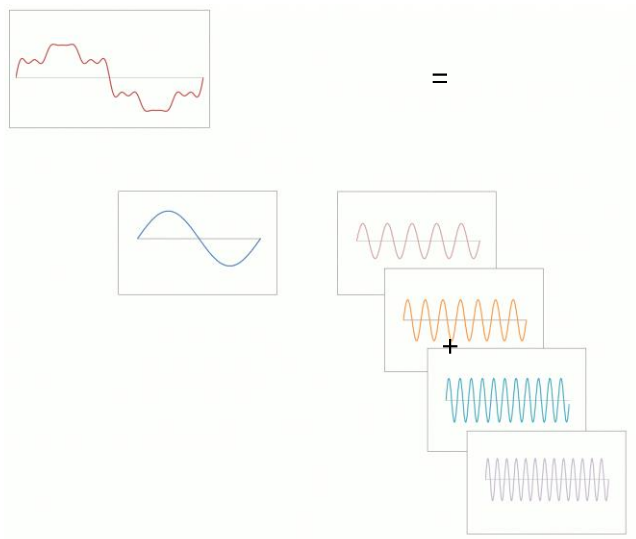


Figure 3 – Decomposition of a distorted waveform

In this way, a superposition of perfectly sinusoidal waveforms can result in a distorted waveform. Conversely, a distorted waveform can always be represented as the superposition of a fundamental frequency waveform with other waveforms of different harmonic frequencies and amplitudes. A good way to visualize the decomposition is the harmonic spectrum diagram shown in figure 4 which shows the spectrum of the distorted waveform in figure 3. This kind of spectrum is also used by almost all power quality measurement devices.

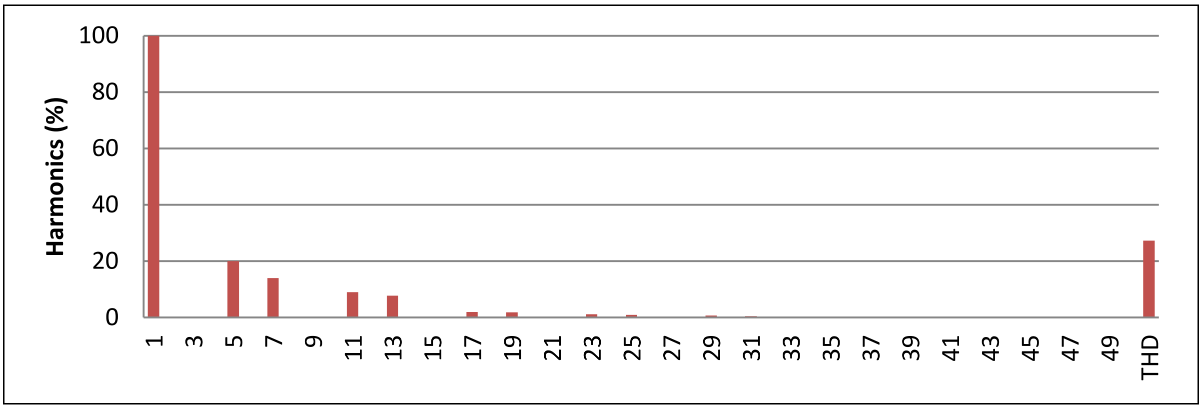


Figure 4 – Spectrum of a distorted waveform

Classification of harmonics

In terms of the type of the distorted waveform, harmonics can exist as voltage or current harmonics. There are two commonly used notions to describe them: the notion of symmetrical components and the harmonic orders. The terms odd and even harmonics are usually well known whereas the term triple harmonics might not. This term refers to the components whose orders are multiples of three. Table 2 shows harmonic orders:

	Odd	Even	Triplen
Harmonic order	5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}	2^{nd}, 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th}	3^{rd}, 9^{th}, 15^{th}, 21^{st},

Table 2 - harmonic orders

Odd harmonics are the characteristic harmonic components in today's power networks. Odd harmonics represent waveforms that are symmetrical to the time axis. Due to the usually three-phase symmetry of the present infrastructures almost all signals are symmetrical even though there is distortion. Even harmonics can only arise from waveforms that are not symmetric to the time axis. Three-phase systems, due to their configurations, have distinct harmonic signatures showing almost only odd harmonics.

Furthermore harmonics in a balanced three-phase system show a simple relation between the harmonic order and the corresponding phase sequence. Similar to the fundamental harmonics can be categorized into positive sequence harmonics, negative sequence harmonics and zero sequence harmonics. Table 3 shows the relations between symmetrical components and harmonic orders:

Symmetrical components	Positive sequence (+)	Negative sequence (-)	Zero sequence (homopolar)
Harmonic order	1	2	3
	4	5	6
	7	8	9
	10	11	12
	…	…	…
	3k+1	3k+2	3k+3
			k=0,1,2,3,…

Table 3 - symmetrical components

Positive sequence harmonics (4^{th}, 7^{th}, 10^{th}, …) have the same phase rotation as the fundamental component. These harmonics circulate between the phases. **Negative sequence harmonics** (2^{nd}, 5^{th}, 8^{th}, …) have the opposite phase rotation with respect to the fundamental component. These harmonics circulate between the phases. **Zero sequence harmonics** (3^{rd}, 6^{th}, 9^{th}, …) do not produce a rotating field. These harmonics circulate between the phase and neutral or ground. Unlike positive and negative sequence harmonic currents third order or zero sequence harmonics do not cancel but add up arithmetically in the neutral bus.

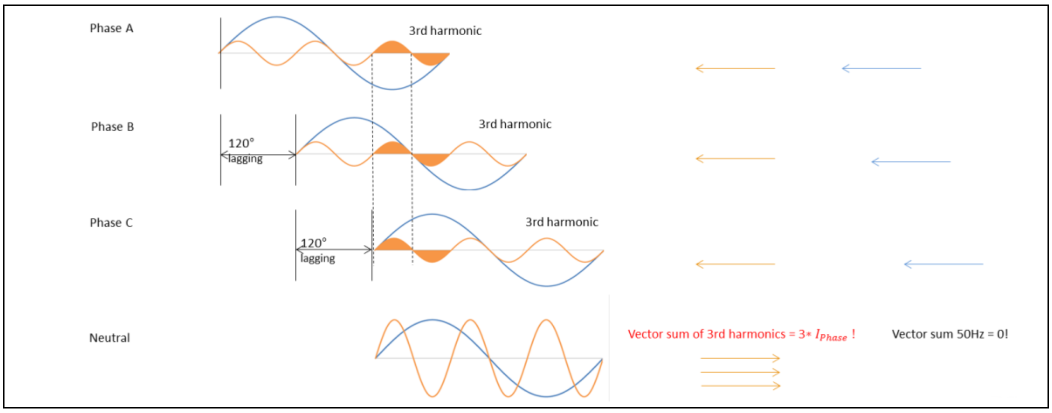


Figure 5 – Triplen harmonics on the neutral

Harmonic currents, voltage and impedance

Almost each individual device can be the source of harmonic currents. Which equipment might cause what current distortion will be explained in the linear and non-linear load section. But besides the individual current harmonics usually the total harmonic distortion at the PCC (Point of Common Coupling) is what needs to be analyzed. Thus, the interaction between current and voltage is an important topic that needs to be understood when dealing with harmonic problems and - more important - when a mitigation solution is required. The propagation of harmonic currents in a power system and the resulting voltage distortion depends on the characteristics of harmonic sources and the characteristics of all devices connected to the electrical network which needs to be analyzed. The influence of the impedance is quite easy to explain. As non-linear currents flow through an electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. This relationship is well known as Ohm's law (U=Z*I). The summation of the harmonic currents of the individual devices is not that straight forward as the total harmonic distortion of current is also depending on the phase shift between the different currents of the same frequency. This phase shift can be close to zero or close to 180 degrees causing a huge difference for the result of the summation. That's why it usually needs experts to interpret harmonic currents. High harmonic currents in a cable near a device do not automatically mean the device is the source. It might be completely different proofing the device as a victim of highly distorted voltage caused by another device or "imported" from the network.

Power quality indices under harmonic distortion

In general any harmonic component can be represented as a percentage of the fundamental (%fund) or a percentage of the rms value (%r) of the total current with the following equation:

$$\boldsymbol{I_h} = \frac{\boldsymbol{I_n}}{\boldsymbol{I_1}} * \mathbf{100}\%$$

with
$\boldsymbol{I_n}$ ...amplitude of the current harmonic n,
$\boldsymbol{I_1}$ …amplitude of the fundamental current (or the rms value of the total current)

This approach is the same for the harmonic voltages.

Total Harmonic Distortion (THD) is a widely used notion in defining the level of harmonic content in alternating signals. This value is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. This THD value is used for low, medium, and high voltage systems. Usually the current distortion is defined as THDi and the voltage distortion as THDv.

Total Harmonic Current (THC) is the accumulated currents of the orders 2 to 40 that contribute to the distortion of the current waveform. This value is particularly useful in determining the required characteristics for installation of modern active harmonic filters:

$$\mathrm{THC} = \sqrt{\sum_{n=2}^{n=40} I_n^2}$$

Total Harmonic Distortion of Current (THDi) indicates the total harmonic current distortion of the wave form. This value is defined as the ratio (in %) of the harmonic current to the fundamental (non-harmonic) current measured at a load point at the particular moment when the measurement is taken. Typically, the geometrical sum of all current harmonics is calculated in relation to the fundamental frequency current up to the 40th harmonic order:

$$\mathrm{THDi} = \frac{\sqrt{\sum_{n=2}^{n=40} I_n^2}}{I_{(1)}} * 100\% \quad = \quad \frac{\sqrt{I_{h2}^2 + I_{h3}^2 + I_{hn}^2}}{I_{h1}} * 100\% \quad = \quad \frac{THC}{I_{(1)}}$$

All harmonic currents created by the loads in the networks must flow through impedances (transformers, reactors, etc.) and all other parallel branches. There will be non-linear voltage drops at the impedances. The harmonic voltages created like that will expand across the entire network and lead to distortions of the supply voltage of other appliances. This means that harmonic distortion of the current (THDi) does also cause voltage distortions (THDv).

Total Harmonic Distortion of Voltage (THDv) indicates the total magnitude of the voltage distortion. This value is defined as the ratio (in %) of the harmonic voltage to the fundamental (non-harmonic) voltage. Typically, the geometrical sum of all voltage harmonics is calculated in relation to the fundamental frequency voltage up to the 40th harmonic order:

$$\mathrm{THDv} = \frac{\sqrt{\sum_{n=2}^{n=40} U_n^2}}{U_{(1)}} * 100\% \qquad = \qquad \frac{\sqrt{U_{h2}^2 + U_{h3}^2 + U_{hn}^2}}{U_{h1}} * 100\%$$

A low THDv is in general synonymous to a good voltage quality.

Total Demand Distortion (TDD) is an especially in North America widely used notion when it comes to harmonics. In difference to the THDi, in which the harmonic content is referred to the fundamental frequency of the rated current value, it is the ratio of the measured harmonic current to the full load fundamental current. The full load fundamental current is the total amount of non-harmonic current consumed by all of the loads on the system when the system is at peak demand. So the TDD is the THD of current (using a 15 or 30 minute averaging measurement period) normalized to the maximum demand load current. TDD equals THDi only at full load condition.

$$\mathrm{TDD} = \frac{\sqrt{\sum_{n=2}^{n=40} I_n^2}}{I_L} * 100\% \quad = \quad \frac{\sqrt{I_{h2}^2 + I_{h3}^2 + I_{hn}^2}}{I_L} * 100\% \quad = \quad \frac{THC}{I_L}$$

with I_L maximum demand load current.

Partial weighted harmonic distortion (PWHD) is the ratio of the rms value of current or voltage, weighted with the harmonic order n, of a selected group of higher order harmonics (from the order 14 to 40) to the rms value of the fundamental:

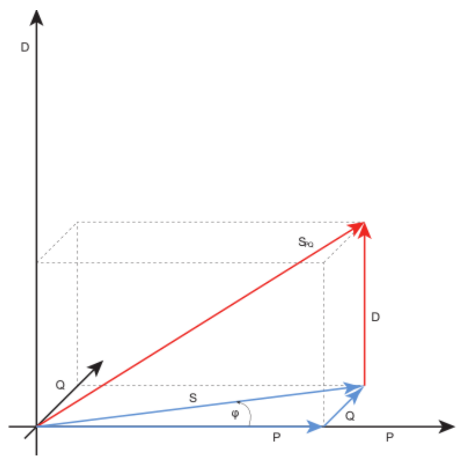
$$\mathrm{PWHD, I} = \frac{\sqrt{\sum_{n=14}^{n=40} I_n^2}}{I_{(1)}} * 100\% \quad \mathrm{or\ PWHD, U} = \frac{\sqrt{\sum_{n=2}^{n=40} U_n^2}}{U_{(1)}} * 100\%$$

Power factor and reactive power

In a three-phase system the phase voltages are displaced to each other by 120°. If the individual phases are equally loaded, the resultant current in the neutral will be zero. If the network is distorted by current harmonics, the triplen harmonics will add up in the neutral so that the current in the neutral can exceed the current of each of the individual phase currents up to factor three. The power factor is a parameter that can be affected by network disturbances such as harmonic distortion or unbalance. It gets worse with an increasing phase shift between current and voltage, and with increasing distortion of the current. It is defined as the ratio of the active power and the apparent power values $\lambda = \frac{|P|}{S}$ and thus serves as measure of the efficiency that a load is using energy. In an electric power system, a load with a high power factor draws less current than a load with a low power factor for the same amount of useful power transferred and thus has a better efficiency. Since no uniform phase shift angle can be specified in case of harmonic loads, the power factor λ and the often used cosine φ must not be equated. Based on the formula $\lambda = \frac{|P|}{S} = \frac{I_1}{I} \cos \varphi_1 = g_1 * \cos \varphi_1$, with $I_1 =$ fundamental component of the current, I= total current, $g_1 =$ fundamental factor and $\cos \varphi_1$= displacement factor, it can be shown that only in case of sinusoidal voltage and current (g=1), the power factor λ equals $\cos \varphi_1$. So the power factor λ equals the cosine of the displacement angle φ only in case of sinusoidal currents and voltages and is defined as $\cos \varphi = \frac{P}{S} =$ active factor. Non-linear loads are typically causing a bad power factor.

Reactive power – The public utilities do transport energy from the power plants to the consumers using their supply grids. The power in an electric circuit is the rate of flow of energy past a given point of the circuit. In alternating current circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power that, averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as real power. The portion of power due to stored energy, which returns to the source in each cycle, is known as reactive power. The reactive power is necessary to generate the magnetic field of machines. However, reactive power does not transfer energy but results in costs for the work it involves and transmission losses. As a consequence of this, the reactive power demand should be kept to the minimum. Based on the source of reactive power, the following types are used:

- Displacement reactive power
  - Caused by displacement of the angle between current and voltage
- Distortion reactive power
  - Caused by harmonics in current and voltage
- Modulation reactive power
  - Caused by periodic load fluctuations
- Asymmetric reactive power
  - Caused by one- or two-phase loads



$$S^2 = P^2 + Q^2$$

$$S_{PQ}^2 = S^2 + D^2$$

$$S_{PQ}^2 = P^2 + Q^2 + D^2$$

$$S_{PQ} = \sqrt{P^2 + Q^2 + D^2}$$

$$Displacement\ Power\ Factor\ DPF = \cos\varphi = \frac{P}{S}$$

$$True\ Power\ Factor\ PF = \frac{P}{S_{PQ}}$$

$$THDi = \frac{D}{S} \rightarrow PF = \frac{1}{\sqrt{1 + THDi^2}} * \cos\varphi$$

Figure 6 – Power under harmonic conditions

Linear and non-linear loads

Linear loads show voltage and current signals following each other very closely. In an AC circuit, that means that the application of a sinusoidal voltage results in a sinusoidal current. As the instantaneous voltage changes over the period of the sine wave, the instantaneous current rises and falls in proportion to the voltage so that the waveform of the current becomes also a sine wave. This behavior of voltage and current can be explained with Ohm’s law which states that the current through a resistance fed by a varying voltage source is equal to the relation between the voltage and the resistance:

$$i(t) = \frac{v(t)}{R}$$

If only linear loads would be part of an electrical network it would be simple to calculate voltage and current waveforms. Even the involved power could be easily calculated from the product of the two quantities, voltage and current. Table 4 shows some linear loads. You will see that loads with the two waveforms in phase with one another (resistive load) but also with leading voltage (inductive load) or leading current (capacitive load) are considered to be linear because even if the two waveforms are out of phase from one another, no waveform distortion can be found.

Resistive loads	**Inductive loads**	**Capacitive load**
Incandescent lighting	Induction motors	Power factor correction (PFC)
Electric heaters	Induction generators	

Table 4 - Linear loads

The explanations for linear loads easily lead to that for non-linear loads. A load is considered non-linear if the current drawn by the load will not be sinusoidal even when it is connected to a sinusoidal voltage.
Therefore, Ohm’s law cannot anymore be used to describe the relation between v and i because resistance is not a constant and current changes during each sine wave of the applied voltage waveform, resulting in a series of positive and negative pulses. Such non-linear current contains frequency components that are multiples of the power system frequency. These harmonic currents interact with the impedance of the electrical power network to create voltage distortion that can affect the power network itself and the loads connected to it. Such effects will be discussed in detail in Chapter 4. A non-linear load on a power system is typically a rectifier such as used in power supplies or some kind of arc discharge device such as a fluorescent lamp, electric welding machine, or arc furnace. The by far most common non-linear loads in today’s power systems are energy efficient variable speed drives and switched mode power supplies (SMPS). These so called power electronics with its non-sinusoidal currents are the most used devices our days. The usage of pure linear loads has decreased to a very low percentage. Table 5 provides a list of various non-linear devices.

Power electronics	Arc devices
Variable speed drives	Welding machines
Switched mode power supplies	fluorescent light ballasts
Battery chargers	ARC furnace
IT equipment	
UPS	

Table 5 - Non-linear loads

References:

(1) IEEE Std. 519-1992 IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.
(2) Baggini, A., Handbook of Power Quality, Wiley, New York, 2008.
(3) International Standard IEC 61000-4-7:2002 ed. 2.0 Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques –General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto
(4) Arrillaga, J. and Watson, N., Power Systems Harmonics, 2nd ed., Wiley, New York, 2003.

CHAPTER 2

Sources of harmonic distortion

Introduction

In general harmonic currents are the result of the non-linear behavior of electrical devices. The sources of harmonic currents and thus subsequently harmonic voltage in power systems are multiple and are varying in size (a few KVA up to several MVA) as well as significance. In earlier times devices with magnetic iron cores like transformers, generators or electric motors have been the most important group of harmonic sources. Also Arc furnaces and arc welders have been of high importance. Nowadays with the demand for energy efficient devices the group of power electronics and electronic equipment has to be considered the most serious source of harmonics. Besides the traditional industrial loads with still high harmonic producing equipment commercial and residential facilities became significant sources of harmonics. This is particularly true when the combined effects of all individual loads served by the same feeder are taken into account.

The harmonic spectra of all these non-linear loads are different but can be identified with some experience and knowledge. Thus, it is important to become familiar with the signatures of the different waveform distortions produced by specific harmonic sources. Without this knowledge the establishment of mitigation methods to lower or remove harmonics is not possible. The following chapters will give a brief overview about the most serious sources of harmonics.

Harmonic Sources with Magnetic Iron Core

Transformers

The relationship between primary voltage and current of a transformer is well known as magnetization curve. These curve is clearly non-linear and especially in the saturation area of it. Thus, a transformer under normal working condition is not a significant source of harmonics. Nevertheless in a transformer in core saturation conditions the harmonic content rises significantly containing a variety of odd harmonics, with the third dominant. Such conditions can occur when operating above rated power (usually during peak demand periods) or when operating above rated voltage with the voltage rising above nominal values (usually during light load conditions) or due to the switching of large reactive power loads (PFC). The reason for the higher harmonic content in the saturation region can easily be seen in the magnetization curve of a transformer like it is shown in figure 7. Around the nominal working point of the transformer a small voltage increase will result in a small magnetization current increase, at a voltage above the nominal voltage, a small increase will cause a large increase of the magnetization current.

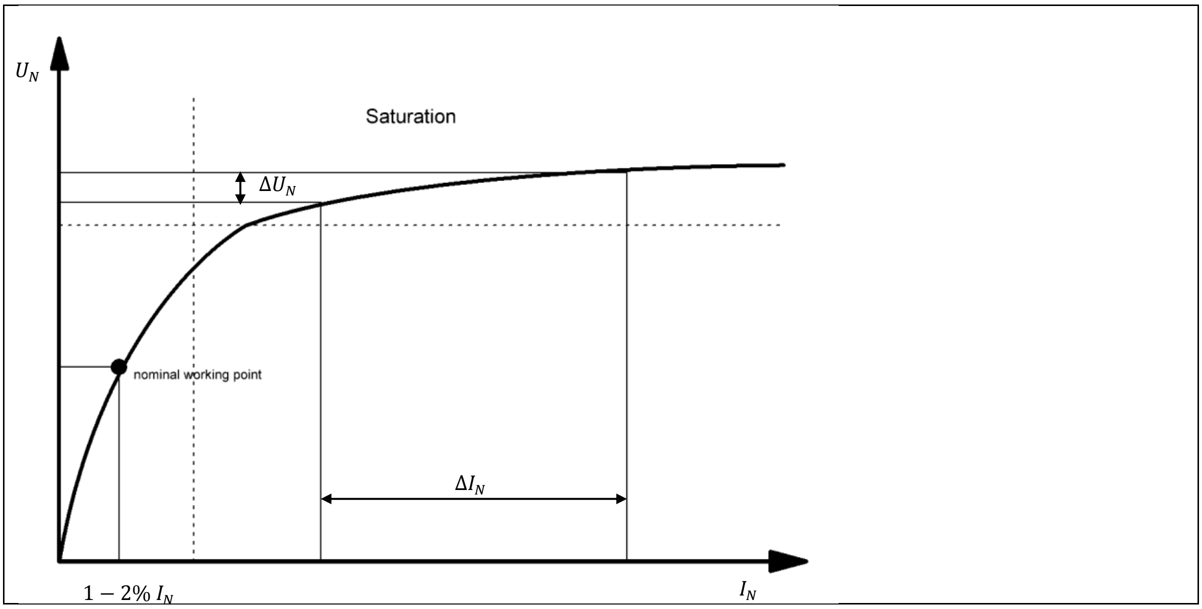


Figure 7 – transformer magnetization curve

Generators and Motors

Motors can – similar to transformers – also be a source of harmonics as they also have to produce a magnetic field. Actually the magnetization curve of a motor is much more linear than this of a transformer and thus their harmonic content is really of no concern. Only very large motors might present a reasonable harmonic source. Generators are producing slightly noticeable voltage harmonics as the spatial distribution of the stator windings is not very practical and most important not very economic. Generators are usually producing a dominant 3rd voltage harmonic which causes 3rd current harmonics to flow.

Arc furnaces and Arc Welders

Arc furnaces and welders are usually very large power consuming applications. This high power combined with a highly nonlinear voltage-current characteristic produce substantial amounts of harmonic distortion which is even worse on a “normal” PCC with a “normal” short-circuit capacity. From the technical point of view arc furnaces are operating in different phases (melting, air refining, refining) with different levels of harmonics. And, additionally they are showing a combination of ignition delays and voltage changes caused by random variations of the arc. This technical circumstances lead to a quite unusual harmonic spectrum with even and odd multiples of the fundamental frequency. These frequencies are additionally decreasing and increasing very quickly.

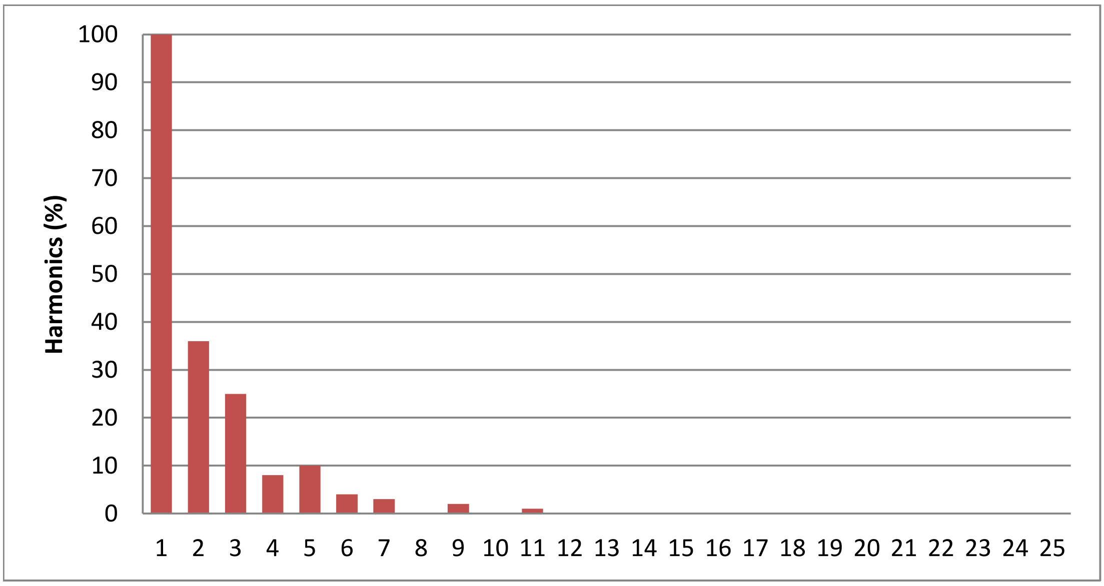


Figure 8 – harmonic current spectrum arc furnace

Power electronic and electronic equipment

Switched mode power supplies (SMPS)

Switched Mode Power Supplies can be found in most of today's electronic devices. The name is derived from the dc-to-dc switching converter for the conversion of the unregulated dc input voltage to a regulated dc output voltage. Like the old linear power supplies, switched mode power supplies do also convert unregulated ac or dc input voltage to a regulated dc output voltage. If the input supply is drawn from the ac mains, the voltage is first rectified and filtered using a capacitor at the rectifier output. This technical approach is very competitive in size, weight and cost and it allows the use in almost all applications. The main difference compared to the older linear power supplies is that the units are drawing pulses of current instead of continuous current. Those pulses contain large amounts of harmonics of the third and higher orders. A typical waveform and the resulting harmonic spectrum is shown in figure 9.

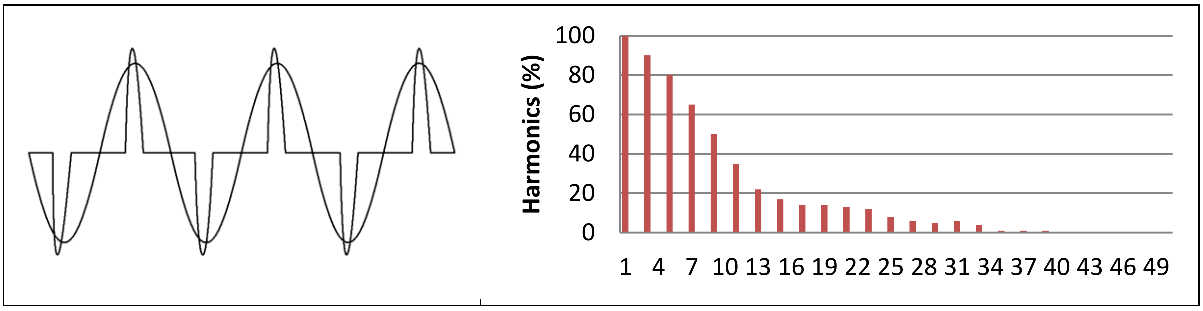


Figure 9 – waveform and harmonic spectrum of a SMPS

Variable Frequency Drives

Variable frequency drives are representing the group of equipment that is using static converters based on a three-phase bridge. This bridge is also known as six-pulse bridge or shortly named B6-bridge. The same technology is also used in UPS units or AC/DC converters, e.g. solar inverters. The name B6 is derived from the six voltage pulses per cycle which result of one pulse per half cycle per phase. As in general the harmonic spectrum is related to the number of pulses of the non-linear load (or the paths of conduction) a B6-bridge is creating current harmonics of the $6n \pm 1$orders which means $5^{th}$and 7^{th}, 11^{th} and 13^{th}, 17^{th} and 19^{th} and so on, the so called pairs with one less and one more than each multiple of 6. As already mentioned, the harmonic spectrum is depending on the number of pulses, thus the harmonic spectrum will look different if a 12- or 18-pulse converter is used. Table 6 shows this relationship. In figure 10 shows a typical waveform and the resulting harmonic spectrum of a Variable Speed drive

Number of pulses	Formula	Possible harmonics
n	$h = (n * p) \pm 1$	
2	$\mathrm{h} = (n * 2) \pm 1$	2,3,4,5,6,7, … (all)
6	$\mathrm{h} = (n * 6) \pm 1$	5,7,11,13,17,19,… (pairs)
12	$\mathrm{h} = (n * 12) \pm 1$	11,13,23,25,35,37, … (pairs)
18	$\mathrm{h} = (n * 18) \pm 1$	17,19,35,37, … (pairs)
24	$\mathrm{h} = (n * 24) \pm 1$	23,25,47,49, … (pairs)

p…number of pulses, n…integer number (1,2,3…), h…harmonic order

Table 6 – pulses and harmonic spectra

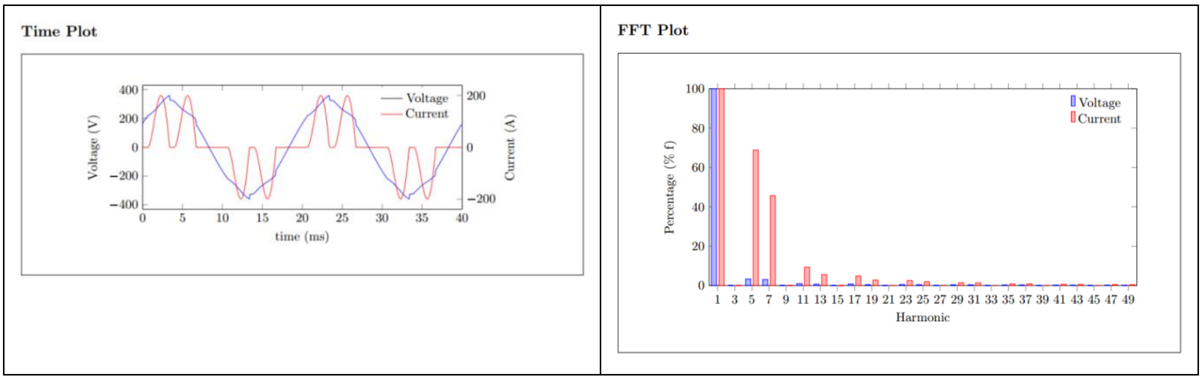


Figure 10 – waveform and harmonic spectrum of a B6-VSD

Commercial and residential facilities

According to a recent study of the EU, approx. 40 % of the total produced electrical energy is used for residential or business buildings such as apartments, office buildings, hospitals, hotels, theaters, schools, or sports facilities. It is true that the individual systems and facilities are different between the buildings but all these infrastructures have one thing in common - from an ecological but also from the economic perspective, the efficient use of energy adjusted to the actual needs is an absolute must. Today, the protection of the resources and of the environment is as important as the technical reliability of appliances, equipment, or systems. This is made possible by the use of state-of-the-art products from the building technology sector, such as dimmers, timers, motion and presence detectors, switches, thermostats, heater controls, speed-controlled drives for HVAC-systems, pumps, fans, and motors supported by intelligent and networked area and building controls. A positive energy balance is only possible if the impacts of the used system technology are compensated to their greatest extent; meaning that products and solutions must be used that reliably and efficiently handle complex mixed loads occurring in building technology. Typical loads in building technology are heating, ventilation and air-conditioning (HVAC), internal and external lighting, communication technology (telephone, faxes, network engineering), elevators, escalators, office machines (computers, screens, copy machines), building automation systems, medical equipment, audio-visual entertainment systems and safety systems (burglary, fire, smoke, gas and water damages). This creates a complex mixed load situation with escalating harmonic spectra caused by diverse and more numerous sources and which are not unique and easy to analyze. The problem becomes complicated with the increased use of sensitive electronics, computers, multimedia and digital communications. Last but not least we should not forget all kinds of renewable energy. Photovoltaic, wind, natural gas are already playing an increasingly important role in managing the electricity needs of buildings and thus adding additional harmonic content.

References:

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CHAPTER 3

Effects of harmonics

Introduction

The burdening of the network infrastructure with all these electrical and electronic consumers with harmonics has drastically increased since several years now. There is a clear tendency worldwide: Voltage distortion increases along with the increasing use of power electronics. At the other hand all the devices are highly depending on a very good power quality to work reliable and efficient. In other words, the sensitivity of the devices against current and voltage distortion has increased along with the harmonic distortion they produce. Most of the equipment is built to function with an (almost) sinusoidal voltage and current. As reality looks quite different, it is important to know what types of effects are caused by harmonics and what consequences do they have.

A good approach to generally describe the effects of harmonics is to classify them by their duration, e.g. short- or long-term effects. The short term effects of harmonics are failures or malfunctions of devices exposed to high harmonic distortion. The long-term effects of harmonics are of thermal nature. Harmonics cause a temperature rise in the electrical network as well as in the equipment. Higher temperatures of electric or electronic devices as well as of machines, cables and transformers mean beside higher losses also a much shorter lifetime.
The following chapter gives some examples for the effect of harmonics on different parameters and equipment.

Power Factor

The **power factor** is a parameter that can be affected by network disturbances such as harmonic distortion or unbalance. It gets worse with an increasing phase shift between current and voltage, and with increasing distortion of the current. It is defined as the ratio of the active power and the apparent power values $\lambda = \frac{|P|}{S}$ and thus serves as measure of the efficiency with that a load is using energy. In an electric power system, a load with a high power factor draws less current than a load with a low power factor for the same amount of useful power transferred and thus has a better efficiency. Since no uniform phase shift angle can be specified in case of harmonic loads, the power factor λ and the often used $\mathrm{cosine}\,\varphi$ must not be equated. Based on the formula $\lambda = \frac{|P|}{S} = \frac{I_1}{I}\cos\varphi_1 = g_I cos\varphi_1$, with I_1= fundamental component of the current, I= total current, g_I= fundamental factor and $\cos\varphi_1$= displacement factor, it can be shown that only in case of sinusoidal voltage and current (g=1), the power factor λ equals $\cos\varphi_1$. So the power factor λ equals the cosine of the displacement angle φ only in case of sinusoidal currents and voltages and is defined as $\cos\varphi = \frac{P}{S}$ = active factor. Non-linear loads are typically causing a bad power factor.

Phase and Neutral conductors

In a three-phase system the phase voltages are displaced to each other by 120°. If the individual phases are equally loaded, the resultant current in the neutral will be zero. If the network is distorted by current harmonics, the triplen harmonics will add up in the neutral so that the current in the neutral can exceed the current of each of the individual phase currents up to factor three. Besides this, the presence of harmonics in the current may subsequently lead to an overload in both, the phase conductors and the neutral. It is also likely to happen, that under the condition of distorted current flowing, the heat in the cables is evidently higher than under ideal conditions. This might lead to an overheating of the cables and in worst case conductors might burn.

Transformer

Transformers are serving all linear and non-linear loads. There are two main effects of harmonics for transformers, additional losses and triplen harmonic currents. The losses originate from stray magnetic losses in the core and eddy current and resistive losses in the windings. As eddy current losses increase with the square of the frequency they are of most concern when harmonics are present. These additional losses are creating extra heat significantly reducing the operating life of the transformer insulation. Especially in industrial applications with primarily non-linear loads, transformers often cannot be operated at rated power due to the high harmonic distortion.

The most common type of transformer coupling for low voltage distribution is the delta-wye. Delta–wye- or delta–delta-connected transformers trap zero sequence currents (triplen harmonics). These currents are all in phase and thus, circulating in the windings. This is increasing the rms value of the current and produce additional heat. It is important to calculate these effects when a transformer rating has to be done.

Motors and Generators

The main effect of harmonics for motors and generators is additional power losses with the result of a significantly rising temperature of the devices. The reason is the effective resistance which goes up with increasing frequency. Thus, a current distorted by harmonics will cause greater losses in the windings which subsequently result in greater heating.
Another effect mainly resulting from the negative sequence harmonics (see chapter 1) are magneto motive forces of different frequencies which are working against the normal motor shaft torque.
This may lead to higher vibrations inside the bearings with the danger of an wear out and thus subsequently an earlier equipment fatigue.

Electric and electronic equipment

This kind of equipment is more a source of harmonics than it would be considered as "victim". Nevertheless it is very well known, that electric and especially electronic devices are quite sensitive for harmonic distortion. Usually the result is abnormal function or even malfunction caused by different effects of harmonics. These effects are mainly:

- Zero crossing noise
- The increase of the maximum value of the supply voltage due to harmonics
- Digital signal misinterpretation due to harmonic disturbances
- Incorrect or no operation of IT equipment including memory losses and switch offs
- Malfunction of protective devices due to harmonic distortion

PFC

In general, voltage, temperature current and power overload stresses are the root causes of dielectric breakdowns of capacitors. These factors are known and usually the allowed overload factors (in terms of rated value ratios) are provided by the manufacturers of the capacitor banks. But power factor correction capacitors are also seriously affected by harmonics. An increase in the peak value of the voltage due to high harmonics is an additional dielectric stress which can cause a partial discharge in the insulation (a so called foil short circuit) with a permanent damage to the capacitor. More often harmonic caused capacitor issues are related to current. Because capacitive reactance is inversely proportional to frequency, the impedance towards voltage harmonics decreases with increasing harmonic orders. Thus, the currents absorbed by a capacitor with a distorted voltage present are much higher than the currents that would have been absorbed with no voltage harmonics present. Subsequently this means that a distorted voltage can lead to draw a capacitor's current that results in additional losses, accelerated aging of the insulation and could seriously and permanently damage them. The above described effects become even more serious if they are magnified by parallel or series resonance.

Circuit breakers

The main harmonic related issue with circuit breakers is nuisance tripping. An RCCB (residual current circuit breaker) is an electromechanical device which sums the current in phase and neutral conductors and if the result is not within the rated limit, disconnecting the power from the load. Due to harmonics a RCCB may not correctly sum up the high frequency components and thus, trip erroneously. Another reason for tripping is indirectly related to harmonics. The main harmonic causing equipment is usually also generating switching noise. Such switching noise has usually to be filtered at the equipment power connection. The architecture of such filters shows capacitors from line and neutral to ground causing a small leakage current to earth. This current is usually much lower than 3.5 mA which is the limit given by international standards. This limit can be exceeded in circuits where such equipment is connected to just one circuit. As nuisance tripping may cause production shut down or interruption with corresponding time required to start the installation up again, it is a very serious and costly effect of harmonics.

References:

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CHAPTER 4

Norms and Standards for harmonics

Overview

The reason to establish harmonic standards and limits is easy to see. The harmonic injection into the network has to be limited in order to provide a voltage quality with acceptable distortion levels. As already described in the previous chapters, the harmonic current injection of each individual customer need to be limited in order to not cause a voltage distortion of the overall system. Harmonic emissions are subject to various standards and regulations:

- Emissions standards applying to the equipment causing harmonics
- Compatibility standards for distribution networks
- Recommendations issued by utilities and applicable to installations

These standards will be described in the next chapters.

Standards governing equipment

Standard IEC 61000-3-2 for low-voltage equipment with rated current under or equal to 16 A

IEC 61000-3-2 deals with the limitation of harmonic currents injected into the public supply system by any appliances with a rated current under or equal to 16 A per phase and intended to be connected to public low voltage distribution systems. It specifies limits of harmonic components of the input current which may be produced by equipment tested under specified conditions. The objective of this standard is to set limits for harmonic emissions of equipment within its scope, so that, with due allowance for the emissions from other equipment, compliance with the limits ensures that harmonic disturbance levels do not exceed the compatibility levels defined in IEC 61000-2-2. For the purpose of harmonic current limitation, equipment is classified into 4 classes:

Class A:
- Balanced three-phase equipment
- Household appliances, excluding equipment identified as class D
- Tools, excluding portable tools
- Dimmers for incandescent lamps
- Audio equipment
- Equipment not specified in one of the three other classes shall be considered as class A equipment.

Class B:
- Portable tools
- Arc welding equipment which is not professional equipment

Class C:
- Lighting equipment

Class D:
- Equipment having a specified power less than or equal to 600 W, of the following types:
    - Personal computers and personal computer monitors
    - Television receivers

The limits for class A equipment is shown in Table 7. The limits refer to fixed values for harmonic currents 2nd to 40th order. For class B equipment these limits can be multiplied by a factor of 1.5. Table 8 is showing the limits for class C equipment having an active power greater than 25W. The maximum permissible harmonic currents are given as a percentage of the fundamental input current. For class C equipment with an input power smaller or equal than 25W either the limits of table 8 apply, or the third harmonic current shall not

exceed 86% and the fifth harmonic current shall not exceed 61% of the fundamental current (for further details refer to the standard).
For class D equipment the limits are shown in table 9 as a power related current (mA/W).

Harmonic order n	Maximum permissible harmonic current A
	Odd harmonics
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
15 ≤ n ≤ 39	$0.15 * \frac{15}{n}$
Even harmonics	
2	1.08
4	0.43
6	0.30
8 ≤ n ≤ 40	$0.23 * \frac{8}{n}$

Table 7 – 61000-3-2 Limits for class A equipment

Harmonic order n	Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency
2	2
3	30* λ (λ… circuit power factor)
5	10
7	7
9	5
11 ≤ n ≤ 39	3
(odd harmonics only)	

Table 8 – 61000-3-2 Limits for class C equipment

Harmonic order n	Maximum permissible harmonic current per Watt mA/W	Maximum permissible harmonic current A
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13 ≤ n ≤ 39	$\frac{3.85}{n}$	See table 1
(odd harmonics only)		

Table 9 – 61000-3-2 Limits for class D equipment

Standard IEC 61000-3-12 for low-voltage equipment with rated current higher than 16 A and lower than 75 A

Standard IEC 61000-3-12 deals with the limitation of harmonic currents injected into the public supply system. The limits given in this International Standard are applicable to electrical and electronic equipment with a rated input current exceeding 16 A and up to and including 75 A per phase, intended to be connected to public low-voltage AC distribution systems of the following types:

- Nominal voltage up to 240 V, single-phase, two or three wires
- Nominal voltage up to 690 V, three-phase, three or four wires
- Nominal frequency 50 Hz or 60 Hz.

Other distribution systems are excluded. The limits given in this standard apply to equipment when connected to 230/400 V, 50 Hz systems. The harmonic current limits specified in the tables apply to each of the line currents and not to current in the neutral conductor. For equipment with multiple rated currents, an assessment is made for each current.
The harmonic current limits are specified in Tables 10 to 13. Equipment complying with the harmonic current emission limits corresponding to a short circuit ratio R_{SCE} = 33 is suitable for connection at any point of the supply system. The short circuit ratio can be calculated by

- $R_{SCE} = \frac{S_{SC}}{(3*S_{equ})}$ for single-phase equipment
- $R_{SCE} = \frac{S_{SC}}{(2*S_{equ})}$ for interphase equipment
- $R_{SCE} = \frac{S_{SC}}{S_{equ}}$ for all three-phase equipment

With

S_{SC} = short-circuit power value of the three-phase short-circuit power calculated from the nominal interphase system voltage $U_{Nominal}$ and the line impedance Z at the power frequency of the system at the PCC:

$$S_{SC} = \frac{U_{Nominal}^2}{Z}$$

S_{equ} = value calculated from the rated current I_{equ} of the piece of equipment stated by the manufacturer and the rated voltage U_p (single phase) or U_i(interphase) as follows:

- $S_{equ} = U_p * I_{equ}$ for single-phase equipment
- $S_{equ} = U_i * I_{equ}$ for interphase equipment
- $S_{equ} = \sqrt{3}U_i * I_{equ}$ for balanced three-phase equipment
- $S_{equ} = \sqrt{3}U_i * I_{equ\,max}$ for unbalanced three-phase equipment, where $I_{equ\,max}$ is the maximum of the rms currents flowing in any one of the three phases

I_{equ}= the equipment input current of the piece of equipment as declared by the manufacturer and marked as such on the rating plate of the piece of equipment or stated in the product documents.

For more detailed information, please refer to the standard documentation.

Minimum R_{SCE}	**Admissible individual harmonic current $\frac{I_h}{I_{ref}}$ %**						**Admissible harmonic parameters %**	
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	THC/I_{ref}	PWHC/I_{ref}
33	21.6	10.7	7.2	3.8	3.1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥350	41	24	15	12	10	8	47	47

The relative values of even harmonics up to order 12 shall not exceed 16/h %. Even harmonics above order 12 are taken into account in THC and PWHC in the same way as odd order harmonics.
Linear interpolation between successive R_{SCE} values is permitted.
I_{ref}= reference current; I_h = harmonic current component

Table 10 – 61000-3-12 Current emission limits for equipment other than balanced three-phase equipment

Minimum R_{SCE}	**Admissible individual harmonic current $\frac{I_h}{I_{ref}}$ %**				**Admissible harmonic parameters %**	
	I_5	I_7	I_{11}	I_{13}	THC/I_{ref}	PWHC/I_{ref}
33	10.7	7.2	3.1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46
The relative values of even harmonics up to order 12 shall not exceed 16/h %. Even harmonics above order 12 are taken into account in THC and PWHC in the same way as odd order harmonics. Linear interpolation between successive R_{SCE} values is permitted.						
I_{ref}= reference current; I_h = harmonic current component						

Table 11 – 61000-3-12 Current emission limits for balanced three-phase equipment

Table 12 may be used with balanced three-phase equipment if any one of these conditions is met:

a) The 5th and 7th harmonic currents are each less than 5% of the reference current during the whole test observation period.
b) The design of the piece of equipment is such that the phase angle of the 5th harmonic current has no preferential value over time and can take any value in the whole interval [0°, 360°].
c) The phase angle of the 5th harmonic current related to the fundamental phase-to-neutral voltage is in the range of 90° to 150° during the whole test observation period.

Minimum R_{SCE}	**Admissible individual harmonic current $\frac{I_h}{I_{ref}}$ %**				**Admissible harmonic parameters %**	
	I_5	I_7	I_{11}	I_{13}	THC/I_{ref}	PWHC/I_{ref}
33	10.7	7.2	3.1	2	13	22
≥120	40	25	15	10	48	46
The relative values of even harmonics up to order 12 shall not exceed 16/h %. Even harmonics above order 12 are taken into account in THC and PWHC in the same way as odd order harmonics. Linear interpolation between successive R_{SCE} values is permitted.						
I_{ref}= reference current; I_h = harmonic current component						

Table 12 – 61000-3-12 Current emission limits for balanced three-phase equipment under specified conditions (a,b,c)

Table 13 may be used with balanced three-phase equipment if any one of these conditions is met:

a) The 5th and 7th harmonic currents are each less than 3% of the reference current during the whole test observation period.
b) The design of the piece of equipment is such that the phase angle of the 5th harmonic current has no preferential value over time and can take any value in the whole interval [0 °, 360 °].
c) The phase angle of the 5th harmonic current related to the fundamental phase-to-neutral voltage is in the range of 150° to 210° during the whole test observation period.

Minimum R_{SCE}	**Admissible individual harmonic current $\frac{I_h}{I_{ref}}$ %**											**Admissible harmonic parameters %**	
	I_5	I_7	I_{11}	I_{13}	I_{17}	I_{19}	I_{23}	I_{25}	I_{29}	I_{31}	I_{35}	I_{37}	THC/I_{ref}	PWHC/I_{ref}
33	10.7	7.2	3.1	2	2	1.5	1.5	1.5	1	1	1	1	13	22
≥250	25	17.3	12.1	10.7	8.4	7.8	6.8	6.5	5.4	5.2	4.9	4.7	35	70

For R_{SCE} equal to 33, the relative values of even harmonics up to order 12 shall not exceed 16/*h* %. The relative values of all harmonics from I_{14} to I_{40} not listed above shall not exceed 1 % of I_{ref}.

For R_{SCE} ≥ 250, the relative values of even harmonics up to order 12 shall not exceed 16/*h* %. The relative values of all harmonics from I_{14} to I_{40} not listed above shall not exceed 3 % of I_{ref}.

Linear interpolation between successive R_{SCE} values is permitted.

I_{ref} = reference current; I_h = harmonic current component

Table 13 – 61000-3-12 Current emission limits for balanced three-phase equipment under specified conditions (d,e,f)

Standards governing the quality of distribution networks

Standard EN 50160

The main document dealing with the quality of the distribution in Europe and some other parts of the world is standard EN 50160. It characterizes voltage parameters of electrical energy in public distribution systems and gives the main voltage parameters and their permissible deviation ranges at the customer's point of common coupling (PCC) in public low voltage (LV), medium voltage (MV) and high voltage (HV) electricity distribution systems, under normal operating conditions. It is thus defining a so called minimum quality of power available to the user's equipment at the PCC. This minimum quality is required to have a good chance to get the installed equipment work correctly. The limits given in EN 50160 must be guaranteed by the supplier. However, as mentioned before, for many consumers, even fulfilling the requirements given in EN 50160 does not automatically mean a satisfactory level of PQ without any issues. The voltage characteristics within this standard are defined in terms of frequency, magnitude, waveform and symmetry and include definitions and in some cases measurement methods and compliance levels for 10 characteristics of the supply voltage:

- Power frequency
- Supply voltage variations
- Rapid voltage changes and Flicker
- Supply voltage dips
- Short interruptions
- Long interruptions
- Temporary and transient overvoltages
- Supply voltage unbalance
- Harmonic voltage
- Mains signaling voltage

The harmonic voltage requirements under normal operating conditions are defined for periods of each one week and 95 % of the 10 min mean rms values of each individual harmonic voltage shall be less than or equal to the values given in Table 14. Resonances may cause higher voltages for an individual harmonic. Moreover, the THD of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8 %.

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative amplitude U_h	Order h	Relative amplitude U_h	Order h	Relative amplitude U_h
5	6.0%	3	5.0%	2	2.0%
7	5.0%	9	1.5%	4	1.0%
11	3.5%	15	0.5%	6..24	0.5%
13	3.0%	21	0.5%		
17	2.0%				
19	1.5%				
23	1.5%				
25	1.5%				

NOTE No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.

Table 14 – Values of individual harmonic voltages at the supply terminals given in percent of the fundamental voltage u_1

Standard IEEE 519

IEEE519 presents a joint approach between Utilities and customers to limit the impact of non-linear loads. This recommended practice intends to establish goals for the design of electrical systems that include both linear and nonlinear loads. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling; and observance of the design goals will minimize interference between electrical equipment. This recommended practice addresses steady-state limitation. Transient conditions exceeding these limitations may be encountered. This document sets the quality of power that is to be provided at the point of common coupling.
The philosophy of developing harmonic limits in IEEE519 is to:

a) Limit the harmonic injection from individual customers so that they will not cause unacceptable voltage distortion levels for normal system characteristics

b) Limit the overall harmonic distortion of the system supplied by the utility

Table 15 lists the basis for harmonic current limits while table 16 lists the harmonic current limits based on the size of the load with respect to the size of the power system to which the load is connected. The ratio I_{SC}/I_L is the ratio of the short-circuit available at the point of common coupling (PCC), to the maximum fundamental load current. IEEE standard 519-1992 also introduces the total demand distortion (TDD), the harmonic current distortion in % of maximum demand load current (15 or 30 min demand). The limits listed in Tables 10-3, should be used as system design values for the worst case for normal operation (conditions lasting longer than one hour). For shorter periods, during start-ups or unusual conditions, the limits may be exceeded by 50%.

SCR at PCC	Maximum individual frequency voltage harmonic (%)	Related Assumption
10	2.5-3.0	Dedicated system
20	2.0-2.5	1-2 large customers
50	1.0-1.5	A few relatively large customers
100	0.5-1.0	5-20 medium-size customer
1000	0.05-0.10	Many small customers

Table 15 – Basis for harmonic current limits

Maximum Harmonic Current Distortion in Percent of I_L

Individual harmonic order (odd harmonics)						
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonic are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a dc offset, e.g. half-wave converters are not allowed.						
*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L						
Where I_{SC}= maximum short-circuit current at PCC. I_L= maximum demand load current (fundamental frequency component) at PCC.						

Table 16 –current distortion limits for general distribution systems (120V through 69000V)

Table 17 shows the voltage distortion limits which should be used as system design values. As the current limits these values are also meant for the "worst case" for normal system operation.

Bus voltage at PCC	Individual voltage distortion (%)	Total voltage distortion THD (%)
69KV and below	3.0	5.0
69.001KV through 161KV	1.5	2.5
161.001KV and above	1.0	1.5

Table 17 –voltage distortion limits

Standard G5/4

Engineering Recommendation G5/4 for UK and Hong Kong sets the planning levels for harmonic voltage distortion to be used in the process for the connection of non-linear equipment. These planning levels are set with respect to harmonic voltage distortion compatibility levels. For systems less than 35kV these are set by International Standards. For systems above 35kV by the compatibility levels appropriate to the UK. A process for establishing individual customer emission limits based on these planning levels is described. The planning levels of harmonic voltage distortion should not normally be exceeded when considering the connection of non-linear loads and generating plant to Transmission Systems under the Grid Codes, or to Distribution Networks under the Distribution Codes. Table 18 shows the summary of THD planning levels while table 19 lists the planning levels for harmonic voltages in 400V systems and table 20 the current harmonic limits for loads rated >16A per phase.

System Voltage at the PCC	THD Limit
400V	5%
6.6, 11 and 20kV	4%
22kV to 400kV	3%

Table 18 – Summary of THD planning levels

Odd harmonics				**Even harmonics**	
Not multiples of 3		Multiples of 3			
Order h	Harmonic voltage (%)	Order h	Harmonic voltage (%)	Order h	Harmonic voltage (%)
5	4.0	3	4.0	2	1.6
7	4.0	9	1.2	4	1.0
11	3.0	15	0.3	6	0.5
13	2.5	21	0.2	8	0.4
17	1.6	>21	0.2	10	0.4
19	1.2			12	0.2
23	1.2			>12	0.2
25	0.7				
>25	$0.2+0.5\,(\frac{25}{h})$				

Table 19 – Planning levels for harmonic voltages in 400V systems

Harmonic order h	**Emission current I_h**	**Harmonic order h**	**Emission current I_h**	**Harmonic order h**	**Emission current I_h**	**Harmonic order h**	**Emission current I_h**
2	28.9	**15**	1.4	**28**	1.0	**41**	1.8
3	48.1	**16**	1.8	**29**	3.1	**42**	0.3
4	9.0	**17**	13.6	**30**	0.5	**43**	1.6
5	28.9	**18**	0.8	**31**	2.8	**44**	0.7
6	3.0	**19**	9.1	**32**	0.9	**45**	0.3
7	41.2	**20**	1.4	**33**	0.4	**46**	0.6
8	7.2	**21**	0.7	**34**	0.8	**47**	1.4
9	9.6	**22**	1.3	**35**	2.3	**48**	0.3
10	5.8	**23**	7.5	**36**	0.4	**49**	1.3
11	39.4	**24**	0.6	**37**	2.1	**50**	0.6
12	1.2	**25**	4.0	**38**	0.8		
13	27.8	**26**	1.1	**39**	0.4		
14	2.1	**27**	0.5	**40**	0.7		
These limits are based on a typical fault level of 10MVA. See the standard for more details.							

Table 20 – max permissible harmonic current emissions in amperes RMS for aggregate loads and equipment rated >16A per phase

Standard D.A.CH.CZ

Network operators must have the possibility of keeping the network disturbances, caused by the electrical devices and generating stations connected to their networks and their consequences, within tolerable limits, even under changing framework conditions (See EN50160). For the purpose of an appropriate distribution of the resulting responsibility, the following fields of action come into consideration:

- Suitable design and operative measures in the networks, considering the objective quality requirements and the economic justification.

- An adapted setting of limiting values for requirements on electrical devices and equipment in the relevant EMC-standards as well as their observance.

- If necessary, the imposed duty to take remedial measures to reduce network disturbances

Thus D.A.CH.CZ is defining technical Rules for the assessment of network disturbances in Germany (D), Austria (A), Switzerland (CH) and the Czech Republic (CZ) and is also taken into account in the Technical and Organizational Regulations (TOR) in Austria, in the Regulator ordinance No. 306 in the Czech Republic, in the “Regeln für den Zugang zu Verteilungsnetzen“ (Distribution Code) in Switzerland and in the German “Technische Anschlussbedingungen (TAB).

All types of network disturbances are to be assessed at the point of common coupling V. In every case, the assessment bases on the short-circuit power S_{kV} at the point of common coupling. For the determination of the short-circuit power, one takes into consideration those normal operating conditions, that produce the smallest short-circuit power. Temporary special operational switching states are not taken into account. The network impedance at the point of common coupling V comprises of the impedance of the higher-level network as well as of the impedances of transformers and lines. Within D.A.CH.CZ. technical rules and limits mainly for voltage changes and flicker, voltage unbalance and harmonics are described and listed.

Table 14 shows the values of individual harmonic voltages at the supply terminals as they are defined in EN50160. In order to be able to satisfy these harmonic levels at the supply terminals (usually the low-voltage bus bar of the transformer), the maximum permissible levels must be smaller. To ensure, that the standardized compatibility level for harmonic voltages can be observed, it is necessary to limit the harmonic currents $I\nu$ from the individual installations of the network users. The harmonic voltage results from the corresponding harmonic current and the network impedance for the relevant harmonic. For this, emission limits both for several individual harmonic currents as well as for the total harmonic current are established. Figure 11 shows the harmonic assessment scheme of D.A.CH.CZ. For further details please refer to D.A.CH.CZ. itself in the chapters mentioned in the brackets.

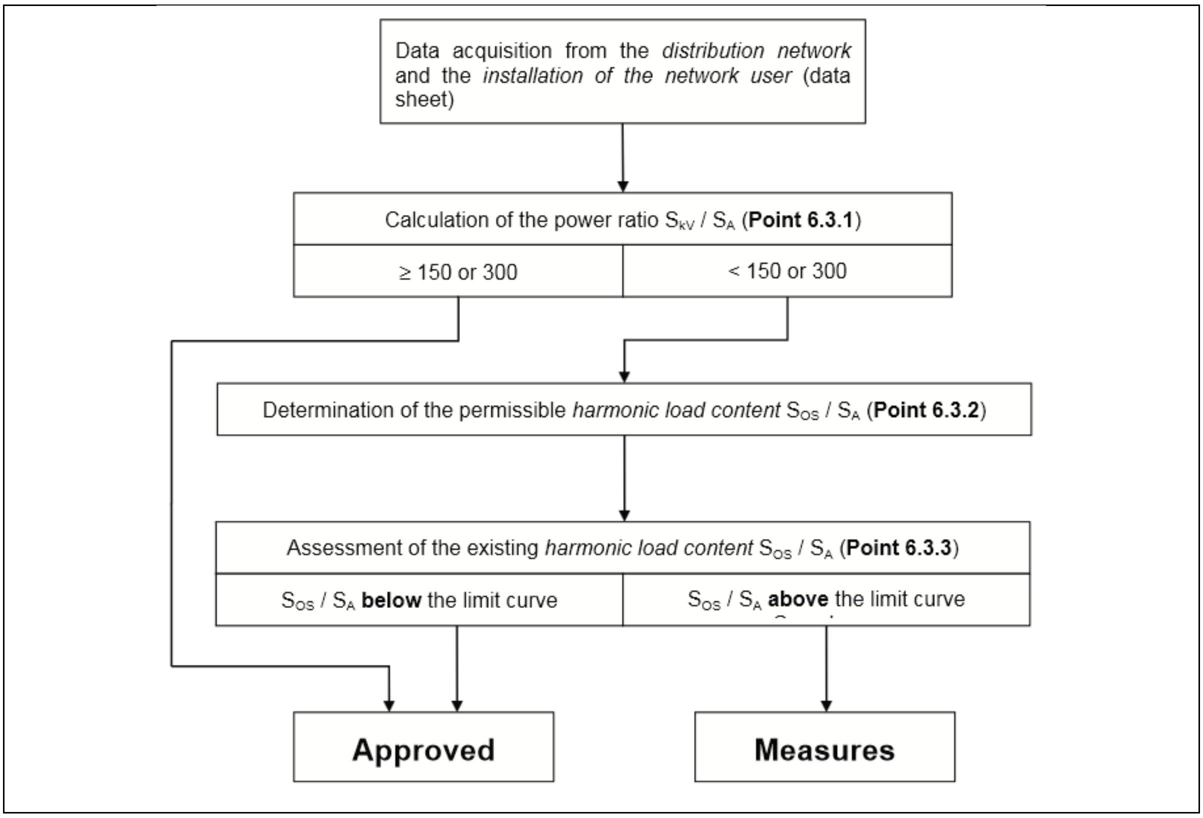

Figure 11 – D.A.CH.CZ. harmonic assessment scheme

Standards governing compatibility between distribution networks and products

These standards determine the necessary compatibility between distribution networks and products:

- The harmonics caused by a device must not disturb the distribution network beyond certain limits
- Each device must be capable of operating normally in the presence of disturbances up to specific levels

Standard IEC 61000-2-2 for public low-voltage power supply systems

The compatibility levels for low frequency conducted disturbances on low voltage networks are defined by IEC 61000-2-2. To ensure compatibility, LV equipment must have immunity levels exceeding the compatibility levels. Also the cumulative effect of emissions should not result in disturbances that exceed the compatibility levels. At present compatibility levels have not been provided for anything other than LV supplies. Thus arguably it is only IEC 61000-2-2 that could be used as a comparison with the quality of power delivered by the ESI. However, it is not a standard for power quality. Essentially, within Europe, it is the CENELEC standard EN 50160 that the ESI uses to define the power quality, in terms of voltage characteristics, that can be expected under normal supply conditions. EN50160 defines maximum acceptable levels for Medium (<35kV) and Low (<1kV) voltage systems. In general the compatibility levels set by IEC 61000-2-2 are comparable to, or slightly less stringent than, those defined by EN50160.

Standard IEC 61000-2-4 for LV and MV industrial installations

This part of IEC 61000 is concerned with conducted disturbances in the frequency range from 0 kHz to 9 kHz. It gives numerical compatibility levels for industrial and non-public power distribution systems at nominal voltages up to 35 kV and a nominal frequency of 50 Hz or 60 Hz. Compatibility levels are specified for electromagnetic disturbances of the types which can be expected at any in-plant point of coupling within industrial plants or other non-public networks, for guidance in
a) limits to be set for disturbance emission into industrial power supply systems;
b) the choice of immunity levels for the equipment within these systems.

References:

(1) EN 50160, Voltage characteristics of electricity supplied by public distribution systems, 2011
(2) Technische Anschlussbedingungen (Technical requirements of connection), VDEW
(3) IEEE Std. 519-1992: Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.
(4) IEC 61000-3-2 Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current <= 16 A per phase) (IEC 61000-3-2:2005 + A1:2008 + A2:2009); German version EN 61000-3-2:2006 + A1:2009 + A2:2009
(5) IEC 61000-3-12 ed. 2 Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤ 75 A per phase
(6) IEC 61000-4-30, 2003: Power quality measurement methods
(7) IEC 61000-2-2: Electromagnetic compatibility — part 2-2, environment compatibility levels for low-frequency conducted disturbances and signaling in public and low voltage
(8) Engineering Recommendation G5/4-2
(9) D-A-CH-CZ- Technical Rules for the Assessment of Network Disturbances, VSE 2007
(10) IEC 61000-2-2 ed. 2 Electromagnetic compatibility (EMC) - Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems
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CHAPTER 5

Harmonic Filtering Techniques

Overview

If you carefully read the previous chapters you can see a lot of reasons why harmonic mitigation is a must rather than a nice to have. For sure it is a must if standards and regulations are forcing actions but it should be also clear that additional losses and the many issues caused by harmonics are a same clear reason to think about harmonic mitigation. The mitigation techniques for power system harmonics can be separated into two categories. First category is including preventive or so called precautionary solutions and second category is including corrective or so called remedial solutions. The following chapters are explaining the techniques including pros and cons of each.

Preventive solutions

Preventive solutions aim to avoid harmonics and their consequences. These technical solutions mainly focus on the reduction of the harmonic emission from non-linear loads. They usually concern modifications in the structure or technology of the loads. The two most popular methods are the use of AC line reactors or DC link chokes with conventional converter systems and the use of multi-pulse converter systems.

AC line reactor

The use of AC line reactors leads to a significantly lower current distortion of converters. Basically a reactor is an inductor which forms a magnetic field around a coil with wires when current flows through it. When energized, it is an electric magnet with the strength of the field being proportional to the amperage flowing and the number of turns. A simple loop of wire is an air core inductor; more loops give a higher inductance rating. Beside the attenuation of harmonics they also are able to absorb voltage transients which may otherwise cause a VFD to trip on overvoltage. AC Line reactors have to be connected in series at the input of typically converter-based devices (VFDs) as they insert series inductive reactance into the circuit. The magnitude of harmonic distortion and the actual spectrum of harmonics depend on the effective impedance that the reactor represents in relation to the load. For reasonable harmonic attenuation, a 4% impedance line reactor has proved to be state of the art. Figure 12 shows an example with an applied AC line reactor on a six-pulse rectifier.

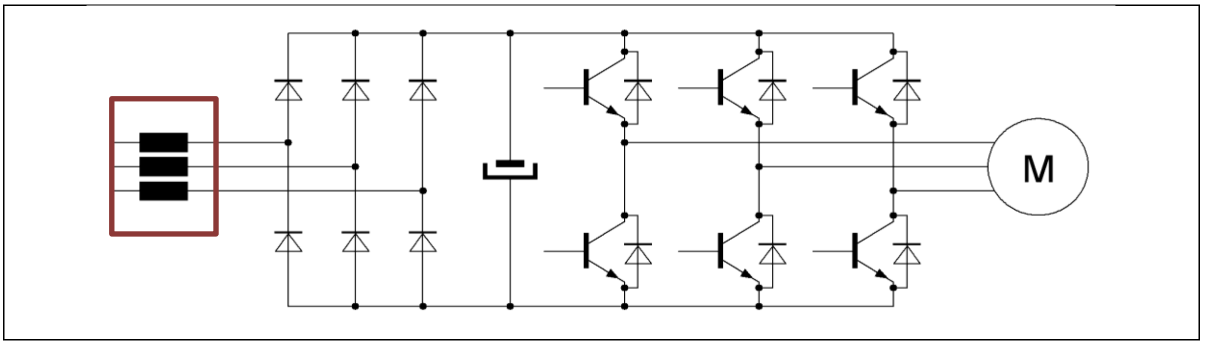

Figure 12 – AC line reactor applied

Line reactors are causing a voltage drop which subsequently slightly increases system losses. With reasonable impedance values line reactors do not achieve current distortion levels much below 35% THD-I. Additionally, the harmonic mitigation capabilities of the reactor reduce proportionately as load current is reduced because the reactor's effective percent impedance is reduced. At full load, a 4% effective impedance reactor achieves harmonic distortion of 37% THDi, while, at 50% load it's effective impedance is only 2.0% {0.5 x 4% = 2.0%}, and THDi will be around 53%. Table 21 shows the input impedance vs. remaining harmonics [%] of AC line reactors for each harmonic number.

Harmonic order	Harmonic Percent Total Input Impedance					
	0.5%	1%	1.5%	2%	3%	4%
5th	80%	60%	51%	46%	40%	34%
7th	60%	37%	28%	22%	17%	13%
11th	18%	13%	11%	9%	7.5%	6.5%
13th	10%	8%	6.5%	6%	5%	4.2%
17th	7.5%	5%	4%	3.6%	3%	2.4%
19th	6%	4%	3.3%	3%	2.3%	2%
23rd	5%	3%	2.6%	2%	1.5%	1.3%
25th	2.3%	2%	1.6%	1.3%	1.1%	1%
%THDi	103%	72%	60%	53%	44%	37%

Table 21 – AC Line reactors – Harmonic number / Input impedance vs. remaining harmonics [%]

DC link choke

DC Link Chokes are a cost effective way of filtering the DC bus voltage and current in a VSD. DC link chokes are installed between the input rectifier and bus capacitor to improve the DC bus waveform and the AC input waveform. A DC link choke is simply an inductor in the ripple filter circuit, ahead of the DC bus capacitors. The added inductance limits the rate of change of line current relative to time (di/dt) into the capacitors. This results in lower peak currents. A DC link choke is capable to reduce current distortion typically by 40% to 60%. Figure 13 shows an applied DC link choke in a six-pulse rectifier.

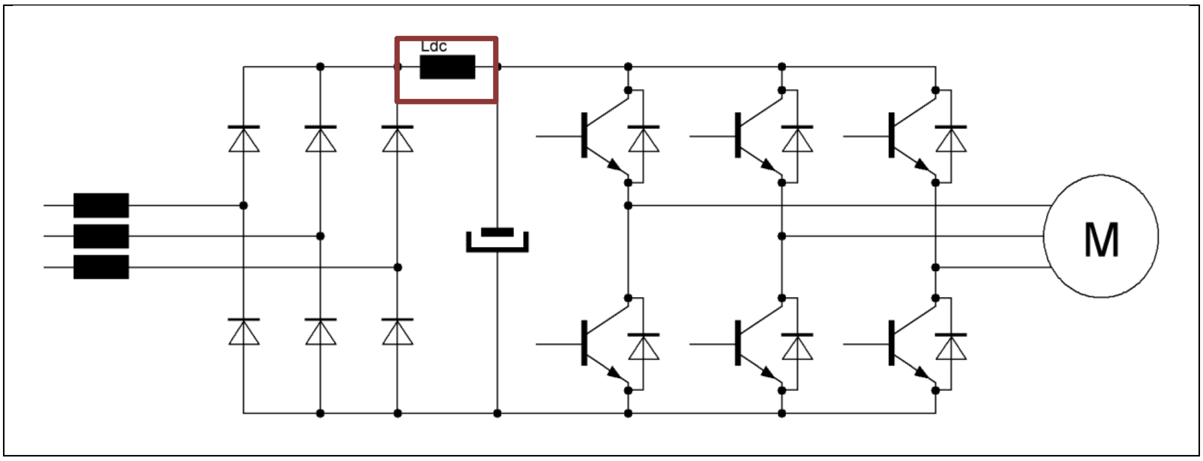

Figure 13 – DC link choke applied

Multi-pulse converter systems

Increasing the number of pulses in a converter has a direct impact on the current distortion factor and thus on the harmonics in the power system. The technical approach is to connect converters of lower numbers of pulses together. Higher pulse order front-end, particularly used in large horsepower configurations are 12 and 18, and 24-pulse designs, which – if properly designed - extend the first characteristic harmonic to the 11th or 17th or 23rd, respectively. In a 12-pulse configuration, the front-end rectifier circuit uses 12 diodes instead of six, in an 18-pulse configuration 18 diodes instead of six and subsequently in a 24-pulse 24 diodes are used instead of six. Table 22 shows the different harmonic spectra with different numbers of pulses (paths of conduction).

Number of pulses	Formula	Possible harmonics
n	$h = (n * p) \pm 1$	
1	$h = (n * 1) \pm 1$	2,3,4,5,6,7,… (all)
2	$h = (n * 2) \pm 1$	3,5,7,9,… (odd)
6	$h = (n * 6) \pm 1$	5,7,11,13,17,19,… (pairs)
12	$h = (n * 12) \pm 1$	11,13,23,25,35,37,… (pairs)
18	$h = (n * 18) \pm 1$	17,19,35,37,… (pairs)
24	$h = (n * 24) \pm 1$	23,25,47,49,… (pairs)
p…number of pulses n…integer number (1,2,3…) h…harmonic order		

Table 22-harmonics vs. pulse-numbers

The multi-pulse operation is realized by the series or parallel connection of 6-pulse converters with an appropriate phase shift between the voltages supplying the diode bridges. Figure 14 shows a 12-pulse setup with a required phase shift of 30 degrees. Figure 15 shows an 18-pulse setup with a required phase shift of 20 degrees.

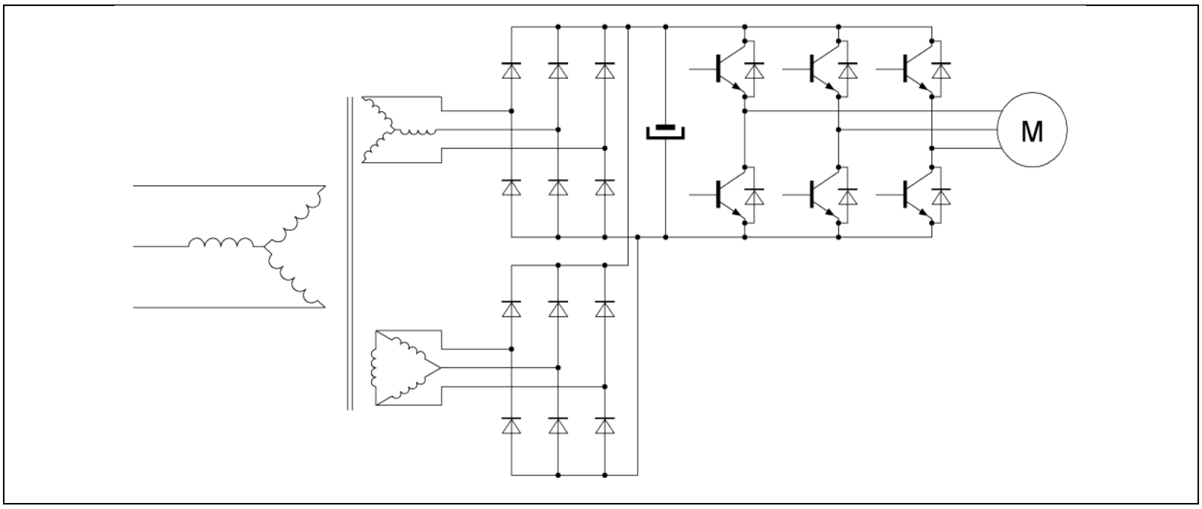

Figure 14 – 12-pulse setup

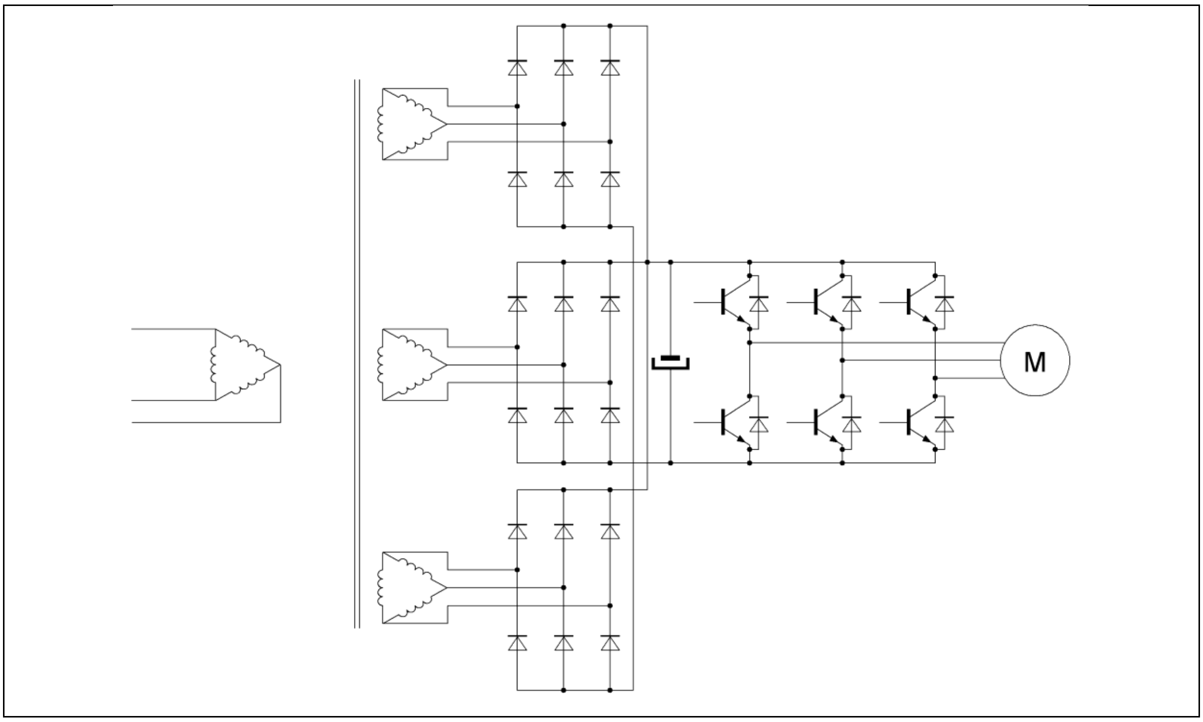

Figure 15 – 18-pulse setup

The reduction of lower order current harmonic magnitudes is evident using 12-pulse or higher setups. Practically, such setups are often causing so called non-characteristic harmonics, e.g. 5^{th} or 7^{th} harmonic with a 12-pulse setup. The reason is mainly the imprecise phase shift of the voltages. But also unbalance and distortion within the voltages as well as the asymmetrical control of the bridges may cause such effects. Such systems have large footprints and contain more steel and copper leading to higher overall losses. Costs and construction are significantly higher due to the requirement for a transformer with two or three phase shifted output windings to accomplish the phase shifting necessary for proper operation. All these facts have to considered and compared to a filter solution when planning a low harmonic application.

Corrective solutions

In the today's real world applications the use of precautionary solutions is often not sufficient to reach harmonic distortion limits required by standards. In most applications there is also a need for harmonic distortion levels which are low enough to ensure a safe and reliable functioning of electric and electronic equipment. To reach such sufficient levels the mitigation of harmonics in a power system with the help of harmonic filters is state of the art. Harmonic filters can be separated into passive and active harmonic filters. Both solutions aim to limit existing harmonic distortion levels to a permissible or wanted level by mitigating the harmonic currents of different orders.

Passive harmonic filter

Passive harmonic filters represent an economical solution to the challenge of load-applied harmonics mitigation in three-phase power systems. All passive harmonic filter configurations have a capacitive character as they are built with inductive, capacitive and resistive elements configured and tuned to be used to control harmonics. The technical approach of such tuned filters is to provide low impedance path to harmonic currents at certain frequencies.

Passive harmonic filters are designed for the operation on the input (grid) side of power electronic equipment with six-pulse rectifier front-ends in balanced three-phase power systems, like typically used in AC or DC motor drives and high power DC supplies. That's why the filter circuits are usually adapted to 5^{th}, 7^{th} and 11^{th} harmonic, and represent very low impedance paths for these currents with the respective frequencies. Figure 16 shows the basic setup of a tuned passive harmonic filter. The basic combination of capacitors and inductors forms a trap circuit, which provides a low impedance path for the targeted harmonic frequency. The challenge is to properly size the LC circuit with respect to its location in the system to achieve the same resonance frequency of the harmonic to be eliminated. The unwanted harmonics are than diverted into the filter, preventing them to flow into the power source. As a result, the harmonic current is dissipated as heat by the passive harmonic filter instead of being exported to the utility system and other end-users. However, this heat dissipation should not be considered a loss due to the harmonic filters as it already existed in the system within unusable frequencies.

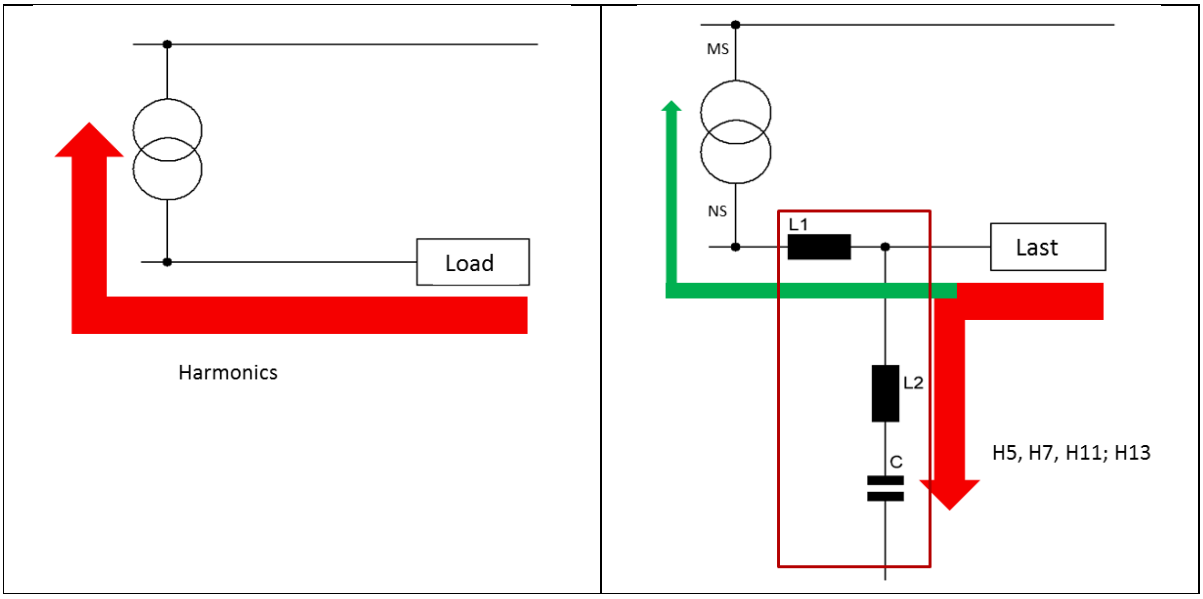

Figure 16 – Passive harmonic filter a.) not applied b.) applied

Passive Harmonic Filters are suitable for use with a single or group of loads. Thus passive harmonic filters should be installed near individual loads or at the supply mains for the group of loads. The full harmonic current will continue to flow between the passive harmonic filter and the nonlinear loads. This means that the benefit provided by the filter is experienced by that part of the electrical system upstream of the filter connection point.

Often the filter performance is only promoted at full load because light load conditions can be a challenge in terms of both harmonics mitigation and capacitive current. Thus a well-engineered and properly sized filter will not only provide excellent harmonic reduction with a guaranteed THDi rating of 8% maximum over the entire load range but also limits the amount of capacitive current under all (load) conditions. Figure 17 shows a state of the art performance curve of a passive harmonic filter.

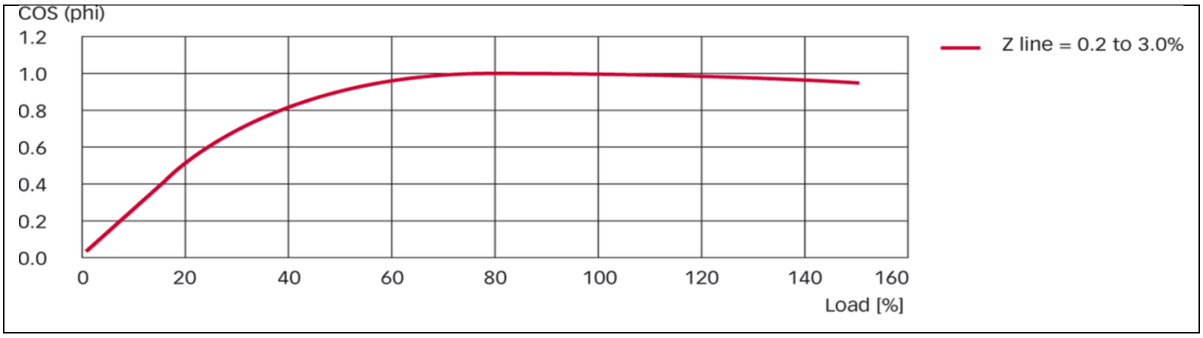

Figure 17 – performance curve passive harmonic filter

One disadvantage of passive harmonic filters is that they cannot absorb other harmonics than they are designed for. They cannot automatically adapt to changes in the electrical system. Thus, passive harmonic filters are an efficient and economical solution if specific harmonic frequencies usually produced by a specific piece of equipment are needed to be mitigated.

Active harmonic filter

An active harmonic filter is a higher sophisticated device to prevent harmonic distortion in a power network. Over the last decade the intensity of the usage of power electronic equipment has caused a dramatic increase of the harmonic disturbances in power systems. Especially the randomly varying amplitudes and harmonic content of the distortion power can make a passive harmonic filter solution become ineffective. Furthermore the load conditions and different configurations nowadays are causing harmonics up to the 50th order. The more sophisticated active filtering concepts operate in such wide frequency ranges, adapting their operation to the resultant harmonic spectrum.
Active harmonic filters (AHF) are power quality devices that permanently monitor the nonlinear load and dynamically provide precisely controlled current. This current has the same amplitude of the harmonic current but is injected in the opposite phase-shift. This cancels out the harmonic currents in the electrical system. As a result, the current supplied by the power source will remain sinusoidal since the harmonics will negate each other and the harmonic distortion is reduced to less than 5% THDi, meeting all standards. In addition, the AHF power electronics platform has been designed to operate at levels that continuously adapt to rapid load variations. Figure 18 shows the function of an active harmonic filter.

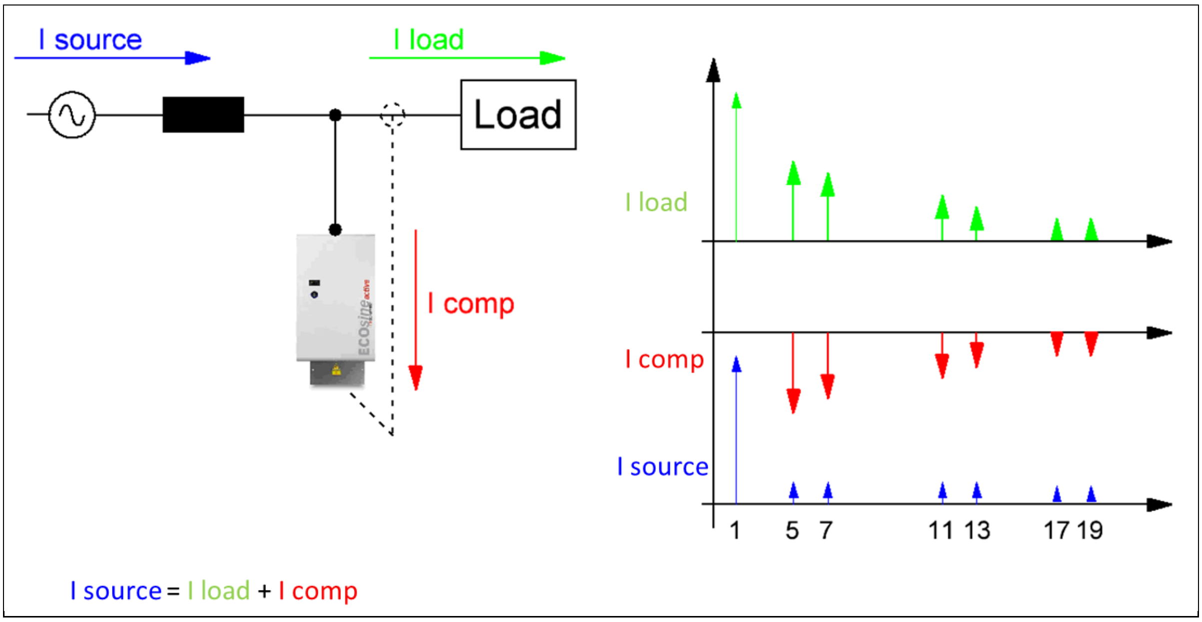

Figure 18 – function of an active harmonic filter

Active harmonic filters also correct poor displacement power factor (DPF) by compensating the system's reactive current. Presently, the higher sophisticated devices are equipped with Insulated Gate Bipolar Transistors (IGBT) and Digital Signal Processing (DSP) components. Generally, active harmonic filters can be installed at any point in a low voltage AC network and they usually offer much more functionality than their passive counterparts:

- Remove all harmonic currents from nonlinear loads (1st – 50th order)
- Compensate reactive power and correct power factor
- Compensate flicker (if caused by reactive power)
- Act as a damping resistor to avoid harmonic resonance

Combining these features with its small physical size and efficient operation, active harmonic filters are best choice for a wide variety of commercial and industrial applications. Active harmonic filters can also be either of the following:

- 3-wire
  - These type is commonly installed in industrial environments with VFDs and other such applications, which have a large number of nonlinear loads

- 4-wire
  - These filters are used to eliminate harmonics that are generated by single phase loads, e.g. switched-mode power supplies (SMPS) and information technology equipment
  - They have the capability to filter triplen harmonics in the neutral conductor

Active harmonics filters can be applied to a single or a group of nonlinear loads. Other possible AHF applications are when:

- PF correction in harmonic-rich systems can't be suitably achieved by capacitors
- Both PF and harmonics correction are required
- Emergency power and distributed generation are present in the electrical system

CHAPTER 6

Costs of Harmonics and Power Losses in Harmonic Distorted Networks

Introduction

To estimate the costs of harmonics is much more difficult than these of other power quality costs. People usually have a good picture about the economic impact of harmonics like:

- Loss of production
- Unrecoverable downtime and resources
- Process restart costs
- Equipment damage
- Increased troubleshooting
- Image losses because of not being recognized as “green or energy-efficient”

Examples of such costs have been assembled in several power-quality surveys all over the world. The results were always the same: the financial losses for the industries due to a power quality incident in electrical installations can easily reach millions of dollars per incident. Such incidents can be avoided by the implementation of appropriate equipment, e.g. harmonic filters.
In opposition to that very well examined numbers the quantifying of the amount of unusable power had never been easily possible. Even so the Institute of Electrical and Electronics Engineers (IEEE) developed a standard to more accurately segment and quantify energy consumption in three-phase electrical systems (IEEE 1459-2000), the effects (losses) of harmonics were not considered in the classical methods. Savings in reactive power can be easily calculated. However, cost reduction due to less wear on equipment, less troubleshooting, or even prevented production downtime are more difficult to quantify. Studies show that this amounts to billions in damages each year. In general it is possible to identify the effects of voltage and current harmonics for the equipment or the entire power system. The main effects are:

- Increased (additional) energy losses if compared with a harmonic free power system
- Premature aging of the equipment and loss of system and equipment reliability because of harmonics
- Lower performance and operating failures if compared with nominal conditions

Additional losses due to harmonic distortion

As already explained in the previous chapters an increased level of harmonic distortion will involve increased rms values of current. This in turn leads to increased heat dissipation in equipment. The resulting effect is causing accelerated aging of solid insulation in transformers, motors and capacitor banks. Beside the equipment itself another part of the power network is very much important when it comes to harmonic losses. The active power transmitted to a load is a function of the fundamental component I_1 of the current. The rms value including the harmonic currents needs to be obtained by the individual harmonic contents. Starting with the definition of the THDi:

$\mathrm{THDi} = \frac{\sqrt{\sum_{n=2}^{n=40} I_n^2}}{I_{(1)}} * 100\%$ it can be seen that $I = \sqrt{\sum_{h=2}^{40} I_h^2} = \sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + I_n^2}$

This subsequently leads to the formula: $I_{rms} = I_1\sqrt{1 + THDi^2}$

As a conclusion it can be told, that, if a harmonic distortion is present, the total losses need to be expressed as the summation of the individual losses at every harmonic frequency. If the current drawn by the load contains harmonics, the rms value of the current, I_{rms}, becomes greater than the fundamental I_1. Putting this in a very simple perspective, the harmonic losses are the amount of additional heat dissipation produced by the non-linear loads in comparison with linear loads of the same size if they are fed off in parallel from the same source. Because most electrical equipment is specified based on 50-/60-Hz parameters, the addition of harmonic losses will directly limit the ability of the equipment to work up to the rated value.
Nowadays measurement equipment as well as on- and offline tools able to directly measure and calculate the economic impact of additional harmonic losses are available on the market.

Premature aging of equipment

In today's high-performance world electric and electronic systems are usually working on high duty. Even under normal conditions this is a challenge regarding thermal stress. The prevention of permanent as well as intermittent catastrophic failure like loss of electronic function is the goal of electronics thermal management. This requires the elimination of large temperature excursions. If a system is not engineered to work in distorted power networks, the additional heat will cause a lot of technical issues. Temperatures higher then rated are inducing large thermo-mechanical stresses, may lead to excessive strain and/or stress levels in the equipment. Furthermore, elevated temperatures, which exceed the design specification of the equipment, will result in premature ageing. Premature ageing of equipment means it must be replaced sooner. The root cause of premature aging does also cause equipment to be chosen oversized right from the start which is much more costly than mitigating the harmonics with appropriate filters.

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