ANALYSIS OF HARMONICS REDUCTION METHODS

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ABSTRACT: This paper deals with additional losses and the many problems caused by harmonics. These are a very good reason to think about harmonic reduction. Harmonic reduction is a necessity rather than a "nice to have". It is certainly a necessity if standards and regulations require action to be taken, but it should also be clear that harmonic mitigation techniques in the power system can be divided into two categories. The first category includes preventive or so-called precautionary solutions, and the second category includes corrective or so-called remedial solutions. The aim is to explain the techniques, including the advantages and disadvantages of each.

KEYWORDS: current, distortion, filter, harmonic, voltage.

1. INTRODUCTION

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.

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 [5, 6, 18, 19].

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. But in general it can be said that harmonic distortion in former times did not have the same dangerous potential like it has today.

Harmonics and unbalanced voltage can also cause negative effects on power system components, such as: overheating of transformers and transmission lines, vibration and torque reduction of rotating machines, additional losses of lines and transformers, interference with communication systems, failures of protective relays, errors of measuring instruments [7, 8, 13, 14].

Total Harmonic Distortion (THD) is a widely used notion in defining the level of harmonic content in alternating signals. Total Harmonic Current (THC) is particularly useful in determining the required characteristics for installation of modern active harmonic filters:

$$THC = \sqrt{\sum_{n=2}^{n=40} I_n^2} \qquad (2)$$

Total Harmonic Distortion of Current (THDi) indicates the total harmonic current distortion of the wave form:

$$THDi = \frac{\sqrt{\sum_{n=2}^{n=40} I_n^2}}{I_{(1)}} \cdot 100\% = \frac{\sqrt{I_{h2}^2 + I_{h3}^2 + I_{hn}^2}}{I_{h1}} \cdot 100\% = \frac{THC}{I_{(1)}} \qquad (3)$$

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. Sum of all voltage harmonics is calculated in relation to the fundamental frequency voltage up to the 40th harmonic order:

$$THDv = \frac{\sqrt{\sum_{n=2}^{n=40} U_n^2}}{U_{(1)}} \cdot 100\% = \frac{\sqrt{U_{h2}^2 + U_{h3}^2 + U_{hn}^2}}{U_{h1}} \cdot 100\% \quad (4)$$

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

2. ALTERNATIVE CURRENT (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. Beside the reduction of harmonics they also are able to absorb voltage transients which may otherwise cause a VFD (Variable Frequency Drives) 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 [9, 10, 20]. 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 reduction, a 4% impedance line reactor has proved to be state of the art. Figure 1.shows an example with an applied AC line reactor on a six-pulse rectifier.

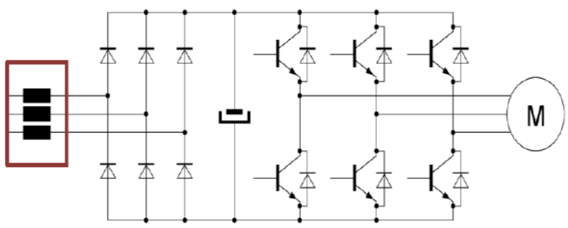

Figure 1. AC line reactor applied

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% THDi. 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 1.shows the input impedance versus remaining harmonics [%] of AC line reactors for each harmonic number.

Table 1. AC Line reactors – Harmonic number / Input impedance vs. remaining harmonics [%]

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	10 3%	72%	60 %	53%	44%	37%

3. DC LINK COIL

The name reactance coil is assigned to the elements of an electrical circuit or power system which in the quasi-stationary electromagnetic regime are considered as having only an inductivity, i.e. an inductive reactance.

The purpose of introducing them into the power system is to produce a voltage drop when an alternating current or time-varying current flows through it, i.e. to achieve a reactive power exchange with the system.

The voltage drop is proportional to the effective value of the current *I* and the frequency *f*, if the inductance *L* of the coil is assumed to be constant.

The reactive power varies in proportion to the square of the voltage at the coil terminals if the inductance *L* is assumed constant. In iron core coils, as the voltage increases, saturation of the ferromagnetic core occurs; the inductance *L* decreases, resulting in an increase in reactive power as a function of terminal voltage faster than the square of the voltage value.
The construction of cylindrical coils without ferromagnetic core with the dimensions shown in Figure 2 corresponds to a technical-economic optimum, achieving at a given value of the inductance, a minimum volume of windings.

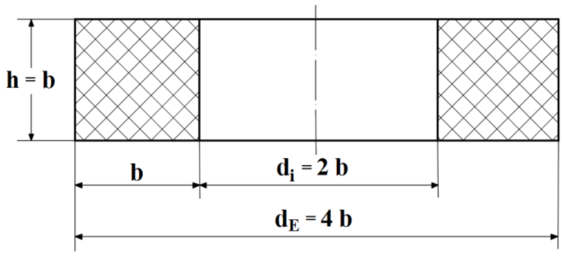

Figure 2. Optimum coil dimensions without ferromagnetic core

Reactance coils are used for various purposes: for reactive-capacitive power compensation in electrical networks, for limiting short-circuit currents in the power system or for limiting inrush currents in induction motors, for filtering harmonics in the AC curve or for smoothing DC currents in rectifier installations, for treating electrical networks against earthing and for protecting high-voltage lines against overvoltages [3].
DC link coil are a cost effective way of filtering the DC bus voltage and current in a VSD. DC link coilsare installed between the input rectifier and bus capacitor to improve the DC bus waveform and the AC input waveform [1, 2]. A DC link coil 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 coil is capable to reduce current distortion typically by 40% to 60%. Figure 3 shows an applied DC link coil in a six-pulse rectifier [21].

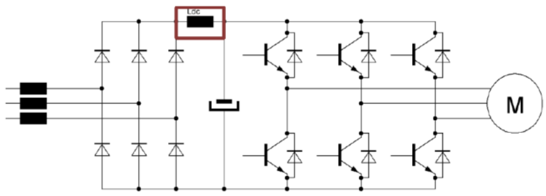

Figure 3. DC link coil applied

4. 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. 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 2 shows the different harmonic spectra with different numbers of pulses (paths of conduction).

Table 2. Harmonics versus pulse-numbers

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)

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

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 4 shows a 12-pulse setup with a required phase shift of 30 degrees.

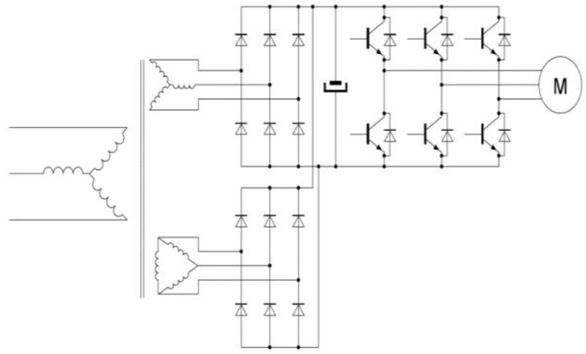

Figure 4.12-pulse setup

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. 5th or 7th 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. All these facts have to considered and compared to a filter solution when planning a low harmonic application [11, 16].

5. PASSIVE HARMONIC FILTER

Passive harmonic filters represent an economical solution to the challenge of load-applied harmonics mitigation in three-phase power systems. 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 5th, 7th and 11th harmonic, and represent very low impedance paths for these currents with the respective frequencies. Figure 5 shows the basic setup of a tuned passive harmonic filter.

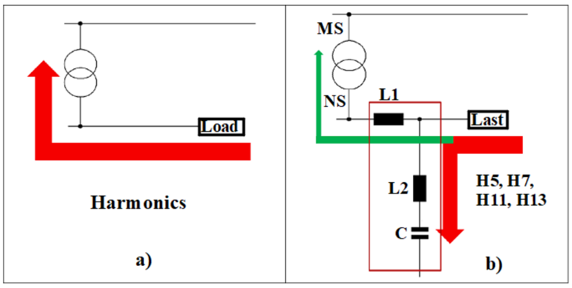

Figure 5. Passive harmonic filter a.) not applied b.) applied

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.

Passive harmonic filters should be installed near individual loads or at the supply mains for the group of 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 [12, 15].

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 6 shows a state of the art performance curve of a passive harmonic filter.

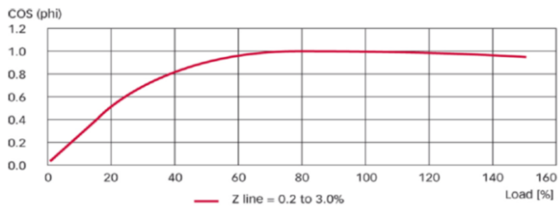

Figure 6. Performance curve passive harmonic filter

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.

6. 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 7 shows the function of an active harmonic filter [17].

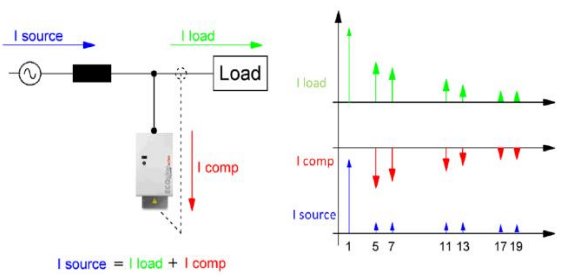

Figure 7. Function of an active harmonic filter

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.

7. CONCLUSION

A series of technical solutions are adopted to prevent harmonics. These solutions aim to reduce harmonic emissions from tasks that are non-linear and consist of changes in the structure of the load. The most commonly used methods are AC line reactors or DC link coils with conventional converter systems and multi-pulse conversion systems.
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.
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.

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