HARMONICS IN THREE-PHASE ELECTRICAL GRIDS

EFFECTS AND MITIGATION WITH ACTIVE POWER QUALITY IMPROVEMENT SOLUTIONS

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1 ABSTRACT

There is an increasing number of low, medium and high voltage electrical equipment with nonlinear voltage-current characteristics connected to the electrical grid. Such equipment introduces harmonic currents to the electrical grid which cause harmonic voltages across the network impedance which add to the fundamental system voltage resulting in voltage distortion. Voltage distortion is experienced by all electrical equipment connected to the grid, leading to higher thermal loading of generators, motors, transformers, reactors, capacitors, switchgears and cabling. Renewable power sources like wind and solar farms are just as affected as conventional ones. Some of the electrical consumers emit more audible noise when supplied with distorted voltage. Sensitive electronic devices, computers, PLCs as well as protection and control systems are likely not to operate properly when supplied with distorted voltage.

There are two ways to mitigate harmonics in the electrical grid:

1.) Passive harmonic filter (tuned parallel resonance circuit)
Elimination of harmonics at tuning frequencies by connecting reactors in series with capacitors, as the circuit branches are having low impedances for harmonic frequencies.
2.) Active harmonic filter
Neutralization of harmonics by a controlled current source connected in parallel to nonlinear loads. The controlled current source introduces to the mains the same harmonic currents as the nonlinear load but with opposite phase.

This paper is explaining the behaviour of harmonics in three-phase electrical grids and the ways to compensate harmonic currents. Finally, case studies illustrate two active harmonic filter solutions.

2 INTRODUCTION

2.1 Harmonics in General

Harmonics are a distortion of the normal (sinusoidal) electrical current waveform generally transmitted by nonlinear loads. Switched power supplies, variable speed drives, inverters of solar and wind generators, personal computers, printers, battery chargers and UPSs are examples of nonlinear loads. Single-phase nonlinear loads are prevalent in modern office buildings, while three-phase nonlinear loads are widespread in factories and industrial applications as well as at generation plants and transmission and distribution grids.

The annual growth rate of the global harmonic filter market for the last 10 years has been 10% [2].

2.2 Active and Reactive Power

In a simple alternating current (AC) circuit consisting of a source and a linear load, both the current and voltage are sinusoidal. If the load is purely resistive, the two quantities reverse their polarity at the same time. At every instant the product of voltage and current is positive (consumption, see Figure *1*),

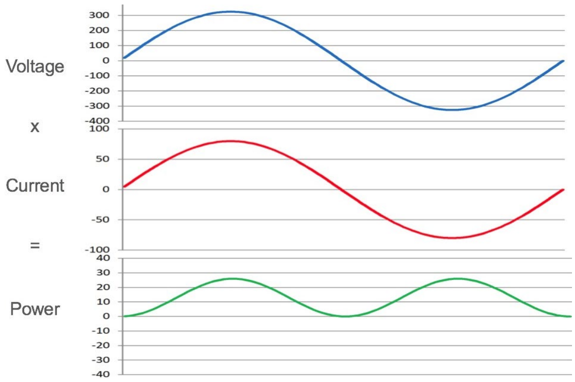

Figure 1: Active Power; Consumption

or negative (generation, see Figure *2*), with the result that the direction of energy flow does not reverse. In this case, only active power is transferred.

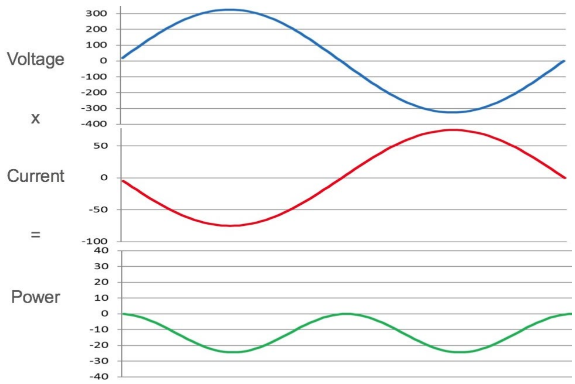

Figure 2: Active Power; Generation

If the loads are purely reactive, then for a part of the cycle, the product of voltage and current is positive, but for another part of the cycle, the product is negative, indicating that on average, exactly as much energy flows toward the load (consumption) as flows back (generation). There is no net energy flow over one cycle. In this case, only reactive power flows - there is no net transfer of energy to the load (see Figure *3* and Figure *4*).

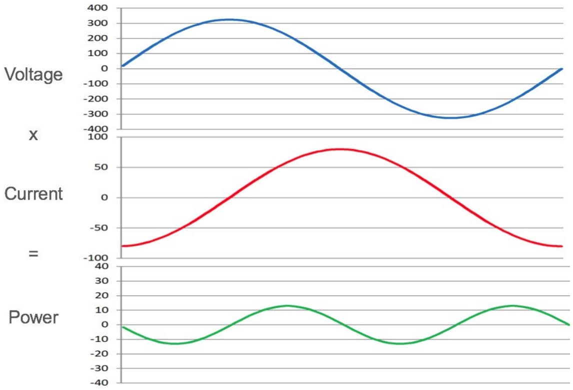

Figure 3: Inductive Reactive Power

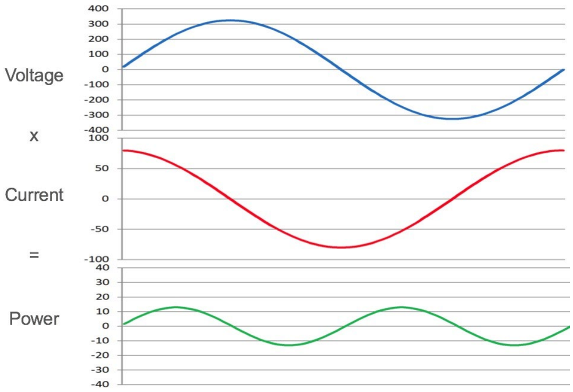

Figure 4: Capacitive Reactive Power

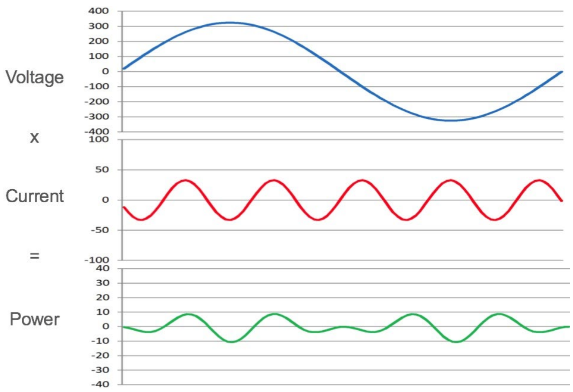

Figure 5: Harmonic Reactive Power (5th)

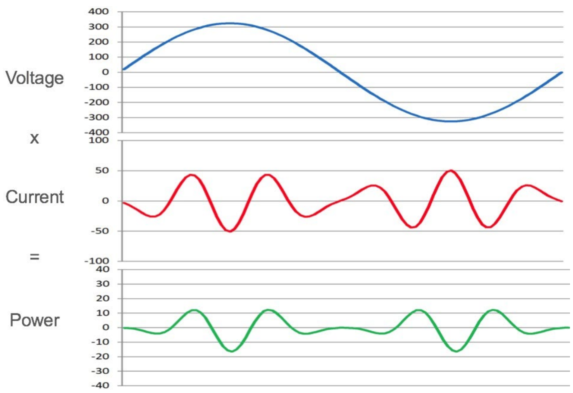

Figure 6: Harmonic Reactive Power (5th + 7th)

Now, consider non-sinusoidal situations where currents in the electrical grid contain harmonics. Also, in these situations, for a part of the cycle, the product of voltage and current is positive, but for another part of the cycle, the product is negative (see Figure *5* and Figure *6*).

2.3 Harmonics, Fourier Transformation

A harmonic is defined as a sinusoidal wave with a certain amplitude and an integer (whole number) multiple of a fundamental frequency. A harmonic is a component of a periodical signal with a fundamental frequency. If the fundamental frequency is f, the harmonics have frequencies 2f, 3f, 4f, 5f, etc. The mathematical procedure to calculate amplitudes, frequencies and phase shifts of harmonics is the "Fourier Transformation" [3]!

In practice, data is often available in the form of a sampled time function, represented by a time series of amplitudes, separated by fixed time intervals of limited duration. When dealing with such data, a modification of the Fourier transform, the discrete Fourier transform (DFT), is used. The implementation of the DFT by means of the so-called Fast Fourier transform (FFT) forms the basis of most modern spectral and harmonic analysis systems [1].

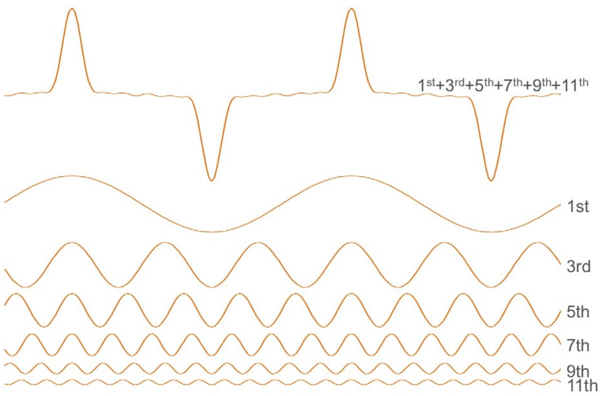

Figure 7: Harmonics; Fourier Transformation

The presentation of harmonics containing currents takes place in bar graph (see Figure *8*) or table form (see Table 1).

Order	Frequency	Irms	Phase	THDr	THDf	Total
1	50Hz	100A	0°	(67%)	(100%)	**Irms:**
3	150Hz	80A	180°	54%	80%	149A
5	250Hz	60A	0°	40%	60%	**THDabs:**
7	350Hz	40A	180°	27%	40%	110A
9	450Hz	20A	0°	13%	20%	**THDr:**
11	550Hz	10A	180°	7%	10%	74%

Table 1: Harmonics containing current

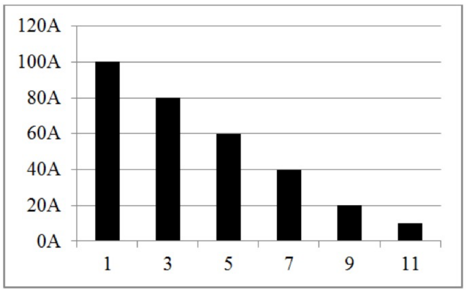

Figure 8: Bar-graph of a harmonics containing current

The total harmonic distortion factor THD is the geometrical sum of all harmonics:

$$THD_i = \sqrt{\sum_{H>1}^{\infty} I_H} \tag{1}$$

Indices are used such as "i" for current-THD (THD_i) or "u" for voltage-THD (THD_u). Further, total harmonic distortion factors are regularly used as relative values related to the fundamental (THD_f) or to the root mean square (RMS) value (THD_r).

$$THD_f = \frac{\sqrt{\sum_{H>1}^{\infty} I_H}}{I_1} \tag{2}$$

$$THD_r = \frac{\sqrt{\sum_{H>1}^{\infty} I_H}}{I} \tag{3}$$

3 HARMONICS IN 3-PHASE ELECTRICAL GRIDS

3.1 Balanced 3-phase-load

There are two kinds of balanced 3-phase-loads:

1.) Balanced 3-phase-load with neutral wire
2.) Balanced 3-phase-load without neutral wire

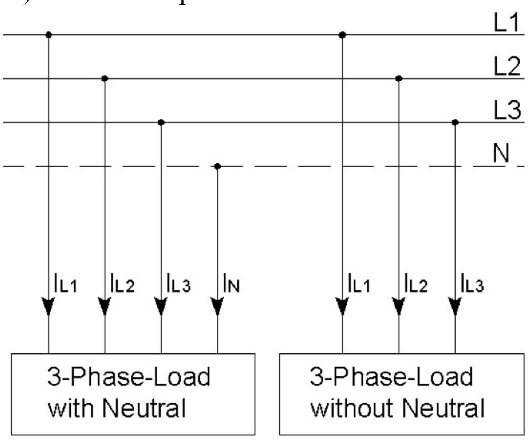

Figure 9: Balanced 3-phase-loads

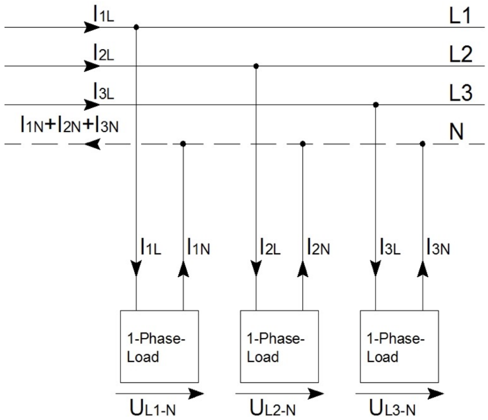

Figure 10: 3-phase-load consisting of three 1-phase-loads

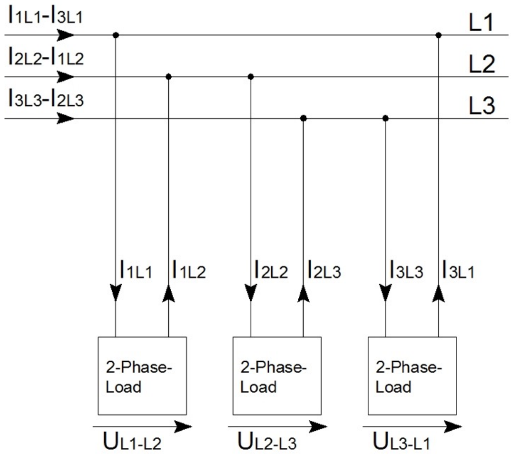

Figure 11: 3-phase-load consisting of three 2-phase-loads

"3-phase-load" is a theoretical description. Each 3-phase-load consists of three pieces 1-phase-loads respectively three pieces 2-phase-loads. Electrically there is no difference in between 1-phase-load and 2-phase-load. 1-phase-loads are connected in between one network phase and neutral (see Figure *10*), 2-phase-loads are connected in between two network phases (see Figure *11*).

3.2 Balanced, purely resistive (active) 3-phase-load

Assuming that a balanced 3-phase-load with neutral connection consists of three identical resistive (purely active) 1-phase-loads, the neutral current of that 3-phase-load results to the sum of the three currents which flow back from each of the 1-phase-loads (see Figure *10*). These three currents - because they are active currents - are sinusoidal and in phase to the voltage. So, they are 120° phase shifted from each other (see Figure 12).

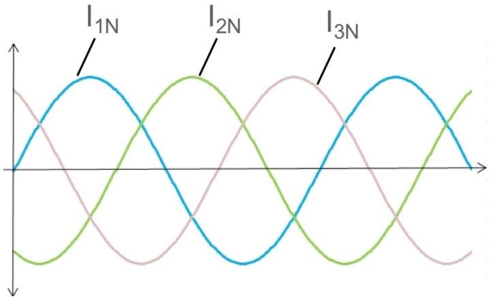

Figure 12: Currents of three balanced resistive 1-phase-loads

According to Figure *10* the currents I_{1N}, I_{2N} and I_{3N} cumulate in the neutral wire, so the neutral wire results to zero because the sum of three 120° phase shifted sinusoidal waveforms is zero.

$$I_{1N} + I_{2N} + I_{3N} = 0 \qquad (4)$$

In case of a 3-phase-load consisting of three 2-phase-loads, the three phase-currents of the 3-phase-load result to the difference of two 2-phase-load currents (see Figure *11*):

$$I_{L1} = I_{1L1} - I_{3L1} \qquad (5)$$
$$I_{L2} = I_{2L2} - I_{1L2} \qquad (6)$$
$$I_{L3} = I_{3L3} - I_{2L3} \qquad (7)$$

So, the resulting 3-phase-load current (of the 3-phase-load without neutral) is a sinusoidal current which is phase shifted against both of the 2-phase-load currents (see Figure 13).

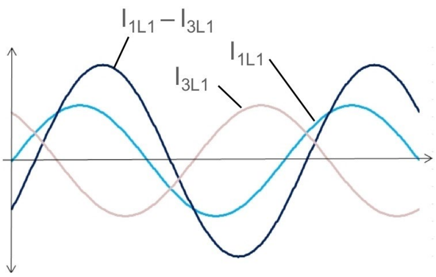

Figure 13: I_{L1} of a balanced resistive 3-phase-load without neutral connection

3.3 *Balanced harmonic loads in 3-phase electrical grids*

For all of the following nonlinear 3-phase-load considerations, nonlinear loads with 100% fundamental, 80% 3rd, 60% 5th, 40% 7th and 20% 9th harmonic currents will be used. The phase shift of the fundamental current against the voltage is 0°, the phase shift of the 3rd harmonic 180°, the phase shift of the 5th 0°, the phase shift of the 7th 180° and the phase shift of the 9th harmonic again 0° (see Figure 14 and Figure 15). These harmonic phase shifts lead to the effect, that one peak of each harmonic match to the peak of the fundamental. So, the peak of the resulting nonlinear current results to the sum of the amplitudes of all harmonics plus the amplitude of the fundamental (see Figure 15). This nonlinear example current is a simplification with a waveform which is close to a real single-phase-load current.

Note: In all of the following diagrams the voltage and current of network phase L1 is dark (voltage) and light (current) blue, voltage and current of network phase L2 is dark and light green, voltage and current of network phase L3 is dark and light red!

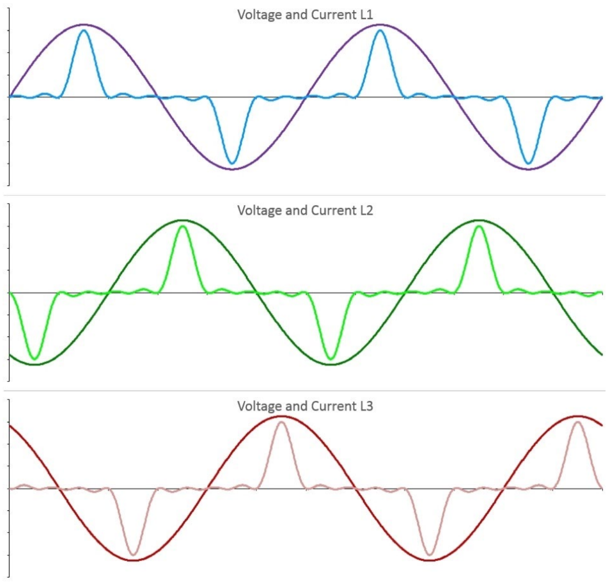

Figure 14: Voltages and currents of a balanced nonlinear 3-phase-load, in three separate diagrams

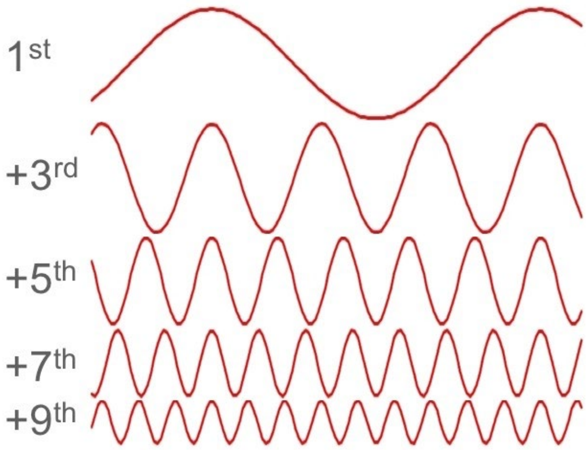

Figure 15: Fundamental and harmonic current of a nonlinear load

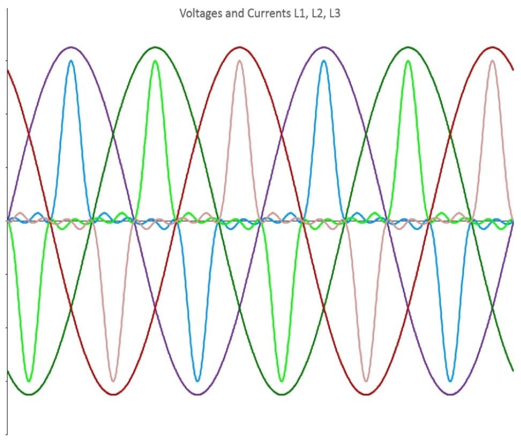

Figure 16: Voltages and currents of a balanced nonlinear 3-phase-load, in one diagram

3.4 *Balanced nonlinear 3-phase load with neutral*

The following equations show the harmonic content of the currents of a nonlinear 3-phase-load, consisting of three 1-phase-loads like in Figure *10*.

$$I_{1N} = I_{1L} = I_{1H1} + I_{3H1} + I_{5H1} + I_{7H1} + I_{9H1} \quad (8)$$
$$I_{2N} = I_{2L} = I_{1H2} + I_{3H2} + I_{5H2} + I_{7H2} + I_{9H2} \quad (9)$$
$$I_{3N} = I_{3L} = I_{1H3} + I_{3H3} + I_{5H3} + I_{7H3} + I_{9H3} \quad (10)$$

Note: For example, index "3H2" means: The **3**rd **H**armonic current of the 1-phase-load number **2**.

In follow, each harmonic order will be considered in separate diagrams.

Because I_{1H1}, I_{1H2} and I_{1H3} are fundamental currents with phase shifts against the voltage of 0°, they are representing the active parts in the currents I_{1L}, I_{2L} and I_{3L} in Figure *10*.

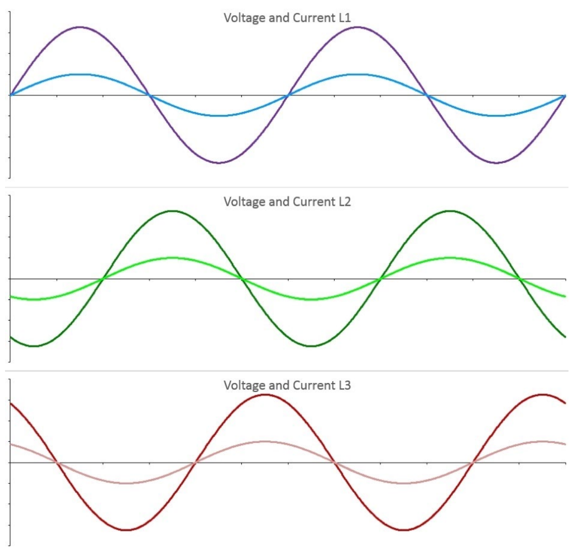

Figure 17: Voltages and currents I_{1H1}, I_{1H2} and I_{1H3} of a nonlinear 3-phase-load with neutral, in separate diagrams

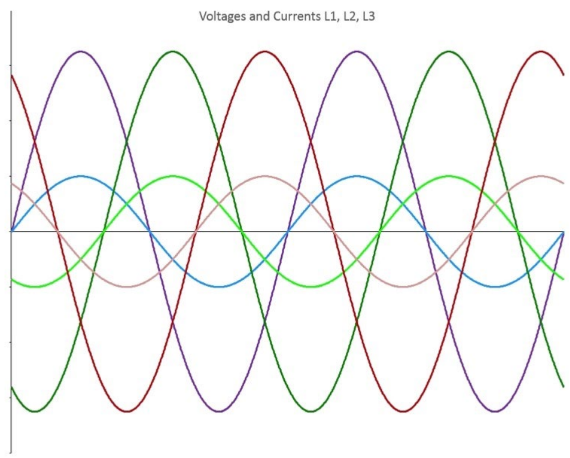

Figure 18: Voltages and currents I_{1H1}, I_{1H2} and I_{1H3} of a non-linear 3-phase-load with neutral, in one diagram

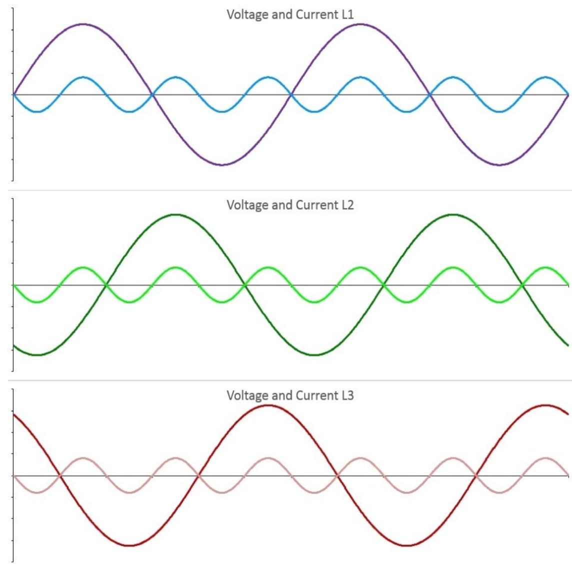

Figure 19: Voltages and currents I_{3H1}, I_{3H2} and I_{3H3} of a non-linear 3-phase-load with neutral, in separate diagrams

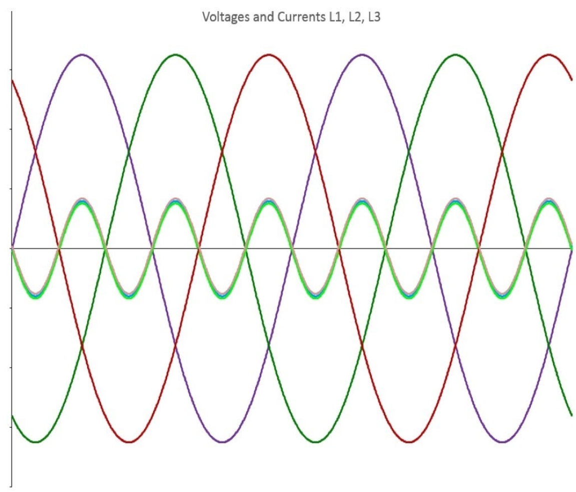

Figure 20: Voltages and currents I_{3H1}, I_{3H2} and I_{3H3} of a nonlinear 3-phase-load with neutral, in one diagram

Because the frequency of the currents I_{3H1}, I_{3H2} and I_{3H3} is three times the frequency of the fundamental currents I_{1H1}, I_{1H2} and I_{1H3}, and because they are situated in a 3-phase-system, the phase shift of the so called "Triplen-Harmonics" against each other is 0°.

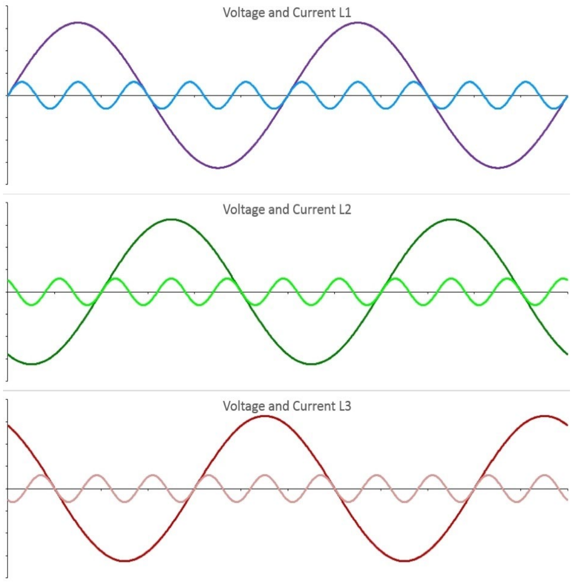

Figure 21: Voltages and currents I_{5H1}, I_{5H2} and I_{5H3} of a nonlinear 3-phase-load with neutral, in separate diagrams

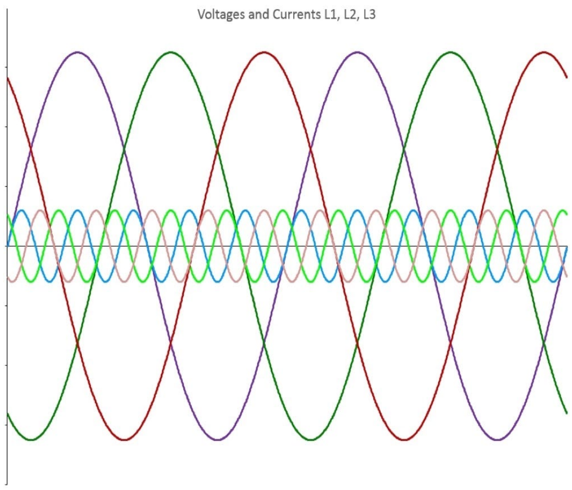

Figure 22: Voltages and currents I_{5H1}, I_{5H2} and I_{5H3} of a nonlinear 3-phase-load with neutral, in one diagram

Figure 22 shows the fifth harmonic currents I_{5H1}, I_{5H2} and I_{5H3} of I_{1L}, I_{2L} and I_{3L}. In chapter 3.3 it's mentioned that the colours of the currents relate to the colours of the voltages (voltage and current of network phase L1 is dark and light blue, voltage and current of network phase L2 is dark and light green, voltage and current of network phase L3 is dark and light red). If following the sequence order of the colours of the voltages U_{L1}, U_{L2} and U_{L3} from left to the right, it is blue, green and red. If following the sequence order of the fifth harmonic currents I_{5H1}, I_{5H2} and I_{5H3} from the left to the right, it is blue, red and green! This means the rotation direction of the fifth harmonic currents is opposite the rotation direction of the fundamentals. Hence e.g. in an electric motor, the fifth harmonic currents want to turn the rotor of the machine to the opposite direction than the fundamental currents. Therefore, harmonics with this characteristic are called "Negative Sequence Harmonics".

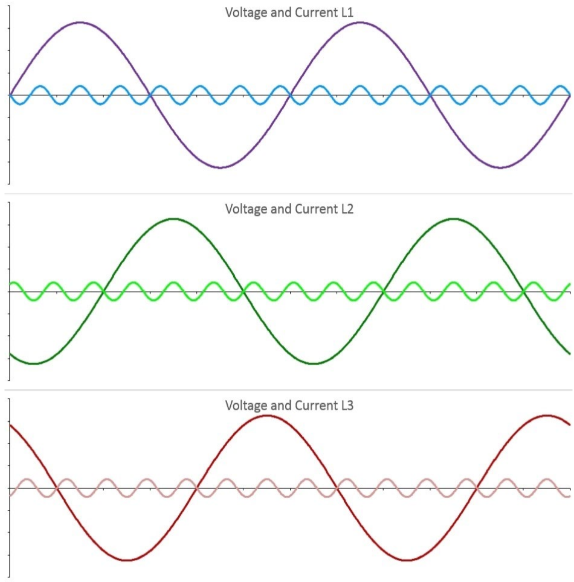

Figure 23: Voltages and currents I_{7H1}, I_{7H2} and I_{7H3} of a nonlinear 3-phase-load with neutral, in separate diagrams

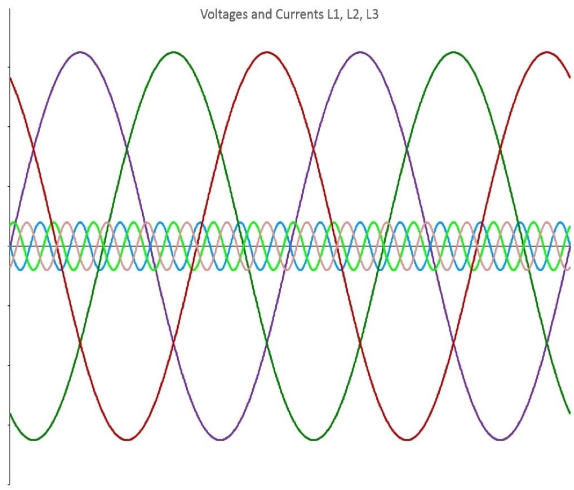

Figure 24: Voltages and currents I_{7H1}, I_{7H2} and I_{7H3} of a nonlinear 3-phase-load with neutral, in one diagram

When following the sequence order of the seventh harmonic currents I_{7H1}, I_{7H2} and I_{7H3} in Figure 24 from the left to the right, it is - like the voltages - blue, green and red! Harmonics with this characteristic are called "Positive Sequence Harmonics".

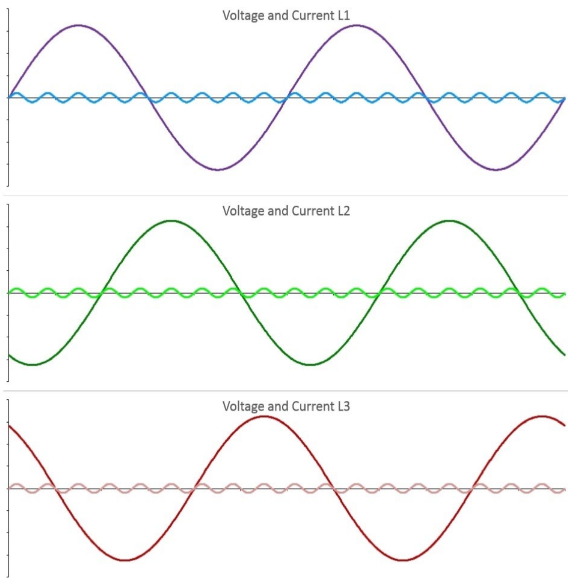

Figure 25: Voltages and currents I_{9H1}, I_{9H2} and I_{9H3} of a nonlinear 3-phase-load with neutral, in separate diagrams

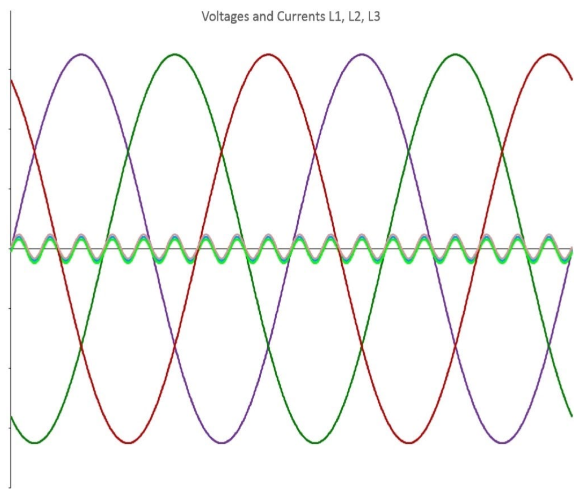

Figure 26: Voltages and currents I_{9H1}, I_{9H2} and I_{9H3} of a nonlinear 3-phase-load with neutral, in one diagram

Like I_{3H1}, I_{3H2} and I_{3H3} (Figure 20), I_{9H1}, I_{9H2} and I_{9H3} are Triplen Harmonics because their phase shifts against each other are 0°. Triplen Harmonics don't have a rotation direction, therefore they are also called "Zero Sequence Harmonics".

According to Figure *10* the neutral current results to:

$$I_N = I_{1N} + I_{2N} + I_{3N} \tag{11}$$

if

$$I_{1N} = I_{1L} = I_{1H1} + I_{3H1} + I_{5H1} + I_{7H1} + I_{9H1} \tag{12}$$
$$I_{2N} = I_{2L} = I_{1H2} + I_{3H2} + I_{5H2} + I_{7H2} + I_{9H2} \tag{13}$$
$$I_{3N} = I_{3L} = I_{1H3} + I_{3H3} + I_{5H3} + I_{7H3} + I_{9H3} \tag{14}$$

then

$$\begin{aligned} I_{1N} + I_{2N} + I_{3N} = &\ I_{1H1} + I_{3H1} + I_{5H1} + I_{7H1} + I_{9H1} \\ &+ I_{1H2} + I_{3H2} + I_{5H2} + I_{7H2} + I_{9H2} \\ &+ I_{1H3} + I_{3H3} + I_{5H3} + I_{7H3} + I_{9H3} \\ = &\ I_{1H1} + I_{1H2} + I_{1H3} \\ &+ I_{3H1} + I_{3H2} + I_{3H3} \\ &+ I_{5H1} + I_{5H2} + I_{5H3} \\ &+ I_{7H1} + I_{7H2} + I_{7H3} \\ &+ I_{9H1} + I_{9H2} + I_{9H3} \end{aligned} \tag{15}$$

The sum of three 120° phase shifted sinusoidal wave forms results to zero. Therefore

$$\begin{aligned} I_{1H1} + I_{1H2} + I_{1H3} &= 0 \\ I_{5H1} + I_{5H2} + I_{5H3} &= 0 \\ I_{7H1} + I_{7H2} + I_{7H3} &= 0 \end{aligned} \tag{16}$$

but

$$\begin{aligned} I_{3H1} + I_{3H2} + I_{3H3} &\neq 0 \\ I_{9H1} + I_{9H2} + I_{9H3} &\neq 0 \end{aligned} \tag{17}$$

This means the neutral current is loaded only with Zero Sequence Harmonics (see Figure 27).

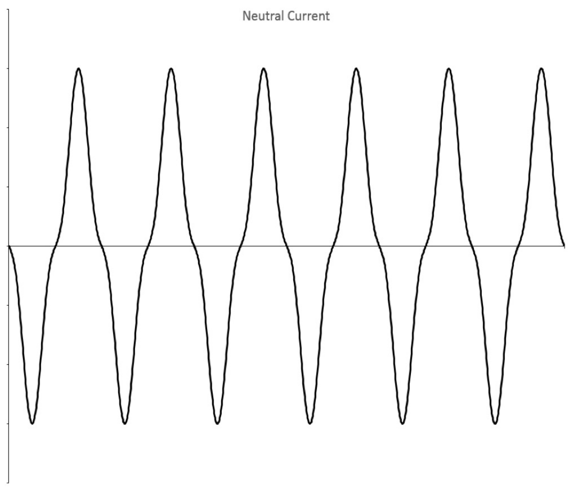

Figure 27: Neutral current of a nonlinear 3-phase-load

3.5 Balanced nonlinear 3-phase load without neutral connection

For the balanced nonlinear 3-phase-load *without* neutral connection, the three nonlinear 2-phase-loads shall be considered same as the three nonlinear 1-phase loads for the approach of the balanced nonlinear 3-phase-load *with* neutral connection (see Figure 14, Figure 15 and Figure 16).

Hence the currents I_{1L1}, I_{1L2}, I_{2L2}, I_{2L3}, I_{3L3} and I_{3L1} (see Figure *11*) result to:

$$I_{1L1} = I_{1L2} = I_{1H1} + I_{3H1} + I_{5H1} + I_{7H1} + I_{9H1} \tag{18}$$
$$I_{2L2} = I_{2L3} = I_{1H2} + I_{3H2} + I_{5H2} + I_{7H2} + I_{9H2} \tag{19}$$
$$I_{3L3} = I_{3L1} = I_{1H3} + I_{3H3} + I_{5H3} + I_{7H3} + I_{9H3} \tag{20}$$

Because the line currents of the balanced nonlinear 3-phase-load without neutral connection are the differences in between two of the 2-phase-load currents:

$$I_{L1} = I_{1L1} - I_{3L1} \tag{21}$$
$$I_{L2} = I_{2L2} - I_{1L2} \tag{22}$$
$$I_{L3} = I_{3L3} - I_{2L3} \tag{23}$$

the line currents result to:

$$\begin{aligned} I_{L1} = (I_{1H1} + I_{3H1} + I_{5H1} + I_{7H1} + I_{9H1}) \\ - (I_{1H3} + I_{3H3} + I_{5H3} + I_{7H3} + I_{9H3}) \end{aligned} \tag{24}$$
$$\begin{aligned} I_{L2} = (I_{1H2} + I_{3H2} + I_{5H2} + I_{7H2} + I_{9H2}) \\ -(I_{1H1} + I_{3H1} + I_{5H1} + I_{7H1} + I_{9H1}) \end{aligned} \tag{25}$$
$$\begin{aligned} I_{L3} = (I_{1H3} + I_{3H3} + I_{5H3} + I_{7H3} + I_{9H3}) \\ -(I_{1H2} + I_{3H2} + I_{5H2} + I_{7H2} + I_{9H2}) \end{aligned} \tag{26}$$

or:

$$\begin{aligned} I_{L1} = {} & (I_{1H1} - I_{1H3}) \\ & +(I_{3H1} - I_{3H3}) \\ & +(I_{5H1} - I_{5H3}) \\ & +(I_{7H1} - I_{7H3}) \\ & +(I_{9H1} - I_{9H3}) \end{aligned} \tag{27}$$
$$\begin{aligned} I_{L2} = {} & (I_{1H2} - I_{1H1}) \\ & +(I_{3H2} - I_{3H1}) \\ & +(I_{5H2} - I_{5H1}) \\ & +(I_{7H2} - I_{7H1}) \\ & +(I_{9H2} - I_{9H1}) \end{aligned} \tag{28}$$
$$\begin{aligned} I_{L3} = {} & (I_{1H3} - I_{1H2}) \\ & +(I_{3H3} - I_{3H2}) \\ & +(I_{5H3} - I_{5H2}) \\ & +(I_{7H3} - I_{7H2}) \\ & +(I_{9H3} - I_{9H2}) \end{aligned} \tag{29}$$

The difference in between two sinusoidal waveforms with the same amplitude and a phase shift of 0° is zero (see Figure 20 and Figure 26) therefore:

$$(I_{3H1} - I_{3H3}) = 0 \tag{30}$$
$$(I_{9H1} - I_{9H3}) = 0 \tag{31}$$
$$(I_{3H2} - I_{3H1}) = 0 \tag{32}$$
$$(I_{9H2} - I_{9H1}) = 0 \tag{33}$$
$$(I_{3H3} - I_{3H2}) = 0 \tag{34}$$
$$(I_{9H3} - I_{9H2}) = 0 \tag{35}$$

So, the line currents of a balanced nonlinear 3-phase-load without neutral connection result to:

$$\begin{aligned} I_{L1} = {} & (I_{1H1} - I_{1H3}) \\ & +(I_{5H1} - I_{5H3}) \\ & +(I_{7H1} - I_{7H3}) \end{aligned} \tag{36}$$
$$\begin{aligned} I_{L2} = {} & (I_{1H2} - I_{1H1}) \\ & +(I_{5H2} - I_{5H1}) \\ & +(I_{7H2} - I_{7H1}) \end{aligned} \tag{37}$$
$$\begin{aligned} I_{L3} = {} & (I_{1H3} - I_{1H2}) \\ & +(I_{5H3} - I_{5H2}) \\ & +(I_{7H3} - I_{7H2}) \end{aligned} \tag{38}$$

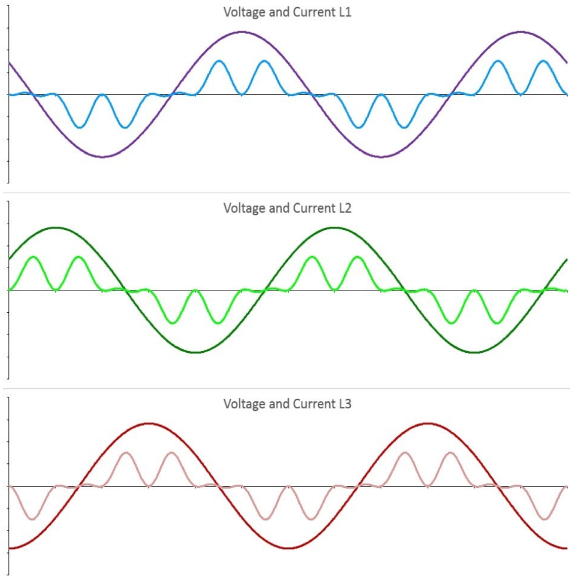

Figure 28: Voltages and line currents of a balanced nonlinear 3-phase-load without neutral connection

3.6 Harmonic Consequences

The impact of harmonic reactive power to the electrical grid is the same as the impact of fundamental reactive power to the electrical grid, but additionally harmonic currents cause harmonic voltages across the network impedance which add to the fundamental system voltage resulting in voltage distortion. Consequences are:

- Equipment heating
- Equipment malfunction
- Equipment failure
- Life span reduction
- Communications interference
- Fuse and breaker mis-operation
- Process problems
- Conductor heating
- Noise emission
- Metering problems
- Computer breakdowns

And after all, zero sequence harmonics in low voltage applications cumulate in the neutral wire which causes overload and dramatic effects like:

- Cable fire
- Transformer breakdown
- Noise emission

3.7 Measures against harmonics

Basically, there are two technologies for the compensation of harmonic reactive power:

- Passive harmonic filters (tuned parallel resonance circuits)
- Active harmonic filters

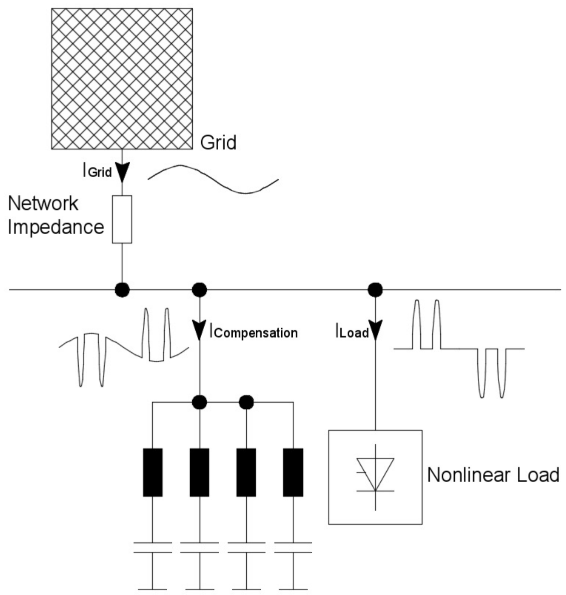

Figure 29: Passive harmonic filter (tuned parallel resonance circuits)

Passive tuned parallel resonance circuits are reactors connected in series with capacitors in order to form low impedance circuits for harmonic frequencies. One effect is fundamental reactive power compensation (power factor correction) because the circuits are capacitive for the fundamental frequency. Further the inrush current of the capacitor banks when steps are switched is reduced due to the series reactors. And finally, harmonics at tuning frequencies are eliminated as the circuit branches are having very low impedances at tuning frequencies. The reactors must be dimensioned to the desired tuning frequencies and the current capability must be high enough for the harmonic current absorption that can be expected. If several harmonic frequencies need to be eliminated, a number of filters with different tuning frequencies will be connected to the bus system, for instance the 5th, 7th and 11th harmonic of the fundamental frequency (50Hz or 60Hz).

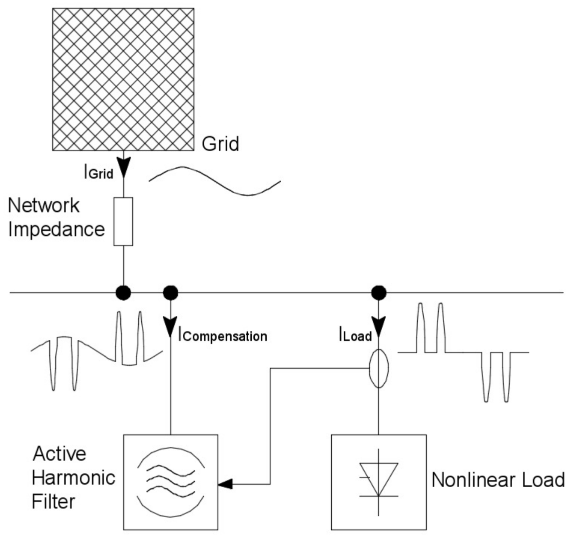

Figure 30: Active harmonic filter

An active harmonic filter eliminates disturbances such as harmonics, flicker, voltage variations, resonances and reactive power using a highly dynamic, step-less digitally controlled compensation and filtering approach. By continuously monitoring the load current and injecting exactly the right amount of compensation current at exactly the right time, the most efficient and accurate solution to any power quality problem can be achieved. This approach enables the current waveform to be restored instantaneously, the current consumption to be lowered and changes in load or installation conditions to be fully compensated at all times. For modern facilities, where load and network change constantly, this solution represents the most efficient way for power quality improvement.

4 ACTIVE HARMONIC FILTER CASE STUDIES

4.1 Case Study, Abbott Vascular, Ireland

Abbott Vascular, located in Clonmel, Ireland, manufactures medical vascular devices, including stent delivery systems. It is part of the Abbott group with headquarter in Chicago, Illinois, USA.

The power to the factory is fed via 9 transformers with total power of almost 20 MVA. A bad power quality was suspected as the reason for occasional malfunctions and damages of electrical equipment in the company. A harmonic survey was made by Leslie Mantle, Mantle Power Quality Design, including power quality measurements and electrical network simulations.

Finally, two active harmonic filter branches were installed, one with 400V/200A and another one with 400V/300A. The installation took place at the most harmonic distorted network parts in the company: The network part supplied by transformer 6 (T6) and the one supplied by transformer 7 (T7). The challenge in this installation was, that the two network parts aren't normally supplied by their appropriate transformer, the normal case is that both network parts together are supplied by T7, while T6 is only used in emergency cases or during maintenance periods. This means, the bus coupler (see Figure 31) is normally closed. Anyway, both active harmonic filters must work properly in all possible situations:
1.) Bus coupler open, T6 and T7 in operation
2.) Bus coupler closed, T6 in operation
3.) Bus coupler closed, T7 in operation
4.) Bus coupler closed, T6 and T7 in operation

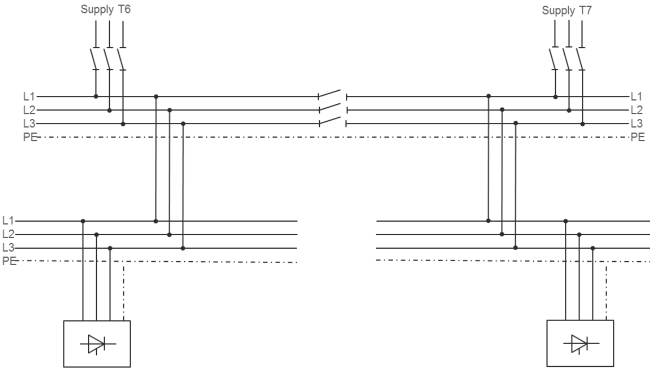

Figure 31: Abbott Vascular; Supply transformers for harmonic loads

The requirement regarding power quality (with operating active harmonic filters) was to be always below the limits of the British power quality standard G5/4, which limits the harmonic currents in the electrical grids (see Table *2*).

Item	Limit
5^{th} harmonic current:	28,9 A
7^{th} harmonic current:	41,2 A
11^{th} harmonic current:	39,4 A
13^{th} harmonic current:	27,8 A
Total voltage THD:	5%

Table 2: Accepted harmonics according to the British power quality standard G5/4

Figure 32: Abbott Vascular; Active harmonic filters; Left side: 300A; Right side 200A

Harmonic Order	Compensation Factor
5^{th}	100%
7^{th}	75%
11^{th}	100%
13^{th}	100%

Table 3: Active Harmonic Filter settings

It's possible to set the compensation factor of the active harmonic filters for each harmonic order separately from 0% to 100%. Because the standard G5/4 is a bit more tolerant for the 7^{th} harmonic than for other harmonic orders, the compensation factor for the 7^{th} harmonic was only set to 75% (see Table *3*).

The installation requirement of proper operating active harmonic filters in each transformer supply situation (see Figure 31) was solved as follow:

1.) With the active harmonic filter feature "Dual Page Setting", which allows the selection of two completely independent setting parameter pages, by switching a digital input of the active harmonic filter.
2.) With the active harmonic filter feature, which allows internal additions (summations) of current transformer (CT) signals.

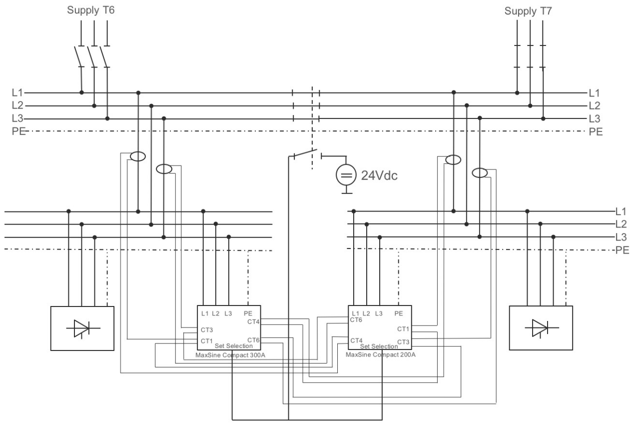

Figure 33: Active harmonic filters installation; Situation with closed bus coupler

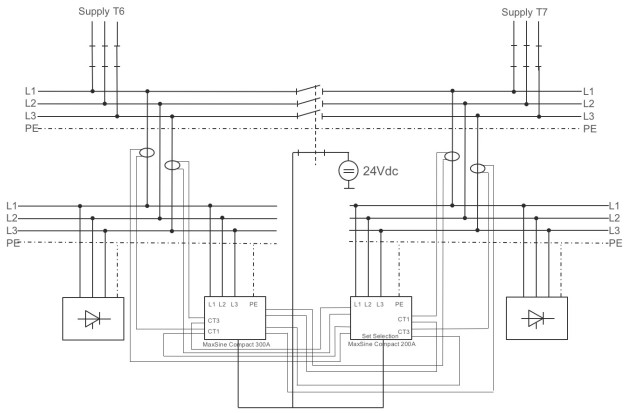

Figure 34: Active harmonic filters installation; Situation with opened bus coupler

Figure *33* and Figure *34* show the network situations with opened (Figure *33*) and closed (Figure *34*) bus coupler. A fourth switch contact of the bus coupler contactor switches a 24VDC voltage to the digital input "Dual Page Setting" of both active harmonic filters. In closed bus coupler situation, the CT values of T7 are added to the CT values of T6, and both active harmonic filters together are operating like one big device.

In opened bus coupler situation, the CT values of T7 are only used for the 200A active harmonic filter, and the CT values of T6 are only used for 300A active harmonic filter. This means that in opened bus coupler situation, both active harmonic filters act completely independent from each other like two separate devices.

The compensation effect was recorded with a TOPAS power analyser, connected to T7. The circumstances when the active harmonic filters were switched off were as follow:
- The network was highly distorted
- The G5/4 limits for both, harmonic current emissions as well as voltage harmonic distortion were exceeded
- Value of the voltage distortion: THD_u = 7%
- Value of the current distortion, THD_i = 299A

The circumstances when the active harmonic filters were switched on were as follow:
- The network power quality improved significantly
- The G5/4 limits for both harmonic current emissions as well as voltage harmonic distortion were achieved
- Value of the voltage distortion: THD_u = 3%
- Value of the current distortion, THD_i = 92A

The measurement results with and without operating active harmonic filters are presented in the following figures:

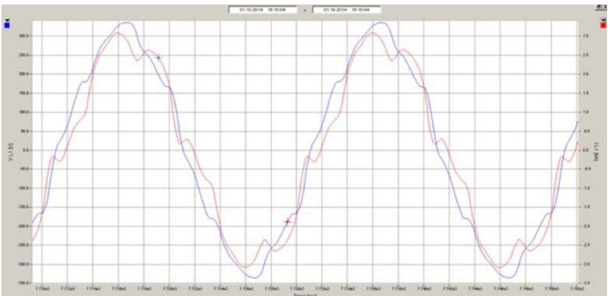

Figure 35: Voltage (blue) and current (red) waveforms without active harmonic filter compensation

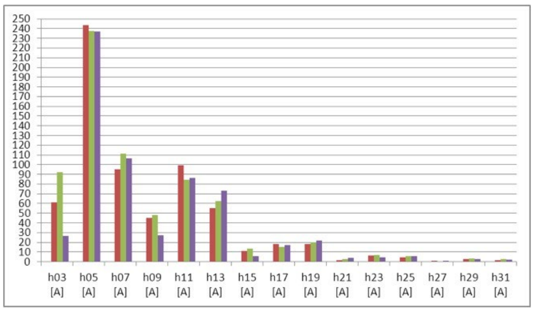

Figure 36: Current harmonics L1 (red), L2 (green) and L3 (violet) without active harmonic filter compensation

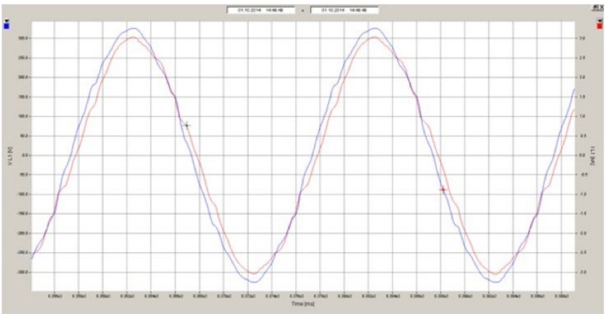

Figure 37: Voltage (blue) and current (red) waveforms with active harmonic filter compensation

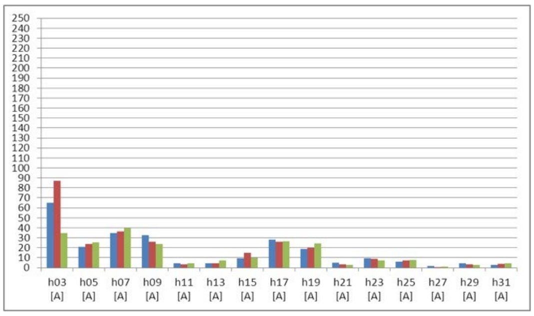

Figure 38: Current harmonics L1 (blue), L2 (red) and L3 (green) with active harmonic filter compensation

4.2 Case Study, Harjutarhat Oy, Finland

Harjutarhat Oy is an automated greenhouse, located 70 km northwest from Helsinki. The company produces about 400 tons tomatoes per year, with less than 10 persons in a more or less fully automated process.

Figure 39: Tomato production at Harjutarhat Oy

One of the most important issue by growing tomatoes as fast as possible, is the illumination of the tomato plants. Best results are achieved by the usage of sodium-vapor lamps. In the Harjutarhat greenhouse, 3000 pieces of sodium-vapor lamps are operating, and sometimes all of them at the same time. For sufficient tomato growing results, the illumination must be perfectly adjusted. Low power quality doesn't allow exact illumination adjustments and the electronic of each sodium-vapor lamp emits lots of harmonics to the electrical network. The biggest problem of Harjutarhat

Oy was the huge neutral current, consisting of zero sequence harmonics, mostly 3rd harmonic current.

Therefore, power quality improvement measures were highly recommended, and the installation of a 350kvar active harmonic filter, with a neutral wire compensation capability of 1500A took place. The compensation effect was again recorded with a TOPAS power analyser, connected to the point of common coupling (see Figure 40).

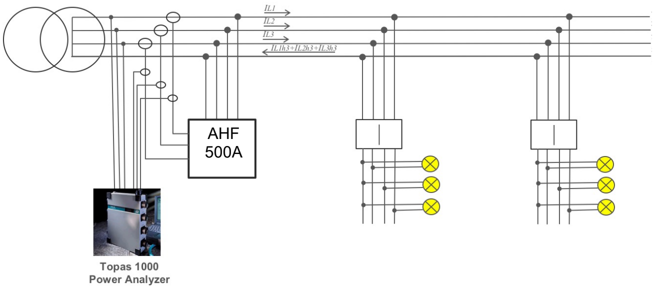

Figure 40: Active harmonic filter installation at Harjutarhat Oy

The measurement results with and without operating active harmonic filter are presented in the following figures and tables:

	AHF OFF		
	L1	L2	L3
Vrms [V]	228	228	228
Irms [A]	1626	1638	1668
Irms - Neutral [A]	1438		
Uthd [%]	5,2	5,6	6,2
Ithd [A]	444	482	516
Total Active Power [kW]	1058		
Total Reactive Power [kVar]	223		
h01 [A]	1567	1567	1587
h03 [A]	440	479	513
h05 [A]	57	53	54
h07 [A]	4	5	6
h09 [A]	3	3	4
h11 [A]	10	9	10
H13 [A]	7	7	7

Table 4: Measurement results without active harmonic filter compensation

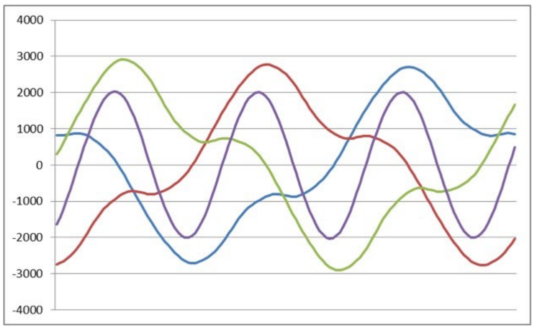

Figure 41: Current waveforms L1 (green), L2 (red), L3 (blue) and N (violet) without active harmonic filter compensation

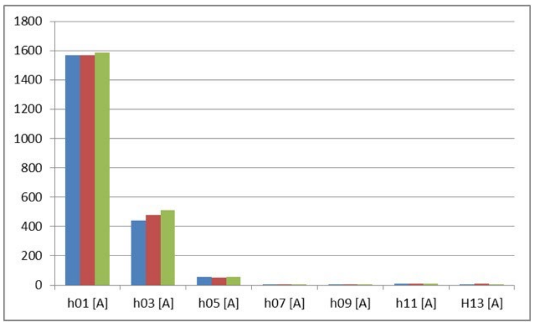

Figure 42: Current harmonics L1 (blue), L2 (red) and L3 (green) without active harmonic filter compensation

	AHF ON		
	L1	L2	L3
Vrms [V]	228	228	228
Irms [A]	1584	1586	1609
Irms - Neutral [A]	30		
Uthd [%]	0,8	0,7	0,6
Ithd [A]	54	53	46
Total Active Power [kW]	1070		
Total Reactive Power [kVar]	200		
h01 [A]	1608	1585	1584
h03 [A]	11	10	10
h05 [A]	71	56	67
h07 [A]	4	6	6
h09 [A]	1	2	1
h11 [A]	10	9	10
H13 [A]	8	8	7

Table 5: Measurement results with active harmonic filter compensation

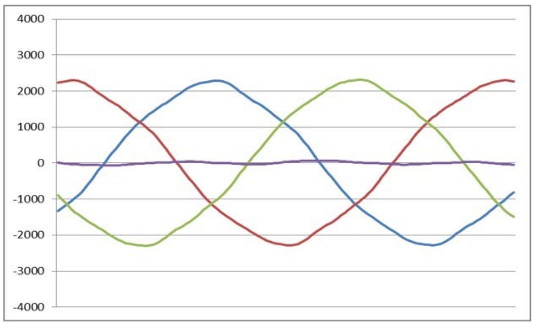

Figure 43: Current waveforms L1 (green), L2 (red), L3 (blue) and N (violet) with active harmonic filter compensation

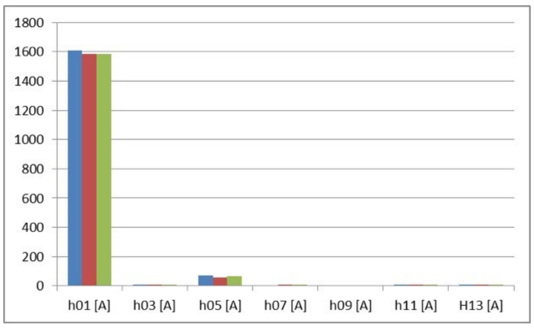

Figure 44: Current harmonics L1 (blue), L2 (red) and L3 (green) with active harmonic filter compensation

The active harmonic filter achieved significant improvements:

- Improved transformer stability
- Less transformer losses
- Improved voltage stability
- Less harmonic distortion
- Much smaller neutral current
- Better luminous efficiency

5 CONCLUSIONS

Harmonics can have a significant impact on electrical systems and the facilities they feed. It is important to consider the impact of harmonics when contemplating additions or changes to a system. In addition, identifying the size and location of nonlinear loads should be an important part of any maintenance, troubleshooting and repair program.

6 REFERENCES

1. J. Arrillaga, N. R. Watson, (2003), Power System Harmonics
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