Active filtering is superior

Although harmonic currents may be reduced by different means, the latest development in the semiconductor industry allows Active Filters to take over the performance of traditional harmonic solutions. Compared to the passive solution used nowadays, the installation of AF offers superior harmonic mitigation, a more widely compensated harmonic spectrum, adaptive compensation of reactive power according to the installation needs and improved stability of the power system due to the lack of parallel resonance. Being fitted with sensors, the AF has major advantages over previous harmonic solutions: safe operation, stability, self-testing and protection. A case-study comparison validates all the value proposition points of the shunt Active Filter.

Frequency converters are commonly used in the Water/Wastewater industry due to energy saving, increased equipment life-time and automation. Optimization of the process, reduction of chemical consumption, minimization of losses in water distribution, improvement of pressure control, prevention of over/under loading and the elimination of water hammer effect are all benefits of frequency converters, which promotes their extensive utilization in Water/Wastewater industry.
For frequency converters the most used front-end topology is the 6-pulse diode rectifier, due to well-known advantages such as high efficiency, low cost, robustness and reliability. Furthermore, regenerative power applications are not largely met in the Water/Wastewater industry, which leaves the existing 6-pulse frequency converters the most desired power conversion solution in terms of efficiency and cost.

The major disadvantage of the diode rectifier is that it draws non-sinusoidal currents from the power supply, referred to as harmonic currents. Harmonic currents cause harmonic voltage distortion, additional losses and heating in the electrical equipment, unwanted torque, vibration and noise in motors, malfunction and failures of the sensitive equipment, resonances, interference with electronic equipment and premature ageing (Arrillaga *at al.* 2000) and these effects increase significantly as the power rating of frequency converters increase. To overcome the effects of harmonic currents, different harmonic mitigation solutions have been proposed and implemented over the years. The simplest solutions were found in passive harmonic filters, either series inductors or parallel capacitors, connected such that their impedance would block or sink the harmonic currents. Several other solutions emerged from case to case, such as pulse-multiplication, magnetic wave shaping, reconfiguration of the power system and mixed non-linear loads (Hansen, 2000).

Lately, the use of active solutions (involving power converters and dedicated control algorithms) came to improve the efficiency of mitigating harmonic currents. An active harmonic filter injects harmonic current of opposite phase to the non-linear load current so that all harmonic currents are ideally cancelled and only the fundamental current is left to be supplied by the power system.

Mitigation of harmonic currents by active filters (AF) has been acknowledged as being the harmonic solution of the future (Akagi, 1996). Although several manufacturers exist, the active filter is still considered as an emerging technology.

However, the technological progress of the last decade in the semiconductor industry has allowed a constant increase of the power rating and switching frequency of the static power switch, a key element that has changed the perception of active filters.

This paper analyzes the advantage of using active filters in the Water/Wastewater industry. A comparison of AF against other common harmonic mitigation solutions is given, which concludes that the AF is the best harmonic mitigation solution to suit existing frequency converter installations.

Further, it is shown that the enhanced harmonic filtering achieved is not the only advantage of active filters. Fitted with dedicated control algorithms, it can provide additional functionality such as reactive power compensation, damping of network resonances, and flicker mitigation. Self protected and readily configurable, AF increases the reliability of the power network, either installed locally at the frequency converter or as a central solution.

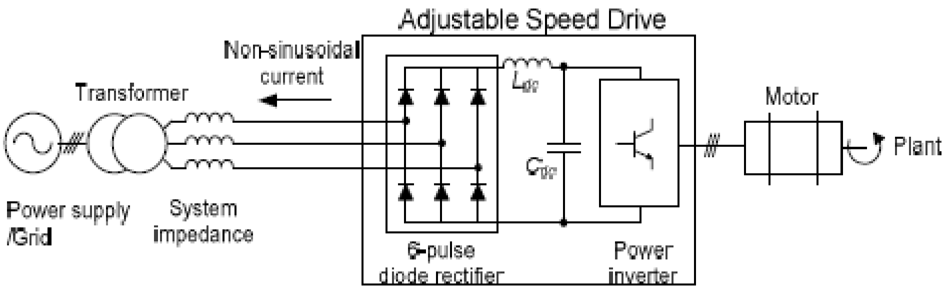


Fig. 1

Electrical diagram of the Variable Speed Drive based on front-end 6-pulse diode rectifier.

Fundamentals of harmonics

The line current of a diode rectifier is naturally determined by the voltage applied on the diode terminals and the existing passive components. Although the line current is repetitive and provides power to the frequency converter, the current is not sinusoidal. The current is a complex summation of the fundamental current (i.e. the active power) and multiple harmonic currents, generated due to the non-linear behaviour of power conversion. Such a load where the current does not have the sinusoidal shape of the line voltage is said to be ‘non-linear’.

Circulation of these harmonic currents creates losses in and determines overheating and overrating of the power system. Furthermore, harmonic currents cause harmonic voltage distortion, undesirable for all other equipment connected to the power system, such as capacitors, ac machines, control and protection equipment, measuring instruments and electronic power converters.

In the early age of electricity, due to the smaller amount of harmonic current generated the impact was of little significance, although it is reported in literature (Owen, 1998). However, nowadays with extensive utilization of the non-linear loads, most of them being power electronics, the effects of harmonics must be considered. A detailed description of harmonic sources and their effects may be found in (Arrillaga *at al.* 2000).

An overview of the effect of harmonics on different components of the power system is gathered in Table 1. As most industrial applications, the Water/Wastewater industry includes all the components described in Table 1, although not at to very large extent communications, IT and lighting. However, the latter can be less exposed to the effect of harmonic distortion by a proper decoupling from the non-linear loads circuit, with a separate power supply source and a careful design of grounding and neutral cabling. Harmonic distortion may also affect motors connected to the network, although it depends on their location and utilization in the process. The components that are continuously exposed to the harmonic distortion are power transformers, cable paths and circuit breakers. The same components are the most critical in any given plant in case of failure, when analyzing the risks and costs of plant downtime and repair / replacement.

Due to the potential damaging effect of harmonics, the international Power Quality standards have been updated with dedicated chapters on harmonics. The subject of harmonics is treated with regard to both immunity to harmonic voltages and permissible limits of generation of harmonic current (IEEE 519, IEC61000). In order to quantify the amount of harmonic currents that must be monitored, several terms are practically used:

- individual harmonic amplitudes given by the Fourier analyses: I_5, I_7, I_{11}, I_{13}, etc.
- Total Harmonic Distortion (THD), a term that quantifies the degree of distortion relative to the fundamental component: $THD = 100 \cdot \sqrt{\frac{\sum_{h>1} I_h^2}{I_1^2}}$

• Harmonic distortion D_N caused by the presence to the harmonics. Assuming sinusoidal voltages, the harmonic distortion power is calculated as: $D\ S\ THD\ _{N} = \cdot\ _{1}$, where S_1 is the apparent power of the load related to the fundamental current, and THD_i is the Total harmonic current distortion.

Table 1 - *Description of the harmonic effects on power system components.*

Component	**Effect of harmonics**	**Water/Wastewater**			
		Occurrence of the specified effect	**Risk due to failure of component**		
			Low	**Med**	**High**
Power generators	- additional heating - rotor heating - appearance of pulsation torque - increase in torsion force	NA [1]			
Transformer and inductors	- winding stray losses - hysteresis losses increase - additional heating - derating	Yes			✓
Conductors and cables	- skin and proximity effect - additional heating - dielectric puncture	Yes			✓
Circuit breakers and fuses	- skin and proximity effect - additional heating due to overload - failure in protection - changes in rise-time and fall-time	Yes			✓
Relays	- changes in delay characteristic - false tripping	Yes		✓	
Motors	- increase of stator and rotor losses - additional leakage field losses - shaft torque oscillation	Yes		✓	
Capacitors	- dielectric losses increase - resonant over-voltage - life expectancy decrease			✓	

Instrumentation and electronic equipment	- possible erroneous operation - erroneous measurement	Yes [2]	✓		
Communication and IT	- interference over long wires - data loss incidents	Yes [2]	✓		
Lighting	- flicker effect - transformer or choke saturation	Yes [2]	✓		

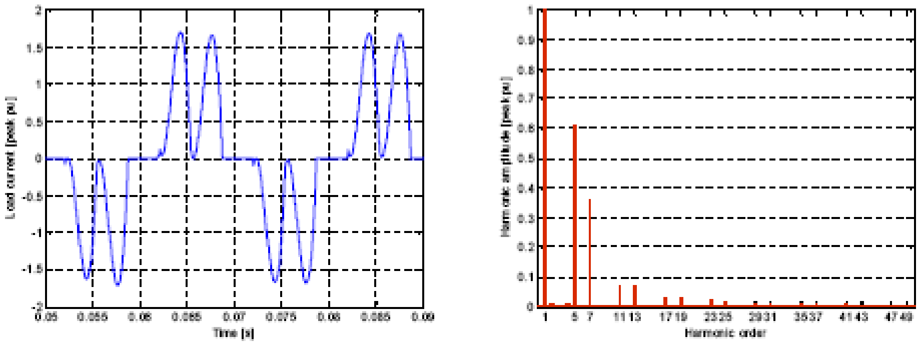
[1] Not commonly applicable in Water/Wastewater industry.

[2] Occurrence is possible but it can be avoided by a proper design of the power supply and grounding.

For 6-pulse based frequency converters, the line-side currents resemble the waveform given in Figure 2. The time domain waveform can be recorded with an oscilloscope and the harmonic spectrum provided by a power analyzer or calculated by Fourier transform applied on the measured signal. For this particular case it can be seen that the frequency converter generates harmonics currents as: 5th of amplitude 60 %, 7th of 35 %, etc. The THD is 70 %, indicating that the harmonic power S_h consumed from the power source is 70 % of nominal active power.

Therefore, for each 100 % active power, which is the power providing motion, the VSD drains another 70 % in the form of harmonic currents.

Figure 2 – *Line side currents of a 3-phase based VSD: a) time domain waveform, b) harmonic spectrum,* $THD_i = 70\ \%$.



(a)　(b)

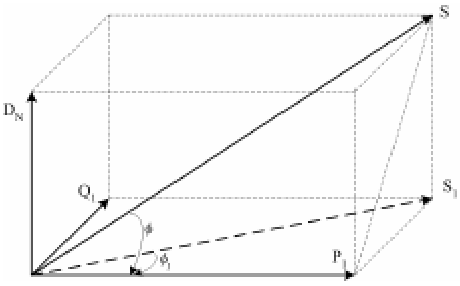
In terms of consumed power, Figure 3 gives the decomposition of the apparent power into different power components. The power vector P_1 is the active power, which is the power transferred to the motor plus losses associated with current flowing through the electrical components. The power vector Q_1 is the reactive power consumed by all capacitors or inductors in the plant. The non-fundamental power vector D_N comes from the frequency converter's non-linearity and represents the amount of power spent on harmonics, i.e. quantified by the THD_i. It can be easily seen that the total apparent power S, paid by the consumer, is determined not only by the active and reactive powers, but also by the amount of harmonics D_N. If harmonic currents are removed, the total apparent power becomes lower, i.e. S_1, lowering the cost of electricity.

$$S = \sqrt{P_1^2 + Q_1^2 + D_N^2} = S_1 \cdot \sqrt{1 + (THD_i)^2}$$
$$S_1 = \sqrt{P_1^2 + Q_1^2}$$
$$S_1 < S$$

The power factor PF, another indicator used to determine the energy paid by the consumer, is also adversely affected by harmonic currents. Therefore, by regulating only the reactive power Q_1 one cannot provide unity power factor.

Figure 3

Decomposition of the total apparent power S in 3 power vectors: P_1 the active fundamental power, Q_1 the reactive fundamental power, D_N the non-fundamental power (harmonics).



$$PF = \frac{P_1}{S} = \frac{P_1}{\sqrt{P_1^2 + Q_1^2 + D_N^2}}$$
$$\cos Phi = \frac{P_1}{S_1} = \frac{P_1}{\sqrt{P_1^2 + Q_1^2}}$$
$$\cos Phi > PF$$

Therefore, it becomes clear that the harmonic currents produced by frequency converters are undesirable; first, because of their hazardous effects on the power system; second, because of the enforced existing Power Quality standards, and third due to the increased energy consumption finally paid by the user.

Harmonic mitigation solutions

Numerous harmonic mitigation solutions have been proposed in literature, sustained by theoretical analysis, simulations and practical implementations. As the studies showed, harmonic mitigation is not possible without additional costs and engineering. Even though the literature is well documented as regards line-side harmonic current reduction, a complete, inexpensive, reliable, highly efficient and off-the-shelf solution has not yet been found.

A complete characterization of all existing harmonic solutions is difficult to present within this paper. However, keeping the focus mainly on harmonic current mitigation, an overview may highlight:-

- grid enhancement, system reconfiguration, change or reinforcement of the return wire
- passive shunt filters (broadband harmonic filter, tuned filters, harmonic trap filters)
- additional ac coils or dc coils installed on frequency converters
- phase multiplication (12-pulse, 18-pulse frequency converters)
- mixing different types of frequency converters, possible involving a phase-shifting transformer
- improved rectifier (Vienna rectifier, Minnesota rectifier, boost rectifier)
- active front-end (active rectifier, matrix converter, soft-switching)
- active filters
- other methods (magnetic wave shaping, third harmonic injection, electronic inductor)

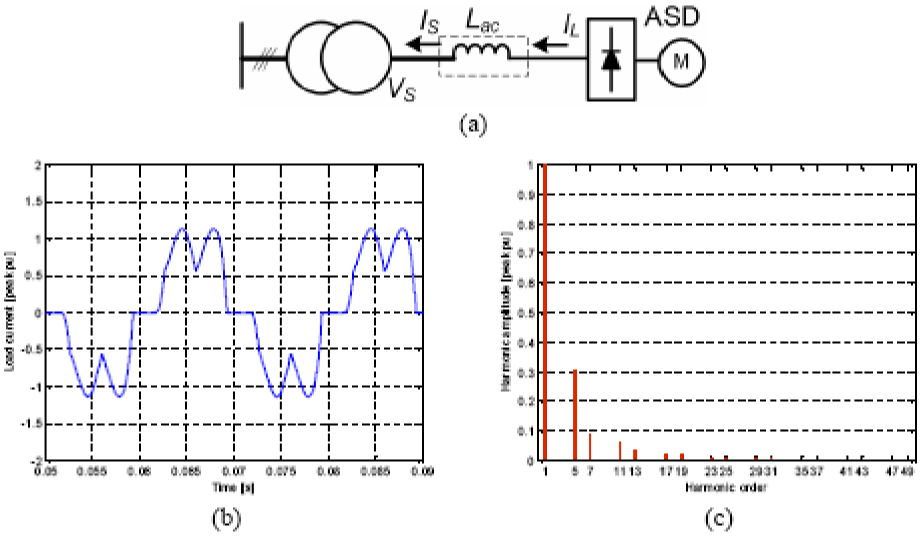
Out of the above solutions, only some are suitable in the Water/Wastewater industry, as both the manufacturer and customer would choose an inexpensive non-invasive method that could be retrofitted to the existing layout and the frequency converters. This practically reduces the applicable harmonic solutions as shown in the following.

AC or DC coil (reactor)

The use of inductors in frequency converters is a known practice often used to smooth the high inrush currents and reduce the harmonics. Manufacturers may include dc-link coils in frequency converters to reduce harmonic currents or for smoothing the dc current but this can be done only during the frequency converter’s manufacture. Once the frequency converter is installed in the field it is impossible to add or remove the dc-link coil. The simplest, fastest and non-invasive solution is to install ac-coils in front of the drive (Figure 4a). The biggest advantage of the ac-coil is the simplicity. As the ac-coil is a passive harmonic solution, there is no need of special setup when commissioning, and the downtime at installation is relatively short.

Figure 4

Harmonic current mitigation with ac-coils, a) topology, b) time domain line side current I_S*, c) harmonic spectrum,* THD_i *= 33 %.*



However, as with any passive solution, the inductor has additional power losses at the fundamental frequency. Furthermore, since the inductor is connected in series with the frequency converter, there is a risk of damaging the frequency converter if the inductor fails and the frequency converter has to cope with the voltage drop at the input terminals, across the ac-coils. The inductor has to be designed for the full nominal current of the frequency converter, but also including the harmonic currents, which may not be efficient and cost effective in large power applications. And, as with any inductive load, the ac-coils decrease the power factor due to their reactive power consumption.

The ac-coil is a broadband solution, i.e. it reduces harmonic current over a wide spectrum. However, the reduced THD_i highly depends on the coil's inductance, the higher it is, the lower the THD_i becomes. However, the inductance is practically limited to values between 1% - 5% per-unit. Figure 4b, and -c show the waveforms respective to the harmonic current spectrum with a 3 % inductance.

Due to its simplicity, ac-coils are still generally preferred in frequency converter applications of low and medium power ratings.

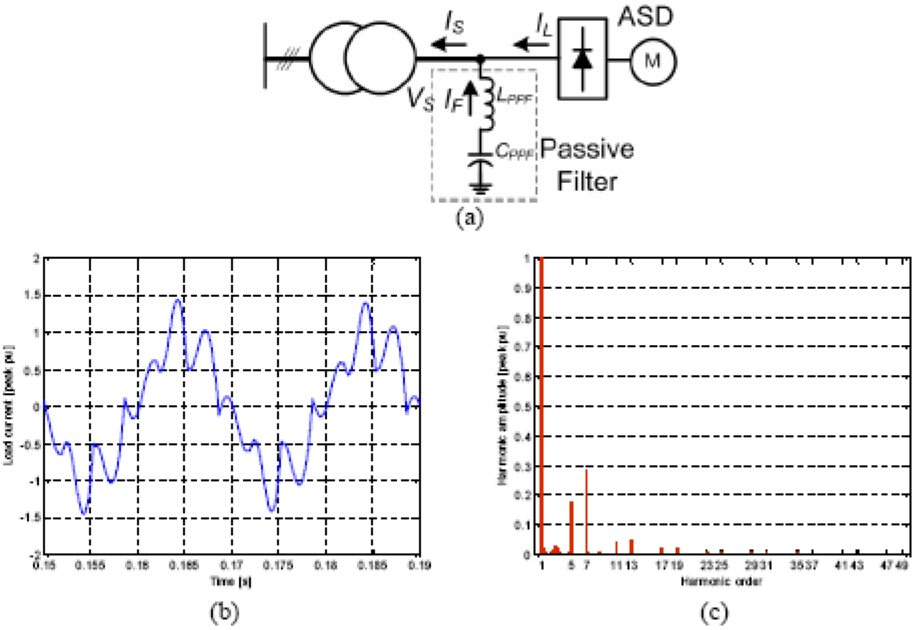
Passive harmonic filters

Passive shunt-tuned harmonic filters (Figure 5a) have been extensively used in industry for the last 50 years due to their robust and simple construction, compensation of the reactive power, and comparatively lower cost compared to other harmonic solutions. Their initial utilization in power factor correction applications was the driving force of their extended use within power networks, although nowadays it still remains the decisive factor for their adoption. If the existing plant has no need to compensate large amounts of reactive power, which may be the case for many Water/Wastewater plants especially where the directly connected ac-motors are fitted with frequency converters, then the use of capacitive harmonic filters is limited.

The design of passive harmonic filters, although extensively covered in literature (Bornitz *at al.*, 1958), is not straightforward because the mitigation efficiency depends on the grid impedance.

Figure 5

Harmonic current mitigation with shunt Passive Filters tuned for 5th harmonic, a) topology, b) time domain line-side current I_S*, c) harmonic spectrum,* $THD_i = 40\ \%$*.*



For stiff grids it becomes difficult to design an efficient shunt passive filter, because the harmonic currents will flow towards the lowest impedance path, which can in this case be the power supply.

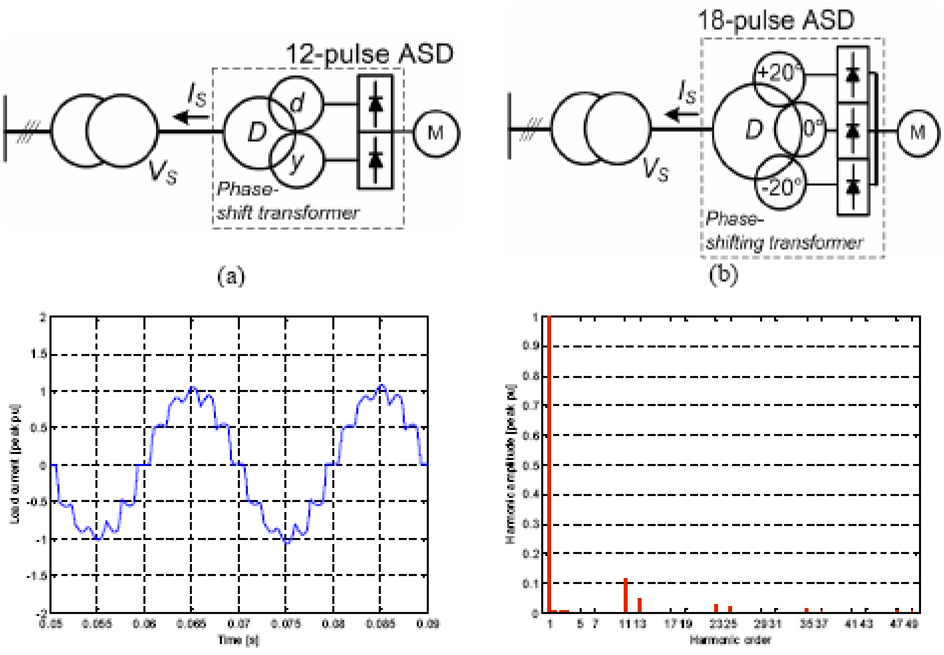
A severe drawback of passive tuned filters is the change to the network impedance due to the interaction between the filter capacitor and transformer. Parallel resonances appear (Das, 2004) and may be responsible for voltage oscillations at certain frequencies if the design does not take into account the temperature drift, parameter tolerance, aging and network changes. In order to decouple some of these drawbacks, the complexity of passive filters may be increased by connecting damping resistors, decoupling inductors, and high-pass capacitors. These will increase the losses even more and complicate the design, which makes them suitable only in particular applications. Usually one branch (capacitor, inductor) controls a single harmonic order, therefore the overall filtering installation requires multiple parallel connected branches tuned at different orders.

Figure 5b and -c show the currents when using a single branch tuned for the 5th harmonic. The 5th harmonic is not completely removed (compare with the initial current from the frequency converter in Figure 2), since the filter is detuned to avoid overloading due to harmonic voltages of the same order. In practice additional branches must be installed to remove at least the 7th harmonic current, thus giving a much lower THD_i than presented.

The protection of passive harmonic filtering is more complex than the previous solution of ac coils, a connection-disconnection logic sequence must exist to protect them from causing or amplifying network faults, but it is manageable and it can be integrated into existing automation.

Figure 6

Harmonic current mitigation with multi-pulse frequency converter*, a) topology of 12-pulse* frequency converter*, b) topology of 18-pulse* frequency converter*, c) time domain line-side current* I_S *with 12-pulse* frequency converter*, d) harmonic spectrum with 12-pulse* frequency converter, $THD_i = 13\ \%$.



(a) (b)

(c) (d)

As the harmonic shunt filters are parallel connected solutions, the commissioning and maintenance can be done without interrupting the process or disconnecting the equipment.

Most of the passive power filters' applications are in the medium-high power range. A high power passive filter is preferably selected and customized from an early stage of the network design of the local network topology, to keep the parallel resonances under control. Medium power range filters are provided by many suppliers for harmonic compensation at either individual loads or at the central point.

Multi-pulse inverters

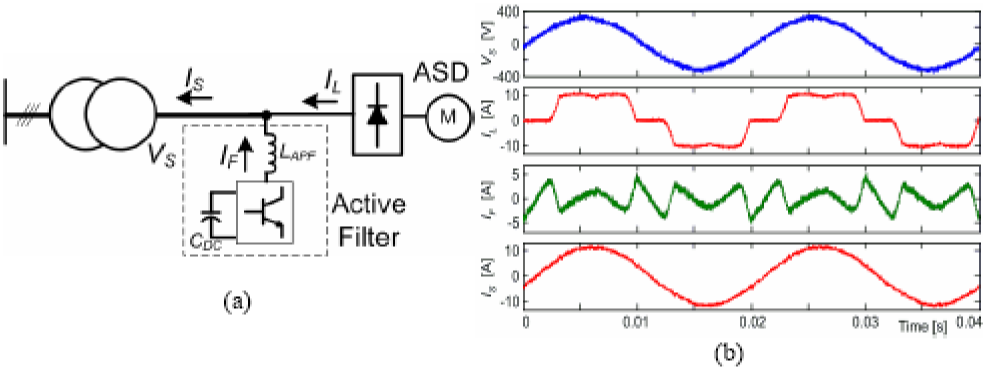
The principle of multi-pulse inverter operation relies on the summation and consequently the cancellation of the harmonic currents of equal amplitude but opposite phase. The change of phase is done by a phase-shifting transformer e.g. delta-primary, star-secondary.

In this case, 12-pulse and 18-pulse rectifiers can be created by using a specially designed phase shifting transformer, having multiple secondary windings that change the supply phase angle. Theoretically, 2, or respectively, 3 identical 6-pulse diode rectifiers can be connected to build a 12-pulse, or respectively an 18-pulse frequency converter (see Figure 6a).

The only harmonic currents left are of orders +12h-1, respectively +18h-1. The harmonic currents of order 5, 7, etc, are cancelled. This can be seen in Figure 6b, for a 12-pulse frequency converter, where 5th and 7th harmonic currents are ideally cancelled but 11th and 13th remain, actually having higher amplitudes compared to the original frequency converter in Figure 2.

Figure 7

Harmonic current mitigation with shunt Active Filter, a) topology, b) typical waveforms: line voltage V_S, load current I_L, filter current I_F, line current I_S.



(a)

(b)

In practice, the design of a multi-pulse frequency converter is not that simple. Some practical limitations are the unbalanced winding ratio, transformer tolerance and unequally distributed power flow.

If these conditions are not overcome, then the ideal cancellation of harmonic currents is lost. The same happens if the 12-pulse / 18-pulse frequency converter operates under unbalanced or distorted voltage systems (MTE Corporation, 2007). In these conditions the achieved THD may be 1.5-2 times higher than ideally estimated.

One potential limitation with multi-pulse frequency converters is that the solution must be considered from the outset when designing Water/Wastewater plant. A later retrofit, such as changing the existing 6-pulse frequency converters into multi-pulse frequency converters is not at all simple, because the existing frequency converters may not be able to share the dc-link connection, there can be some wiring restrictions, and possible lack of connection and control of the newly built power converter.

One common compromise to retrofit existing 6-pulse frequency converters is by installing a phase-shifting transformer in the local network and connecting half of the frequency converters to alternate secondary windings, which reduces the harmonic currents to some degree. The most challenging aspect of this solution is achieving equal power sharing through each of the secondary windings for best harmonic cancellation. As the existing frequency converters may be loaded differently, depending on the process, it may be difficult to obtain optimum harmonic cancellation. Similarly, as with ac-coils, the phase-shifting transformer becomes a critical component that must carry the nominal current of the loads served. Because the transformer is connected in series, protection is required so as not to damage the diode rectifier. The downtime is higher at commissioning/maintenance.

The power losses depend on nominal and harmonic currents, which require a carefully designed transformer capable of dissipating the heat. As opposed to the shunt passive filters, multi-pulse frequency converters do not create parallel resonances with the power supply transformer and their installation on a given network creates no leading power factor. They are used in applications of medium to high power.

Shunt Active Filters

A shunt Active Filter (AF) is a power electronic device used for active mitigation of the harmonic currents from non-linear loads. There has been remarkable progress in the development of shunt Active Filters during the last decades, encouraged mainly by the increased performance of the power switches in terms of power level and switching frequency. Furthermore, the evolution of Digital Signal Processors and new control theories enabled superior harmonic compensation characteristics and stable operation of AF's compared to classical passive filters.

The AF detects the harmonic spectrum of the load current I_L and generates an output current I_F, which ideally is of the same harmonic spectrum as the load current but phase opposed. In this way the AF current cancels out the harmonic current but leaves the fundamental current component I_S to be provided by the power system (Figure 7).

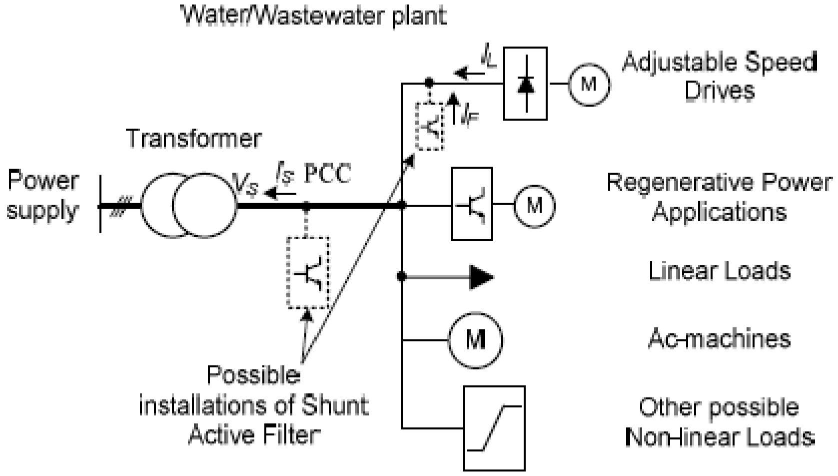
In addition to the harmonic mitigation, the AF may easily compensate the reactive power generated by the plant by supplying capacitive or inductive power to the system, thus reaching unity power factor (Singh *at al.*, 2004). Other auxiliary functions provided are compensation of flicker, active damping of resonances, and mitigation of inrush currents and long transients, e.g. motor start-up (Kalaschnikow, 2003).

Possible points of connection of AF on the power network are either close to the non-linear load, e.g. a high power Adjustable Speed Drive or at the point of the common coupling (PCC) as a central harmonic solution serving multiple frequency converters (Figure 8). Usually the location is selected based on desired performance, network stability, harmonic mitigation efficiency and costs (Akagi, 1996).

The efficiency is higher than that of a shunt Passive Filter, because the AF provides the harmonic current mitigation but does not load the network at the fundamental frequency. Unlike the shunt Passive Filters, there is no need of connecting multiple branches for mitigation of several harmonic orders at once. One single AF is capable of mitigating up to a practical harmonic order of 30-50, meeting the actual harmonic standards and regulations.

Figure 8

Possible connection of AF's in a Water/Wastewater plant.



Unlike shunt Passive Filters, there is no parallel resonance when connecting the AF to the network. If fitted with proper sensors and dedicated control the AF may actively damp existing network resonances created by capacitive loads. Furthermore, the AF can regulate the power factor, and the amount of generated reactive power is completely programmable and depends on the user imposed reference.

Unlike the other harmonic solutions described, AFs can protect themselves against voltage imbalance and pre-distortion, and keep the same high quality of the compensated current. Furthermore, AFs can prioritize the compensation of either harmonic or reactive power depending on momentary demands. This allows the AF to fulfil the harmonic standards and at the same time to achieve an optimum power factor compensation.

Another advantage is the possibility of integrating AFs into the existing automation via a communication bus with the process control computer. This facilitates remote control and changing of the compensation reference as required. Furthermore, it provides data logger of relevant events, such as fault-trips, warnings and network events. There is also the possibility of network monitoring and measurement functions that may be conveniently used by the plant automation system with the purpose of system protection and stability.

Performance evaluation

The performance obtained with the selected harmonic mitigation solution is evaluated based on Total Harmonic Current Distortion (THD_i) factor, which indicates the quality of the supply current after harmonic compensation. A lower THD_i means a better harmonic compensation.

Since all harmonic solutions depend on different factors, for example for ac-coil the impedance value, for passive shunt filter the damping factor and tuning order, etc., the THD_i cannot be precisely indicated. However, an estimated range can be specified for each harmonic solution. Figure 9 shows a comparison of the achieved THD_i (Hansen *at al.*, 2001).

For a frequency converter with no harmonic solution the line-side harmonic currents are limited only by the system short-circuit impedance and the internal dc-choke if any. The estimated THD_i is in the range 50 % - 80 %.

Figure 9

Estimated range of source current THD_i when using selected harmonic solutions.

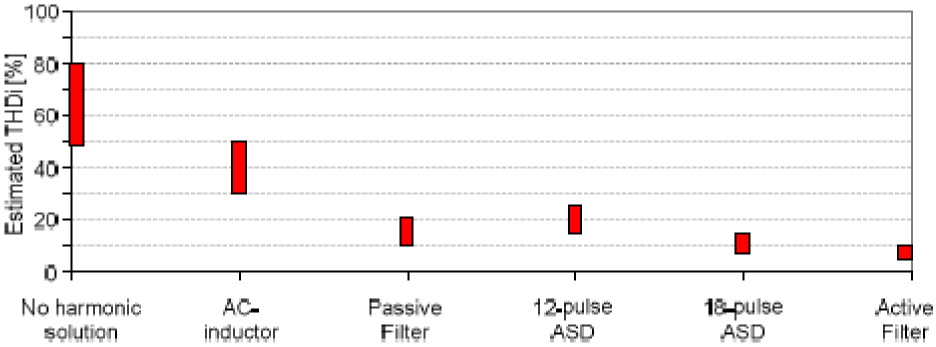
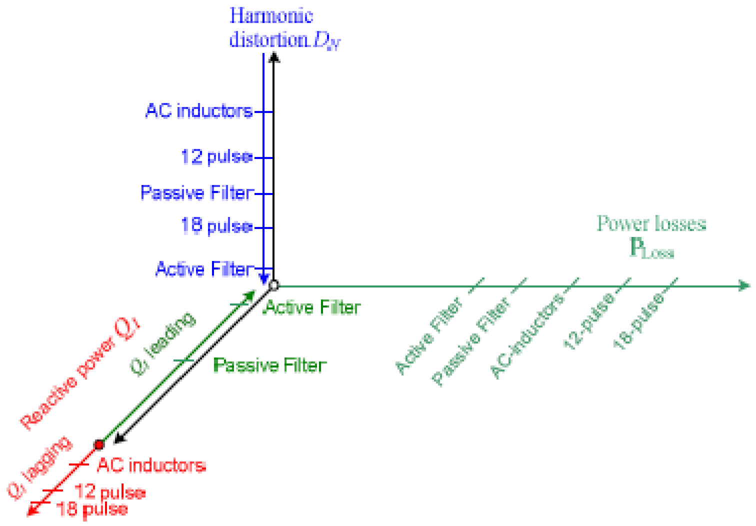


Figure 10

Graphical evaluation of selected harmonic solutions in terms of power losses, harmonic distorted ($D_{N(VSD)}$) and reactive power ($Q_{1(VSD)}$).



By simply adding ac-coils in front of the drive, the line current THD_i is reduced to a value between 30 % - 50 %. The next solution, a shunt passive filter, obtains a THD_i reduction down to 10 % - 20 %, depending on how many tuned branches exist and their total installed power.

The 12-pulse frequency converter offers a THD_i of 15 % - 25 % depending on the given voltage imbalance, while an 18-pulse frequency converter gives a THD_i between 7 % - 15 %. The shunt Active Filter can mitigate the harmonic currents down to 5 % - 10 %. Although 5 % might be expected from an AF, there are cases of 10 % THD_i, due to different factors, as voltage unbalance, transients, etc.

When comparing the performance between different harmonic solutions, the achieved THD_i is not the only decisive factor. As with any electrical equipment installed on the power system, the harmonic solutions have power losses and to some extent they generate reactive power (all passive solutions contain capacitors, inductors or transformers). As explained in the section Fundamentals of Harmonics, the total apparent power has 3 dimensions: active, reactive and harmonic distortion power.

A comparison is given in Figure 10 where selected harmonic solutions are arranged based on three criteria: the ability to compensate the harmonic distorted power (D_N), system power losses (P_{Loss}) and generated reactive power (Q_1 is positive if lagging power and negative if leading). The best performance is obtained from the solution that stays as close as possible to the origin because it means minimum losses, complete compensation of harmonic currents and unity power factor. Regarding power losses, AFs have the lowest losses among the solutions considered here.

Being based on power electronics, the efficiency of AF is higher (estimated at about 97 %) much higher than that of any other passive solution. Furthermore, the AF is a parallel solution, therefore the frequency converter current does not pass through AF.

The same happens with the shunt passive filter, but since the passive filter generates capacitive current it has additional power losses. The other passive solutions (ac-coil and multi-pulse rectifier) are based on series inductors or transformers supporting the full frequency converter current, therefore, the losses are higher.

As regards the compensation of reactive power, the AF achieves unity power factor adjusted to the plant needs. The shunt passive filter may also provide reactive power compensation but the amount of reactive power can practically be controlled in 2-3 steps, or not at all, depending on how many capacitor banks can be switched on/off. However, adjusting the reactive power determines at the same time a direct adjustment of the harmonic compensation that cannot independently be controlled. The other passive solutions (ac-coil and multi-pulse rectifier) cannot provide leading but only lagging reactive power itself dependent on the frequency converter loading. Further comparisons of the selected harmonic solutions are given in Table 2.

Case-study on a water station

The plant investigated here is a water station (electrical diagram shown in Figure 11) that supplies heated water for industrial and residential buildings around it. The water is heated by 3 burner-groups. Each burner mixes the inflow of natural gas with a controlled flow of air provided by a fan, also driven by a frequency converter. The generated heat increases the water temperature then it is delivered out to the customers by 3 pumps, also driven by frequency converters. The fans control the gas burning process and the pumps control the water flow, each device running independently from the others, but controlled by a higher-level control loop that maintains the required outflow. Therefore, depending on the outflow, the Water Station can have fans and pumps running at different speeds and loadings.

Figure 11

Electrical diagram of Water Heating Station showing the main frequency converters and their functions.

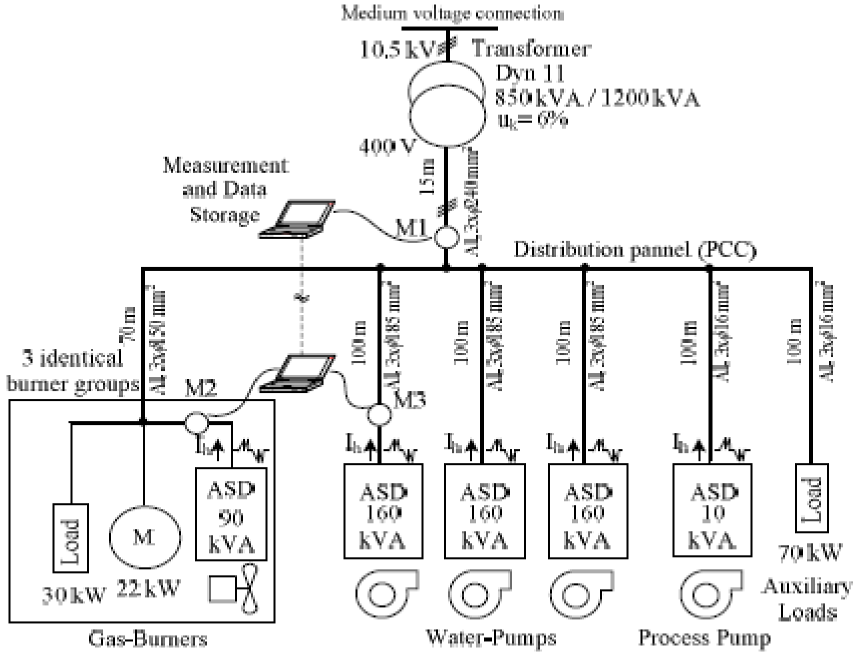
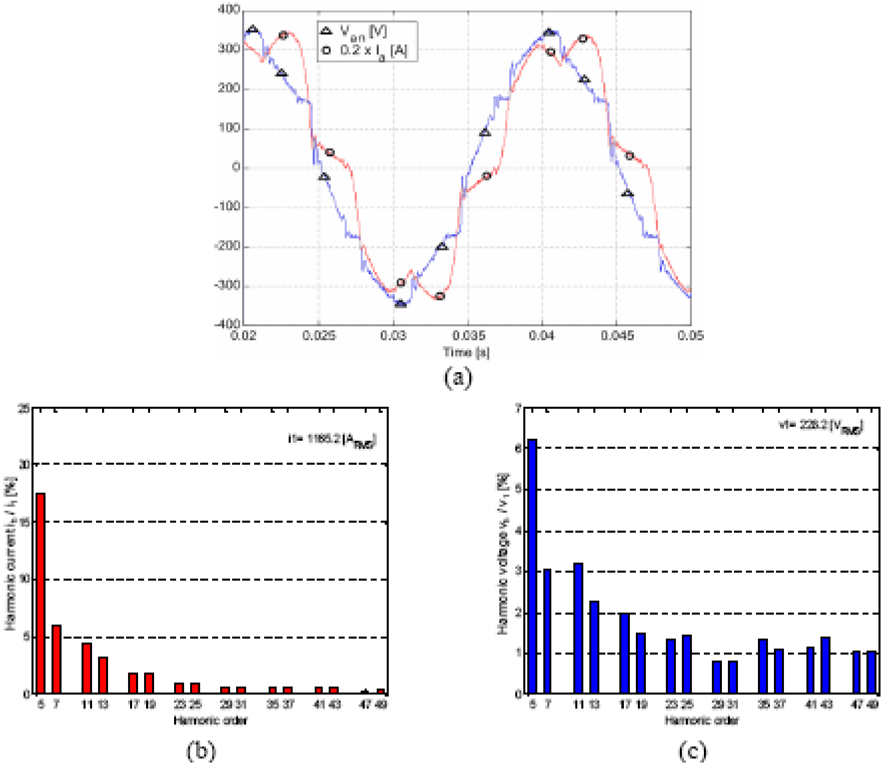


Figure 12

Measurements at the 1200 kVA transformer for 100 % loading capacity of the Water Station a) line current (I_a) and phase voltage (V_{an}), b) current harmonic spectrum, c) voltage harmonic spectrum.



(a)

(b)

(c)

The initial size of the transformer was 850 kVA. As it can be seen in Figure 11, the total power of the non-linear loads (i.e. frequency converters) is in the amount of 730 kVA and represents 85 % of total available power of the transformer. One direct consequence of this large non-linear loading is high voltage drop (alias voltage distortion) and high power losses at transformer.

When the current contains harmonics, the power losses of a transformer are composed from: resistive losses (P_{I2R}), eddy-current losses (P_{EC}), stray losses (P_{SC}).

Another consequence, which is actually critical for this plant, is a fault alarm that occurs at one of the electronic equipments. A sensor trips the alarm when the plant reaches a loading of 60 %, which stops the operation of the entire plant. The trip is caused by the high level of harmonic voltage distortion.

In order to improve the fault level or short-circuit ratio of the local network, thus reducing the losses and the harmonic voltage drop, the 850 kVA transformer was replaced by one of 1200 kVA. The fault-trip still occurs but at a higher loading of 80 %, still interrupting the operation of the water station.

Waveform records of the measured voltage and current on the secondary side, in the case of the 1200 kVA transformer, are shown in Figure 12. The current THD_i is 20 %, while the voltage THD_v is 9 %. The true power factor is 0.94, and the measured reactive lagging power is 278 kVAr.

We must now evaluate the harmonic solutions previously considered, to estimate which one is the best candidate for this water station. The goal is to find a solution that meets the IEEE 519 specifications. Based on the short-circuit power and the installation rating, the current THD_i must be lower than 8 %, and voltage THD_v lower than 5 %.

Several cases are simulated assuming ideal conditions, with no unbalance and pre-distortion:

- Case 1: no harmonic solution
- Case 2: ac-coils of 3 % installed on each drive (i.e. all 90 kW and 160 kW frequency converters)
- Case 3: installing a shunt Passive Filter at the point of common coupling (PCC) with 3 branches tuned at 5th, 7th, and 11th harmonic orders. It is expected that by reducing these harmonic currents, harmonic voltages will be reduced to less than 3 % as specified in IEEE 519 harmonic recommendation. However, there is a limitation, i.e. the total leading power given by the installed capacitor banks must not be higher than the existing lagging reactive power.

- Case 4: replacing the existing frequency converters with 12-pulse frequency converters. Although this solution may not be economically feasible, it is still considered here from a theoretical point of view.

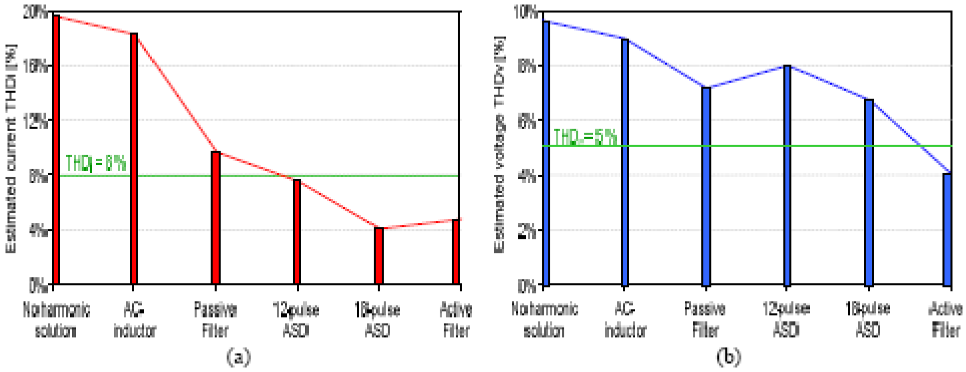
Practically, a phase-shifting transformer could be installed and the total number of frequency converters effectively split in half. It may however not be easy to divide the total power in half in all operating conditions but this solution may offer a compromise that reduces the harmonic distortion.

- Case 5: replacing the existing frequency converters with 18-pulse frequency converters. The assumptions are as in the previous case.
- Case 6: installing a shunt Active Filter for both harmonic and reactive power compensation.

The results are the current and voltage THD estimated for each case (see Figure 13). As it can be seen the ac-inductors do not help much reducing the harmonic currents because the transformer impedance is relatively large for the given non-linear loads, which partially offsets the effect of the ac-coils. The shunt Passive Filter provides a better harmonic compensation, comparable to the 12-pulse frequency converters, but still not enough to provide compliance with IEEE 519 recommendations. A very good performance is obtained by the 18-pulse frequency converter, with a current THD_i of 4 %, slightly better than the Active Filter. However, surprisingly the voltage THD_v in the case of an 18-pulse VSD is higher than of the Active Filter. This is because the 18-pulse frequency converter, even though it ideally leaves only currents of order +18h+1, their individual amplitude is higher compared to the harmonic currents compensated by the Active Filter.

Figure 13

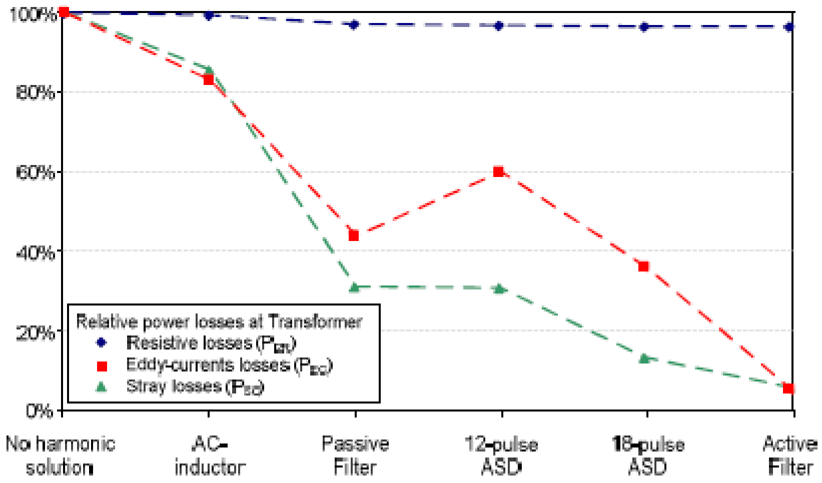
Estimation of the a) current THD_i *and b) voltage* THD_v *for the selected cases at transformer side.*



(a) (b)

Figure 14

Estimation of transformer power losses for the selected harmonic solutions. The losses are relative to the transformer losses with no harmonic mitigation.



As the currents are of high orders, the inductive effect of the grid impedance gives a higher voltage drop at these frequencies, which cumulates into a higher THD_V. Furthermore, the estimations assumes ideal behaviour of multi-pulse frequency converters, therefore, in real life, due to non-ideal voltages and parameter tolerances, the harmonic distortion given by the 12-pulse, 18-pulse frequency converters is even higher.

Based on the simulated results, the reduction in power losses at the transformer is shown in Figure 14. The losses are given in percentages relative to the initial losses obtained with no harmonic solution. For instance the solution of an18-pulse frequency converter reduces eddy-current losses to 40 %, while the AF to 10 %.

The most attractive harmonic solution is the AF, as it gives the lowest transformer losses. Considering that the AF may also provide power factor correction, the losses can be decreased even further. It is estimated that the outcome of using AF, i.e. reduced harmonic distortion and reduced transformer losses, may have negated the replacement of the initial power transformer, allowing the plant to operate in normal conditions at full capacity.

Conclusions

Although the harmonic currents may be reduced by different means, the latest development in the semiconductor industry allows Active Filters to take over the performance of traditional harmonic solutions. Compared to the passive solution currently offered, the installation of the AF offers superior harmonic mitigation, a more widely compensated harmonic spectrum, adaptive compensation of reactive power according to the installation needs and improved stability of the power system due to the lack of parallel resonance. Being fitted with sensors, the AF has significant advantages over the previous harmonic solutions: safe operation, stability, self-testing and protection. A case-study comparison validates all value proposition points of the shunt Active Filter.

Table 2 - Comparison of the most common harmonic mitigation solutions in Water/Wastewater industry

Characteristic of the harmonic solution		AC-inductor	shunt Passive Filter	12-pulse VSD 18-pulse VSD	Active Filter
Connection	**Connection type**	Series	Parallel	Series	Parallel
	Installation on the network	Local solution / possibly shared between several drives	Central solution	Local solution	Configurable at commissioning local or central solution
	Component most exposed to failure	Inductor	AC-capacitors	Phase-shifting transformers	Semiconductors
	Cause drives to stop when it fails	Yes	No	Yes	No
Power rating	**Power rating**	S=100 % S_{VSD}	Depends on harmonics and losses at fundamental frequency	S=100 % S_{VSD}	$S=THD_i\,S_{VSD}$
	Additional losses at fundamental frequency	Proportional to drive current	Proportional to Passive Filter Capacitor	Proportional to drive current	Depending on AF efficiency, estimated 97 %
	Power consumption when VSD stops	No	Yes, proportional to Passive Filter capacitor	No	At minimum level to keep the AF on stand-by
	Overloadable	Yes	Yes	Yes	No
	Future increase of power rating	Not applicable	Yes by additional parallel units. Limited by generated leading PF	Not applicable	Yes by additional parallel AF's
	Compensated spectrum	Broadband	Tuned to individual harmonics	Ideally only harmonic orders 12k+1 (respectively) 18k+1 are left.	Configurable: broadband or selective
	Adaptive compensation of harmonic currents	No	Adjustable by connecting filtering banks by relay-logic	No	Adjustable depending on user imposed limits or operation mode
	Consumed reactive power	Lagging PF	Leading PF	Lagging PF	Configurable and adjustable: non / leading / lagging
Performanc	**Adaptive compensation of power factor**	No	Yes, in discrete amounts based on selected capacitor banks	No	Automatically controlled to meet unity PF

	Supply dependent performance	Yes	Yes, highly dependent	Yes	No, dynamically adjusts to network changes
	Resonance with grid impendence	No	Yes	No	No / Can actively damp resonances if control allows
	Effect of unbalanced / distorted voltages	Decreased harmonic compensation performance	Possible overloading of the Passive Filter capacitor	Decreased harmonic compensation performance	Not affected
	Online monitoring of compliance against harmonic standards	No	No	No	Yes, embedded into the control algorithms
Commissioning & Operation	**Retrofit existing VSDs and the layout**	Yes	Yes	Rewiring or replacement of drives with 12-pulse drives	Yes
	VSD downtime at commissioning	Yes	No	Yes	No
	Programming at commissioning	No	No but relay-logic may exist in some filtering banks	No	Yes
	Allow external control and remote setting	No	Possible by controlling the relay-logic	No	Yes, via communication bus connected to computer
	Event logger and history	No	Only if fitted with additional monitoring equipment	Can be part of the 12-pulse drives control algorithm	Can be part of the 12-pulse VSD control algorithm

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