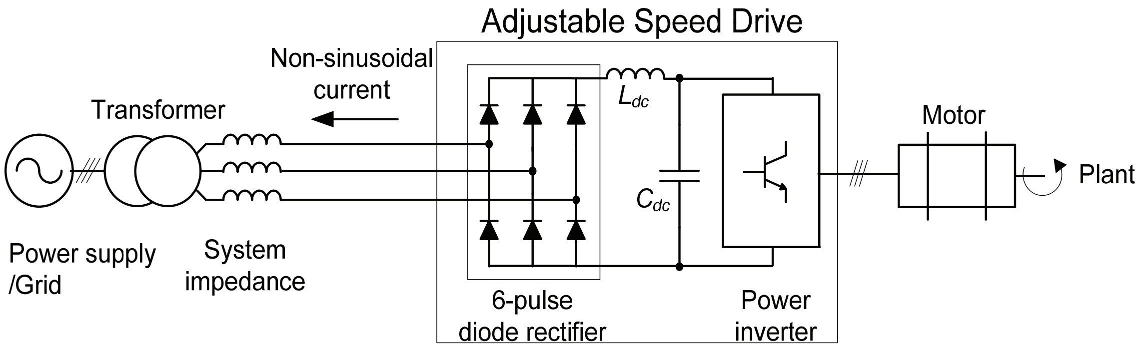
ENERGY SAVINGS AND HARMONIC MITIGATION IN THE WATER AND WASTEWATER INDUSTRY

Variable Frequency Drives (VFDs) provide several advantages to the Water/Wastewater industry, including energy savings, increased equipment life, automation, increased efficiency, and process optimization. The most commonly implemented front-end topology is the 6-pulse diode rectifier, due to its high efficiency, low cost, robustness and reliability. The major concern associated with the diode rectifier is that it generates non-sinusoidal currents, referred to as harmonic currents, into the power supply. Harmonic currents cause harmonic voltage distortion and additional losses and heating in the electrical equipment, lowering efficiency and often creating the need for oversized AC supply transformers. These effects increase significantly as the VFD's power rating increases.

Figure 1 – Electrical diagram of a Variable Frequency Drive with front-end 6-pulse diode rectifier.



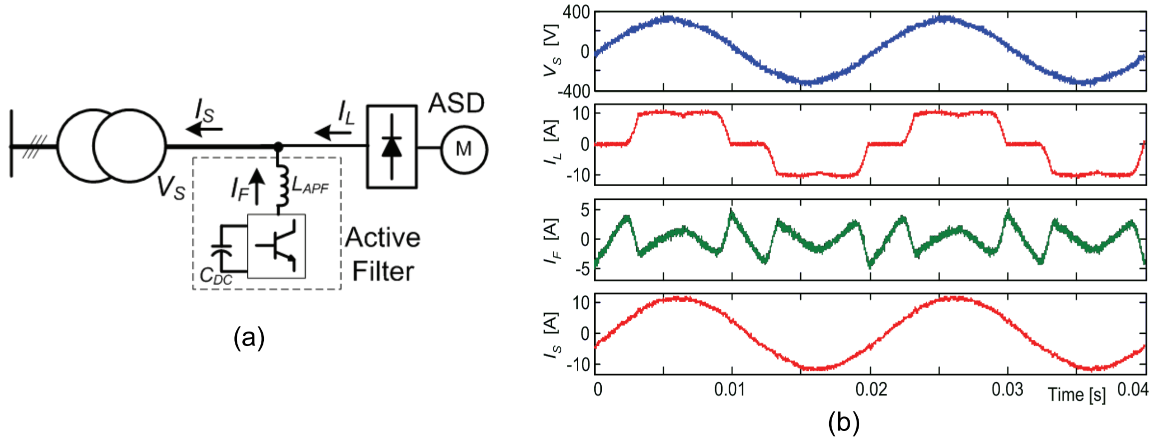
Over the years, many different harmonic mitigation solutions have been utilized. The simplest solutions consisted of passive filters, either series inductors or parallel capacitors, connected such that their impedance would block or sink the harmonic currents. Several other solutions emerged, such as pulse-multiplication, magnetic waveshaping, reconfiguration of the power system, and mixed non-linear loads.

Lately, active solutions (involving power converters and dedicated control algorithms) have been explored in an attempt to improve the efficiency of harmonic mitigation. An active harmonic filter injects harmonic current with opposite phase to the non-linear load current, cancelling all harmonic currents and leaving only the fundamental current. Although several manufacturers exist, the active filter is still considered an emerging technology. However, recent technological progress in the semiconductor industry has allowed a steady increase of the power rating and switching frequency of the static power switch, a key element that has begun to change the perception of active filters. Furthermore, the evolution of digital signal processors and new control theories enabled superior harmonic compensation characteristics and stable operation of active filters compared to traditional passive filters.

Active Filters

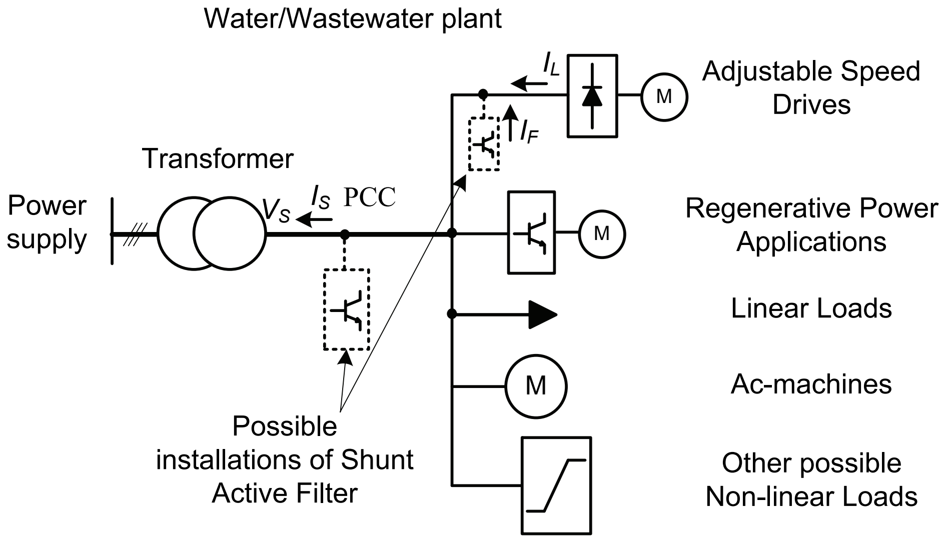
Active filters detect the harmonic spectrum of the load current I_L and generate an output current I_F, which ideally is of the same harmonic spectrum as the load current, but in opposite phase. In this way, the active filter current cancels out the harmonic currents, leaving only the fundamental current I_S (Figure 2).

Figure 2 - 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.



Possible connections of active filters on the power network are either close to the non-linear load (e.g., a high power VFD) or at the point of the common coupling (PCC) as a central harmonic solution serving multiple VFDs (Figure 3).

Figure 3 - Possible connection of active filters in a Water/Wastewater plant.



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

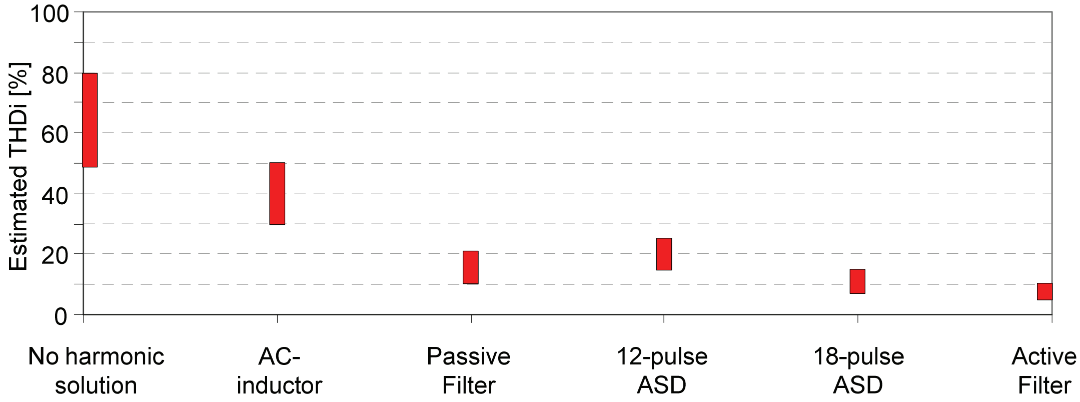
Unlike passive filters, there is no parallel resonance when connecting the active filter to the network. If fitted with proper sensors and dedicated control, the active filter may actively dampen existing network resonances created by capacitive loads. Furthermore, the active filter can regulate the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

Unlike many other harmonic solutions, active filters can protect themselves against voltage imbalance and pre-distortion, and maintain the quality of the compensated current. Furthermore, the active filter can prioritize the compensation of either harmonic or reactive power depending on momentary demands. This allows the active filter to fulfill the harmonic standards while simultaneously optimizing power factor compensation.

PERFORMANCE EVALUATION

The performance obtained with the selected harmonic mitigation solutions 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.

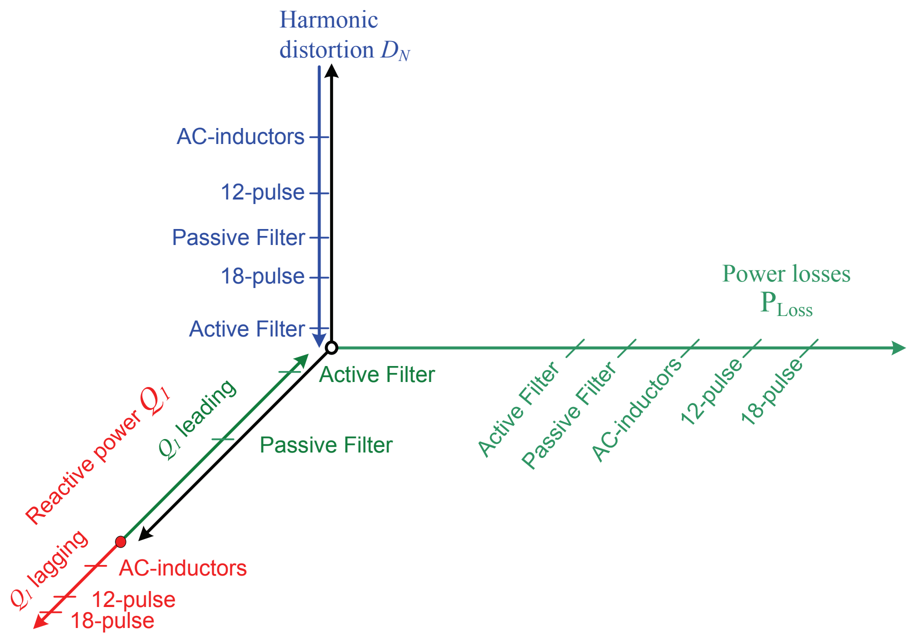
Figure 4 – Estimated range of source current THD_i using harmonic solutions.



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, all harmonic solutions have power losses and to some extent they generate reactive power (all passive solutions contain capacitors, inductors or transformers). The total apparent power has three dimensions: active, reactive and harmonic distortion power.

Error! Reference source not found. compares harmonic solutions 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 by the solution that stays as close as possible to the origin, as this indicates minimum losses, complete compensation of harmonic currents, and unity power factor.

Figure 5 - Graphical evaluation of harmonic solutions in terms of power losses, harmonic distortion ($D_{N(VFD)}$) and reactive power ($Q_{1(VFD)}$).



Regarding the power losses, the active filter has the lowest losses among the presented solutions. Being based on power electronics, the efficiency of active filters is significantly higher (estimated at

97%) than that of any passive solution. Furthermore, the active filter is a parallel solution, meaning that the VFD current does not pass through the active filter. The passive filter is also a parallel solution, but since it 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 VFD current, and the losses are therefore higher.

Regarding the compensation of reactive power, the active filter achieves unity power factor adjusted to the plant needs. The passive filter may also provide reactive power compensation, but the amount of reactive power can practically be controlled in two or three steps or not at all, depending on how many capacitor banks can be switched on and off. However, adjusting the reactive power dictates a simultaneous direct adjustment of the harmonic compensation that cannot be independently controlled. The other passive solutions (AC coils and multi-pulse rectifiers) can only provide lagging reactive power, not leading, dependent on the VFD loading. Further comparisons of the selected harmonic solutions are given in Table 2.

CONCLUSIONS

Although the harmonic currents may be reduced by different means, the latest developments in the semiconductor industry allow active filters to take over the performance of traditional harmonic solutions. Compared to the passive solutions currently used, the installation of active filters offers superior harmonic mitigation, wider compensated harmonic spectrum, adaptive compensation of reactive power according to the installation needs resulting in higher energy efficiency and improved stability of the power system due to the lack of parallel resonance. Being fit with sensors, the active filter has major advantages over the previous harmonic solutions: safe operation, stability, self-testing and protection.

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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 ASD 18-pulse ASD	Active Filter
Connection	Connection type	Series	Parallel	Series	Parallel
	Installation on the network	Local solution / possible shared between several ASD's	Central solution	Local solution	Configurable at commissioning local or central solution
	Component most exposed to failure	Inductor	AC-capacitors	Phase-shifting transform	Semiconductors
	Cause ASD's to stop when it fails	Yes	No	Yes	No
Power rating	Power rating	S=100 % S_{ASD}	Depends on harmonics and losses at fundamental frequency	S=100 % S_{ASD}	$S=THD_i\, S_{ASD}$
	Additional losses at fundamental frequency	Proportional to ASD current	Proportional to Passive Filter capacitor	Proportional to ASD current	Depending on AF efficiency, estimated 97 %
	Power consumption when ASD 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
Performance & Features	Compensated spectrum	Broadband	Tuned on individual harmonics	Ideally only harmonic orders 12k±1 respective 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
	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 the Passive Filter capacitor	Decreased harmonic compensation performance	Not affected
	Online monitor of compliance against harmonic standards	No	No	No	Yes, embedded into control algorithm
Commissioning & Operation	Retrofit existing ASD's and the layout	Yes	Yes	Rewiring or replacement of ASD's with 12-pulse ASD's	Yes
	ASD 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 ASD control algorithm	Yes