



White paper

## Proper selection of passive and active power quality filters for the mitigation of mains harmonics

### Abstract

The steady increase in non-linear loads on the power supply network such as, for instance, variable speed motor drives (VSDs), raises questions about power quality and reliability. In this respect, a great deal of attention has been focused on harmonics as they overload the network infrastructure, cause reliability problems on equipment and system level, and waste energy. Passive and active harmonic filters are used to keep these harmonic problems in check.

The use of both active and passive technology is justified. The difficulty is in how to select and deploy harmonic filters correctly, which is key to achieving a satisfactory performance. This paper explains which specifications are suitable when it comes to choosing active and passive harmonic filters and which mistakes need to be avoided.

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## **Power quality and harmonics**

The load exerted by harmonics on the power network infrastructure has increased dramatically over the past few years. Harmonic currents are caused by non-linear loads. A non-linear load is a consumer of electricity that draws a non-sinusoidal current from the supply network when supplied with a sinusoidal voltage. These harmonic currents flow in addition to the “active” sinewave, generate additional losses in electrical installations, and can result in thermal overload.

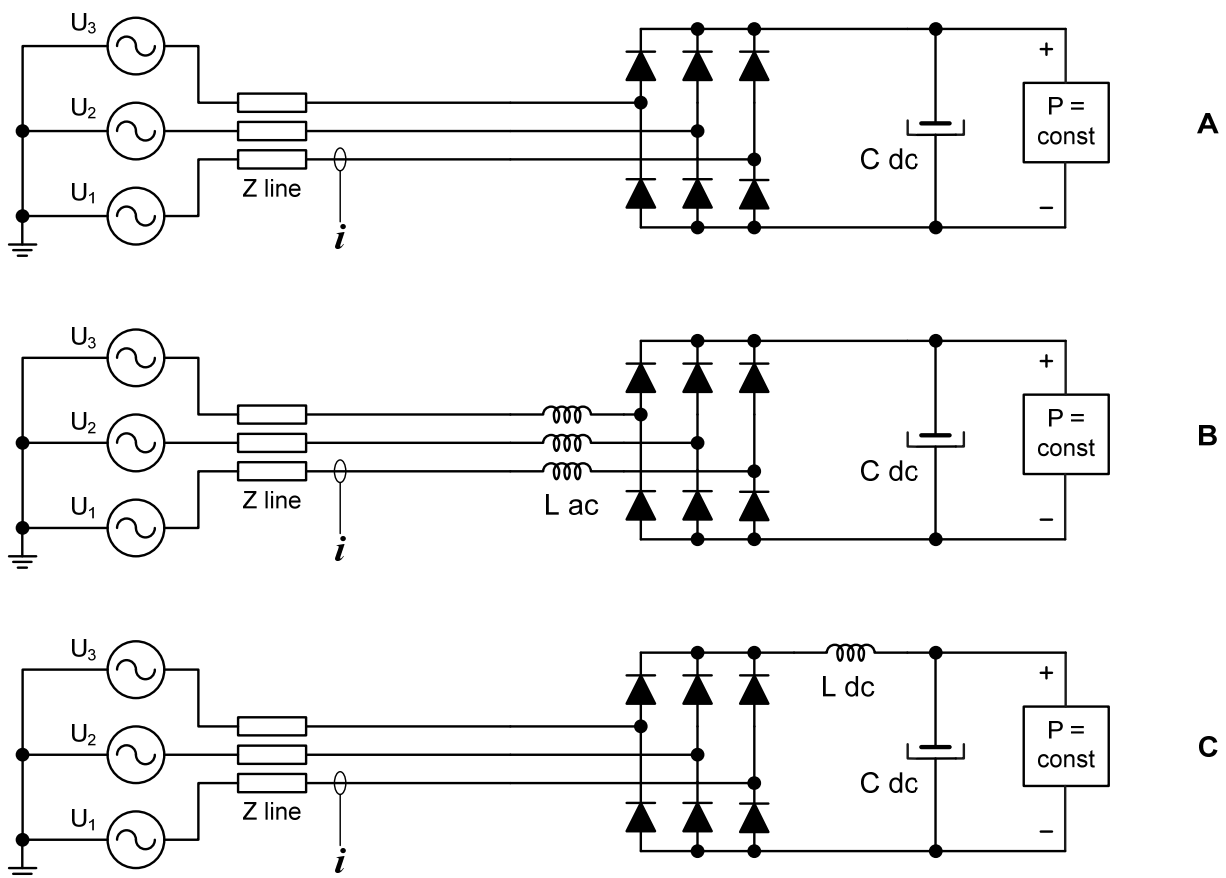
Harmonic currents flow through the system impedance, resulting in non-sinusoidal voltage drops that can compromise network voltage quality. Sensitive loads, such as medical devices or IT infrastructure, can have their operation affected if the voltage supply is distorted.

Measures for reducing harmonics are implemented nowadays in order to resolve this issue and comply with national and international standards at every level of the network infrastructure. In this article, we will focus solely on the use of passive and active harmonic filters in low-voltage installations.

### Typical topologies of non-linear loads

In our further observations we will be focusing on the six pulse rectifier bridge. The three-phase rectifier has a key role to play because a significant portion of the electrical energy is drawn from loads with this type of front-end circuit. One typical application that can be mentioned is the variable speed motor drive, which has been used for years with high growth rates in almost every industrial sector.

The most common six-pulse rectifier topologies are shown in Figure 1. Topology A does not include any magnetic components for smoothing the current. Topology B is operated using an upstream AC inductor  $L_{ac}$ , usually in the form of a laminated line-reactor. Topology C has a built-in DC choke  $L_{dc}$ , which is often integrated in higher power motor drives. In all three topologies the grid, including the line impedance, is depicted on the left-hand side. On the right the constant power sink "P=const" represents the active power drawn from the DC/AC inverter and motor that is taken, for example, to be 20 kW.



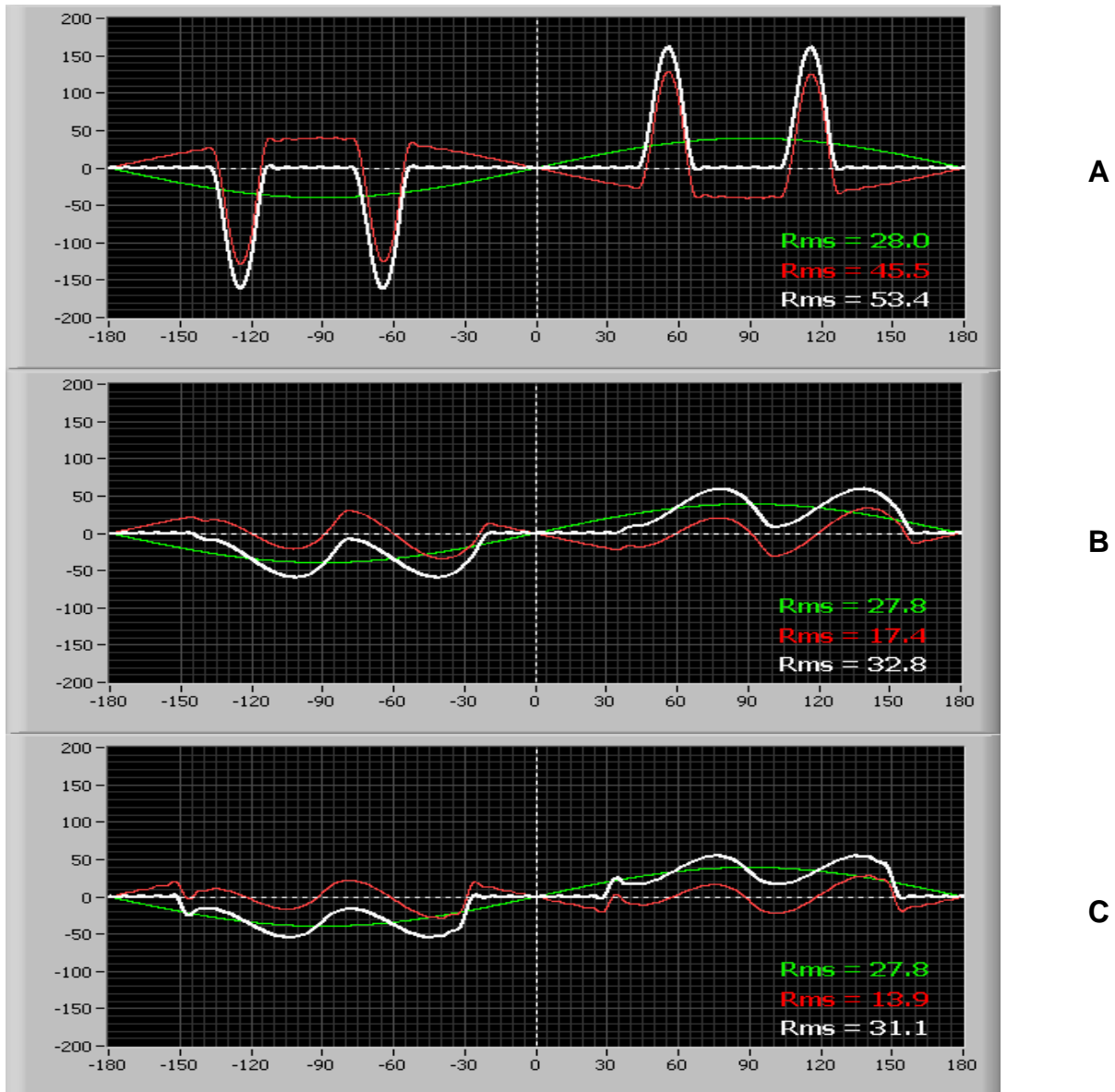
**Figure 1:** Common non-linear load topologies (six-pulse bridge rectifiers): A – without chokes; B – with AC reactor  $L_{ac}$ ; C – with DC-link choke  $L_{dc}$ .

Figure 2 shows the input current  $i$  for topologies A, B and C from a balanced three-phase power line.  $Z_{line}$  represents the equivalent impedance of a distribution transformer, distribution line, fuses, etc., which are assumed to be half inductance and half resistive in our example ( $L=18\mu\text{H}$ ;  $R=6\text{m}\Omega$ ). The following values are used:

DC-link capacitor  $C_{dc}$ : 2000 $\mu\text{F}$

AC-reactor (topology B)  $L_{ac}$ : 500 $\mu\text{H}$  (2%)

DC-link choke (topology C)  $L_{dc}$ : 1mH



**Figure 2:** Input current  $i$  (white) and its active  $i_a$  (green) and reactive  $i_b$  (red) components for topologies A, B and C from Figure 1. All specified values are in  $A_{RMS}$ .

*Note: LabVIEW-based software specially developed by Schaffner was used to decompose the waveforms in Figures 2 and 6, which was presented for the first time at the IEEE International SPEEDAM 2008 (Virtual Laboratory for Harmonics Filtering Visualization).*

The non-sinusoidal currents  $i$  (white waveforms in Figure 2), drawn from the sinusoidal voltage source, can be decomposed into two orthogonal components,  $i_a$  (active) and  $i_b$  (reactive):

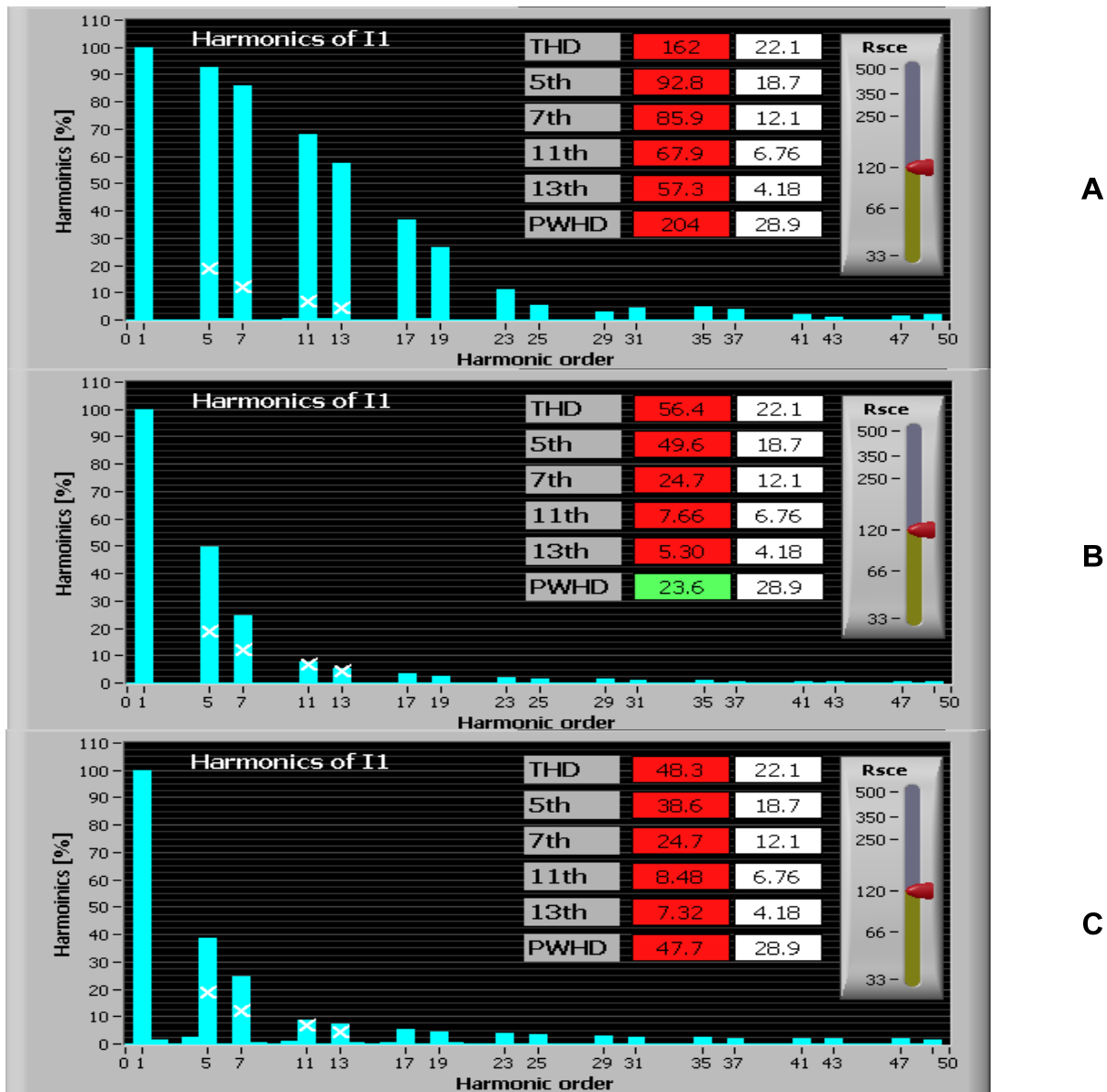
$$i = i_a + i_b$$

The active current  $i_a$  (green), is a sinusoidal fundamental component in phase with the voltage. This is the only component of the current involved in transferring real power from the source to the load.

The reactive current  $i_b$  (red), is therefore the remaining component of the current, representing the difference between the white and green curves. It only moves reactive power back and forth between the source and load, and is not at all involved in transferring real power. The reactive current spectrum consists of harmonics and reactive components of the fundamental frequency.. However, the reactive components of the fundamental in the waveforms in Figure 2 are negligible. The reactive current  $i_b$  mainly comprises the 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th harmonics, where higher-frequency harmonics (>25th harmonic) are also negligible.

The reactive current generates additional losses in the power lines, and results in non-sinusoidal voltage drops across the line impedance, which are ultimately responsible for power line voltage distortions and thus for poor power quality. Consequently, it can be said that the reactive current is counterproductive and should therefore be eliminated as far as possible.

The separation of non-sinusoidal currents (drawn from a sinusoidal voltage source) into active and reactive components was first suggested by S. Fryze (1932).



**Figure 3:** Harmonic spectrum of the line current  $i$  for topologies A, B, and C in Figure 2. In addition to the harmonics (blue bars), the table represents the limits of standard EN61000-3-12 (white fields) and the actual THD values, as well as the individual harmonics (5th, 7th, 11th, 13th) and PWHD (partially weighted harmonic distortion). The values with red background indicate non-compliance with the standard, and the green background compliance with the standard. On the far right of each graph is a slider that can be used to select the  $R_{s_{ce}}$  parameter ( $R_{s_{ce}}=120$  in our example).

The RMS values of the currents  $i$ ,  $i_a$ ,  $i_b$  denoted as  $I$ ,  $I_a$ ,  $I_b$  are related according to the following formula:

$$I^2 = I_a^2 + I_b^2$$

It can be observed that the reactive current  $I_b$  can have a large variety of values, depending on the topology used. In our example the RMS current values are 45.5 A, 17.4 A and 13.9 A (Figure 2). The reactive current has a considerable influence on the input current  $I$ . In this example the RMS value of the line current changes according to the topology (for the same output power) from 53.4 A to 31.1 A. Only the active current  $I_a$  remains more or less identical in all three topologies (28.0 A and 27.8 A respectively).

The conclusion that can be drawn from the above observations is that the RMS value for the active current  $I_a$  (which is proportional to the real power absorbed from the voltage source) can, in the case of non-linear loads such as six-pulse rectifiers, be significantly lower than the value of the input current  $I$ . In other words, it is not possible to determine the active current  $I_a$  if only the value of the input current  $I$  is known.

The most straightforward way to get  $I_a$  is to calculate it from the real power absorbed from the power line:

$$I_a = \frac{P}{3 \cdot U_{p-n}}$$

$P$ : real power drawn from the three-phase power line

$U_{p-n}$ : RMS value of the phase-neutral voltage

The value for the real power  $P$  can be calculated from:

$$P = \frac{P_M}{\eta}$$

$P_M$ : real power absorbed by the motor

$\eta$ : efficiency of the motor drive (typically 0.96)

## The ideal harmonic filter

The ideal harmonic filter can be seen as a device that is capable of completely eliminating reactive current  $i_b$  by removing harmonics and correcting the phase of the fundamental current. As a result, this kind of filter converts the non-sinusoidal line current into a sinusoidal current, and thus the non-linear load into a linear load that only draws useful active current  $i_a$ . If we additionally assume the loss-free operation of the filter, the real power drawn from the power line will not be changed by the presence of the filter and thus the active current  $i_a$  will not be increased.

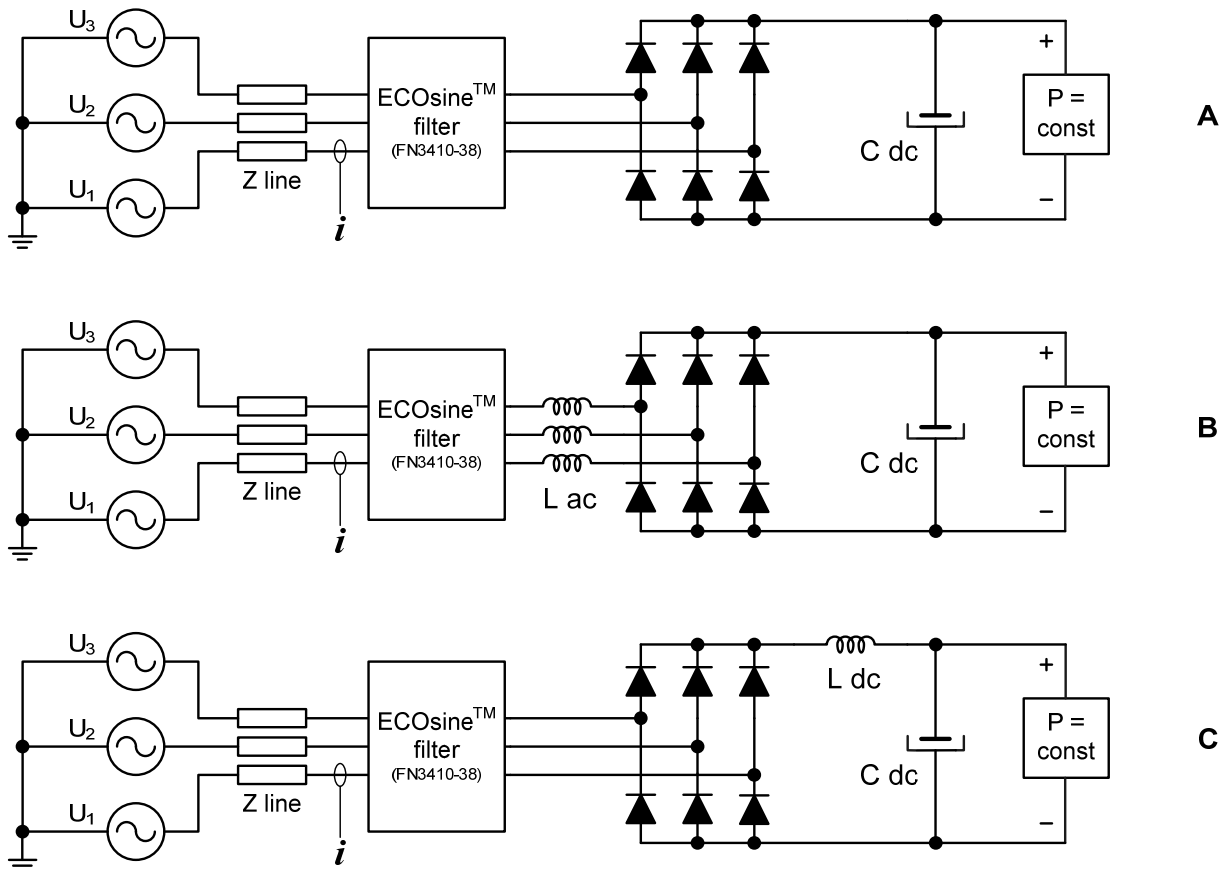


**Figure 4:** ECOsine™ harmonic filters from Schaffner for non-linear loads (six-pulse rectifier loads)

ECOsine™ filters were recently introduced for applications with six-pulse rectifier front end. They provide a state-of-the-art solution and come very close to offering the features of the ideal harmonic filter. Harmonic currents are reduced to a total harmonic current distortion level (THID) of 3.5 to 5.0%, in other words, almost completely eliminated. And with an efficiency of 98.5 to 99.4% (depending on the model), ECOsine™ filters are actually almost loss-free.

Figure 5 shows how ECOsine™ harmonic filters can be installed in series between the power line and the input of the non-linear load, regardless of the rectifier topology being used.

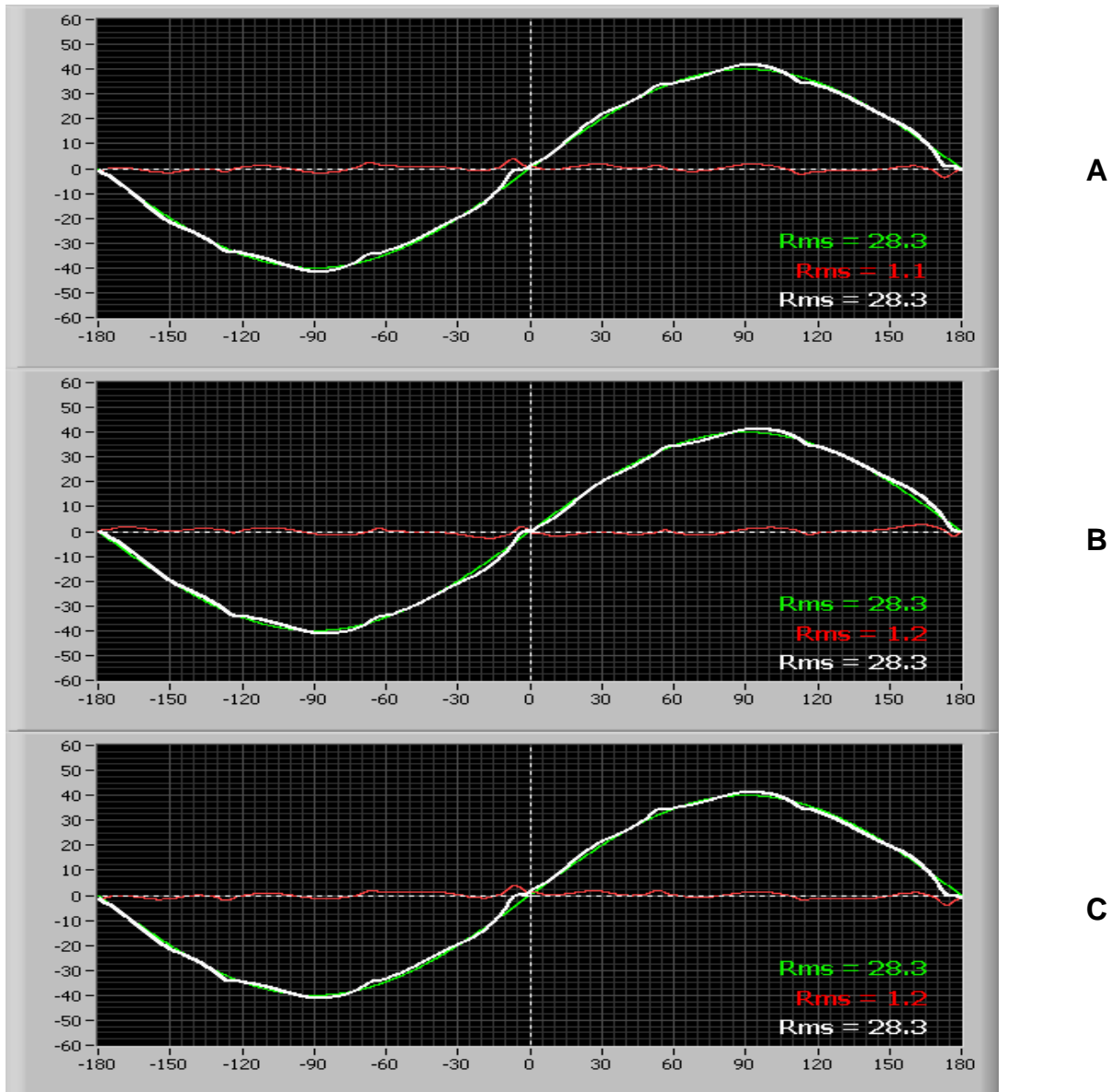




**Figure 5:** six-pulse rectifiers arranged in topologies A, B and C with the ECOsine™ harmonic filter connected on the line side.

*Note: Passive harmonic filters must be connected directly at the input of a non-linear load (or group of non-linear loads). Due to the voltage distortion at the filter output, which occurs as a result of the non-sinusoidal voltage drop across the series impedance, it is not appropriate to supply power to other loads at the filter output.*

Figure 6 illustrates the shape of the waveform for the input current of one phase when ECOSine™ harmonic filters are used, in the case of all three rectifier topologies.



**Figure 6:** The line current  $i$  (white) and its active  $i_a$  (green) and reactive  $i_b$  (red) components for topologies A, B and C with an ECOSine™ harmonic filter installed at the input.

### Important observations

If passive series harmonic filters, like ECOsine™, are used at the input of the six-pulse rectifier, the following important observations can be made:

1. There is barely any reactive current  $i_b$  (red) visible in the waveforms (Figure 6).

Topology	Reactive current $i_b$ without Filter	Reactive current $i_b$ with Filter
A	45.5 A <sub>rms</sub>	1.1 A <sub>rms</sub>
B	17.4 A <sub>rms</sub>	1.2 A <sub>rms</sub>
C	13.9 A <sub>rms</sub>	1.2 A <sub>rms</sub>

2. The RMS values of the line current  $i$  (white) are reduced; the current's shape is almost sinusoidal (free of harmonics).

Topology	Line current $i$ without filter	Line current $i$ with filter
A	53.4 A <sub>rms</sub>	28.3 A <sub>rms</sub>
B	32.8 A <sub>rms</sub>	28.3 A <sub>rms</sub>
C	31.1 A <sub>rms</sub>	28.3 A <sub>rms</sub>

3. The active current  $i_a$  (green) has remained practically unchanged.

Topology	Active current $i_a$ without filter	Active current $i_a$ with filter
A	28.0 A <sub>rms</sub>	28.3 A <sub>rms</sub>
B	27.8 A <sub>rms</sub>	28.3 A <sub>rms</sub>
C	27.8 A <sub>rms</sub>	28.3 A <sub>rms</sub>

*Note: The increase in current is a result of the fact that a harmonic filter is never ideal, but always slightly lossy. However, due to the minimal losses of ECOsine™ filters, the increase in real power is negligible.*

### Proper selection of passive harmonic filters

The conclusions obtained above makes it obvious where the problem lies: the proper rating of a harmonic filter must be concluded from the ratings of a non-linear load without a harmonic filter. The comparison between the following two tables makes it clear that the line current of the non-linear load is not suitable for selecting a harmonic filter, such as the Schaffner ECOSine™, as it changes according to the topology.

Rectifier	Line current $I$ [A <sub>rms</sub> ]	Active current $I_a$ [A <sub>rms</sub> ]	Reactive current $I_b$ [A <sub>rms</sub> ]	Output real power [kW]
A (without magnetics)	53.4	28.0	45.5	20
B (with L <sub>ac</sub> )	32.8	27.8	17.4	20
C (with L <sub>dc</sub> )	31.1	27.8	13.9	20

**Table 1:** Rating of non-linear load (topologies A, B, C) without harmonic filters. The values in red are usually not available from the non-linear load specifications.

Rectifier	Line current $I$ [A <sub>rms</sub> ]	Active current $I_a$ [A <sub>rms</sub> ]	Reactive current $I_b$ [A <sub>rms</sub> ]	Output real power [kW]
A (without magnetics)	28.3	28.3	1.1	20
B (with L <sub>ac</sub> )	28.3	28.3	1.2	20
C (with L <sub>dc</sub> )	28.3	28.3	1.2	20

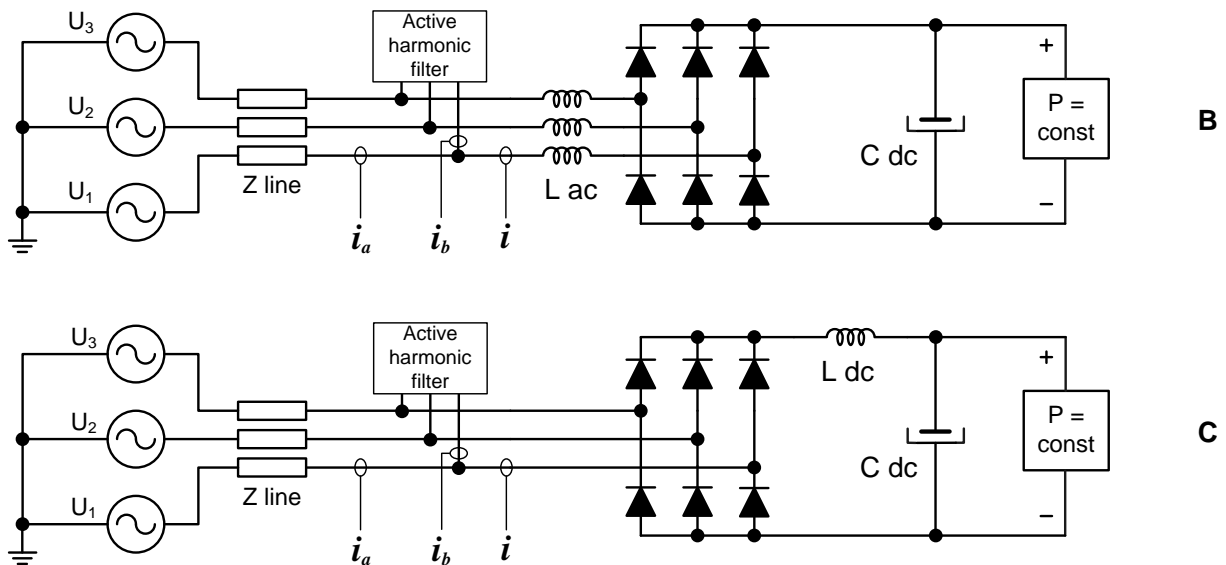
**Table 2:** Rating of the passive harmonic filters for topologies A, B and C. The values in red are usually not available from the harmonic filter specifications.

In fact, only the active current  $I_a$  and real power  $P$  are identical for all three topologies, thus making them suitable for selecting the filter. Unfortunately, the active current  $I_a$  (which is actually the harmonic filter's input rated current) is generally not known based on the specifications of non-linear loads (e.g. motor drives). The only specified value that is suitable without any restrictions for selecting the passive harmonic filter is therefore the real power  $P$  of the non-linear load.

To simplify the filter selection for the user, Schaffner specifies its ECOSine™ harmonic filters based on the motor drive's power rating and not, like other manufacturers of comparable products, on the input current.

### Proper selection of active harmonic filters

Unlike passive harmonic filters, active filters are installed in parallel to the power line (shunt filters). Note that only topologies B and C are represented in figure 7. Topology A is not advisable because active shunt filters require magnetic components on the load for economic reasons. This is obvious from another look at the waveforms in Figure 2. If there were no magnetic components (topology A) the required corrective current of the active filter would be so high that the filter would need to be significantly oversized.



**Figure 7:** six-pulse rectifiers for topologies B and C with an active harmonic filter connected in parallel (shunt filter).

If, for simplicity's sake, an ideal shunt filter is considered based on topologies B and C in Figure 7, it is not difficult to realize that

- the line current corresponds to the active current  $i_a$  in Figure 2 (B and C)
- the filter's corrective current corresponds to the reactive current  $i_b$  in Figure 2 (B and C)
- the rectifier's input current corresponds to the input current  $i$  in Figure 2 (B and C).

These statements are true, provided that the line impedance  $Z_{line}$  is negligible in relation to the impedances of  $L_{ac}$  (topology B) and  $L_{dc}$  (topology C). In our example this condition is fully met.

When selecting active harmonic filters, a similar issue needs to be addressed as when choosing the passive versions. One must dimension the filter based on the rectifier parameters without a filter.

Table 3 lists key parameters for topologies B and C (without a filter). The only value that is really of any use is the reactive current  $I_b$ , which describes the active filter's most important parameter: the corrective current required.

Rectifier	Line current $I$ [A <sub>rms</sub> ]	Active current $I_a$ [A <sub>rms</sub> ]	Reactive current $I_b$ [A <sub>rms</sub> ]	Output real power [kW]
B (with L <sub>ac</sub> )	32.8	27.8	17.4	20
C (with L <sub>dc</sub> )	31.1	27.8	13.9	20

**Table 3:** Rating the active harmonic filter for topologies B and C. The values in red are usually not available from the load specifications.

Unlike in the case of passive harmonic filters, there is a difference when it comes to dimensioning active harmonic filters for topologies B and C. The required corrective current for topology B is 17.4 A<sub>rms</sub>, whereas it is only 13.9 A<sub>rms</sub> for topology C. To give the complete picture, it should also be mentioned at this point that the corrective current required without any magnetic components (topology A) would be 45.5 A<sub>rms</sub>. Unfortunately, the value for the reactive current  $I_b$  is usually not available from the specification of the non-linear load.

The simplest way to find this value would be to calculate it from the following formula:

$$I_b = \sqrt{I^2 - \left(\frac{P}{3 \cdot U_{p-n}}\right)^2}$$

$I$ : rms of the line current of the non-linear load without a harmonic filter

$P$ : real power of the load

$U_{p-n}$ : phase-neutral voltage of the power line

All these values can usually be found in the specification of the non-linear load.

In our example this would be:

$$I_b = \sqrt{(32.8)^2 - \left(\frac{20000}{3 \cdot 240}\right)^2} = 17.4 \quad (\text{Topology B})$$

$$I_b = \sqrt{(31.1)^2 - \left(\frac{20000}{3 \cdot 240}\right)^2} = 13.9 \quad (\text{Topology C})$$

The calculated results match exactly with the values from Figure 2 which were calculated using FFT (Fourier Transformation).

## Conclusion

Proper selection of passive and active harmonic filters may quickly lead to misunderstandings due to a number of unknown parameters of the non-linear load. But selecting the correct size of filter is key to achieving the optimum cost/benefit ratio, i.e. the desired reduction in current harmonics with minimal filtering effort. Given that some motor drive peripherals such as EMI filters, line-reactors or output filters are designed and selected based on the line current  $I$ , it is often wrongly assumed that this is also appropriate for harmonic filters. The correct procedure however is to select passive harmonic filters based on the load's real power  $P$ , and to select active harmonic filters based on the calculated reactive current  $I_b$ .

## Literature

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