Operational Cost Avoidance through Harmonic Mitigation in Industrial Environments

by Karl Kaiser

Executive summary

Industrial sites suffer from margin erosion because operations and equipment costs are not efficiently controlled. For example, premature equipment replacement, caused by excessive current and voltage distortion, can add up to 15% in CAPEX and 10% in OPEX costs. Such costs can be avoided if the proper harmonic mitigation solution is implemented. This paper reviews several approaches to harmonic mitigation and identifies best practices.

998-2095-09-23-13AR0

Schneider Electric

Introduction

Harmonics are unwanted currents that overload wiring and transformers, creating heat and, in extreme cases, fire. These currents are harmful to equipment. They weaken the reliability and shorten the life expectancy of equipment exposed to the distortion. In fact, field experience at Schneider Electric has shown that the right choice of harmonic mitigation can result in an estimated CAPEX reduction of up to 15% as well as an OPEX reduction of up to 10%.

An ideal mains / utility voltage should be a sinusoidal voltage with constant amplitude and frequency (see **Figure 1**). This situation rarely exits, however, because of impedances, voltage distortion, and current distortion. In industrial environments, for example, these distortions are caused by the electromagnetic characteristics of the loads that connect to the power distribution system. Two broad categories of load types exist: linear and non-linear.

If the current has the same waveform as the supply voltage (i.e., sine wave) then this is characteristic of a **linear load**. Examples of linear loads include motors, incandescent lights, heating elements using resistors, capacitors, and inductors.

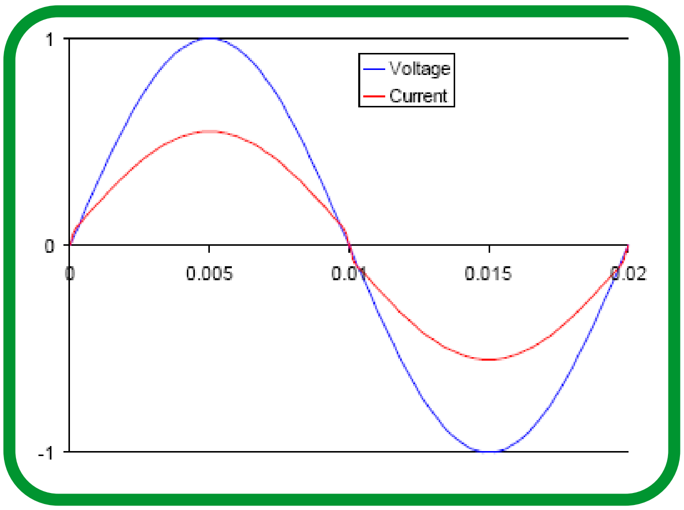

Figure 1
The waveform of a sinusoidal utility voltage (no distortion)

Non-linear loads are common in industrial sites and often comprise of equipment such as welding machines, arc and induction furnaces, battery chargers, variable speed drives for AC or DC motors, and uninterruptible power supplies. The currents of non-linear loads deviate from sinusoidal waveforms. They create some harmonic current through the distribution system and, due to the network impedance, cause voltage distortion (see **Figure 2**). Simply stated, non-linear loads cause harmonics to flow in the power lines.

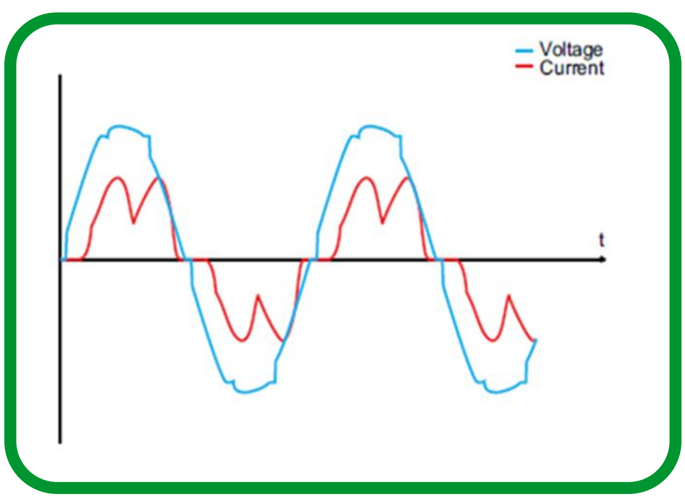

Figure 2
Impact of non-linear current on the voltage

Impact of harmonics on costs

Oversizing of components - In most industrial sites, cables, circuit breakers, and transformers are connected in series with non-linear loads. The harmonic currents produce additional efficiency losses and, as a result, these components may need to be oversized. For example, if the current at the front end of the manufacturing plant has a high content of harmonics, the incoming transformer will have to be oversized and the utility will charge higher fees.

Plant shutdown - For devices that are connected in parallel with non-linear loads, distorted current is likely to produce a distorted voltage. As a result, devices connected to the network may trip and cause plant shutdown. In some cases the current in a capacitor bank which is used to correct the power factor can increase. Eventually resonance can occur and cause voltage peaks and drops.

The negative impact of harmonics may remain unnoticed for a while but can build over time. This results in overloading of the electical system, increased power demand, loss of systems, increased outages and shorter equipment lifetime.

Harmonic mitigation methods for drives

A broad range of solutions for harmonic mitigation exists depending on the nature of the load and the power demand of connected equipment. The following pages review the four most common harmonic mitigation approaches.

AC line reactor and DC link chokes for drives

Both AC line reactors and DC link chokes help to smooth out the flow of current to Variable Frequency Drives (VFDs) and thereby reduce the level of harmonics. AC line reactors are placed in series with the incoming AC power line. DC link chokes are connected after the input diodes in the power circuit (see **Figure 3**). These devices are often used to plan the current peaks in a circuit. They can be used at different locations within a drive for reducing harmonics. Without a choke or reactor in place, the inverter produces high current peaks. When the choke or reactor (or both) is added, the current flow is expanded and the amplitude is reduced. This helps to partially mitigate the level of harmonics.

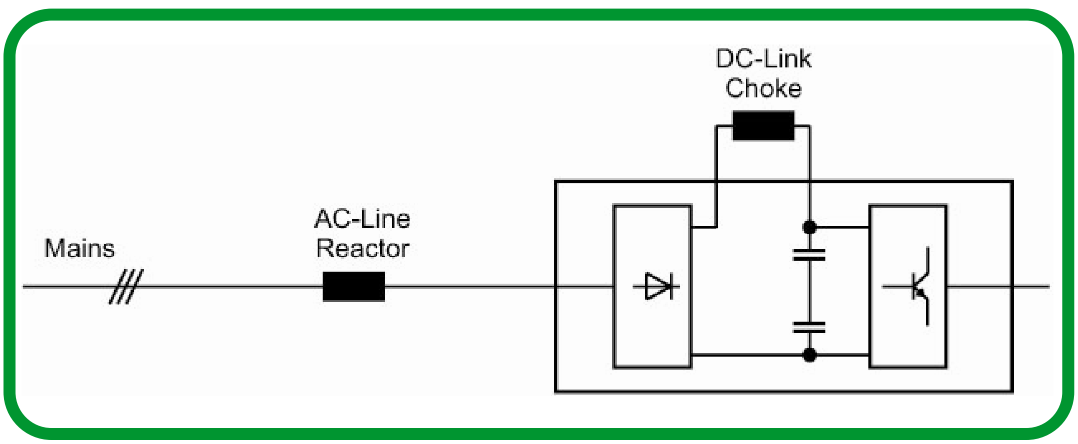

Figure 3
Simplified diagram of and inverter with AC line reactor and DC link choke

These devices are commonly used up to a range of about 500 KW unit power or 1,000 kW total drives power. In this power range the transformer should be sized to at least 1.25 to 1.5 times the drives power. Depending upon the short circuit power of the mains, transformer size, and cabling, the Total Harmonic Voltage Distortion (THDu) can still be up to about 6%. This can result in possible noise disturbance but this range of distortion is usually tolerated within most industrial networks (see **Figure 4**).

When high quantities of drives are present within an installation, the use of AC line reactors or DC link chokes is recommended for each individual drive. Implementing these devices increases the lifetime of the drives. The 3% AC line reactor will protect the diodes against voltage transients, but not drop excessive input voltage to cause nuisance fault trips. The DC link choke provides 3% impedance with no voltage loss due to diode overlap conduction at a lower cost. By incorporating both AC line reactors and DC link chokes 6% impedance is achieved. If AC line reactors or DC link chokes are not sufficient for a large drive, a multi-pulse arrangement is the next step to consider.

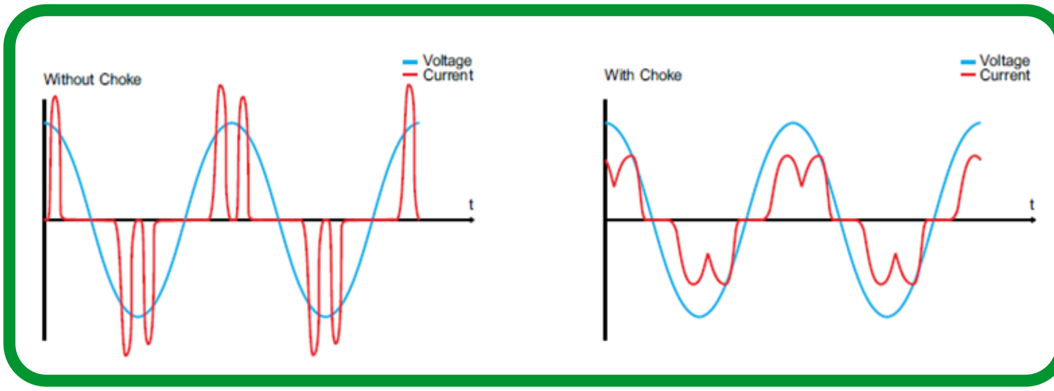

Figure 4
Comparison of waveform distortion both with and without choke

12-pulse arrangement

For larger drives, another option for reducing harmonics is to configure VFDs with 12 diodes in the rectifier section. This is known as a 12-pulse drive. In order to make the 12-pulse option work correctly, a 30° phase shift transformer must be included. The 30° phase shift transformer is used to power 2 sets of VFDs, one from the standard part of the transformer and the other from the 30° phase shift part. To enable harmonic cancellation advantages of the 12-pulse, a 6-pulse converter bridge is connected to each of the outputs (see **Figure 5**). With multi-winding-transformers in different variations, configurations can be created for industrial users of up to 18-pulse and 24-pulse.

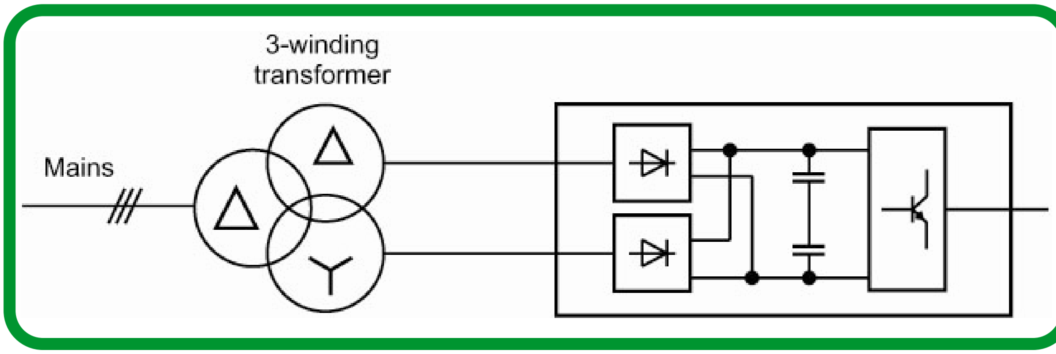

Figure 5
Simplified diagram of a 12-pulse inverter

Multi-pulse supply is often used for drives above 400 kW, but could also be used for smaller power ratings. The precondition is a dedicated transformer directly supplied from the medium voltage (MV) network.

The standard is to deploy a 3-winding transformer providing a 12-pulse supply for the drive. This limits the harmonic emission and usually no further mitigation is necessary. Multi-pulse solutions are also the most efficient in terms of power loss (see **Figure 6**).

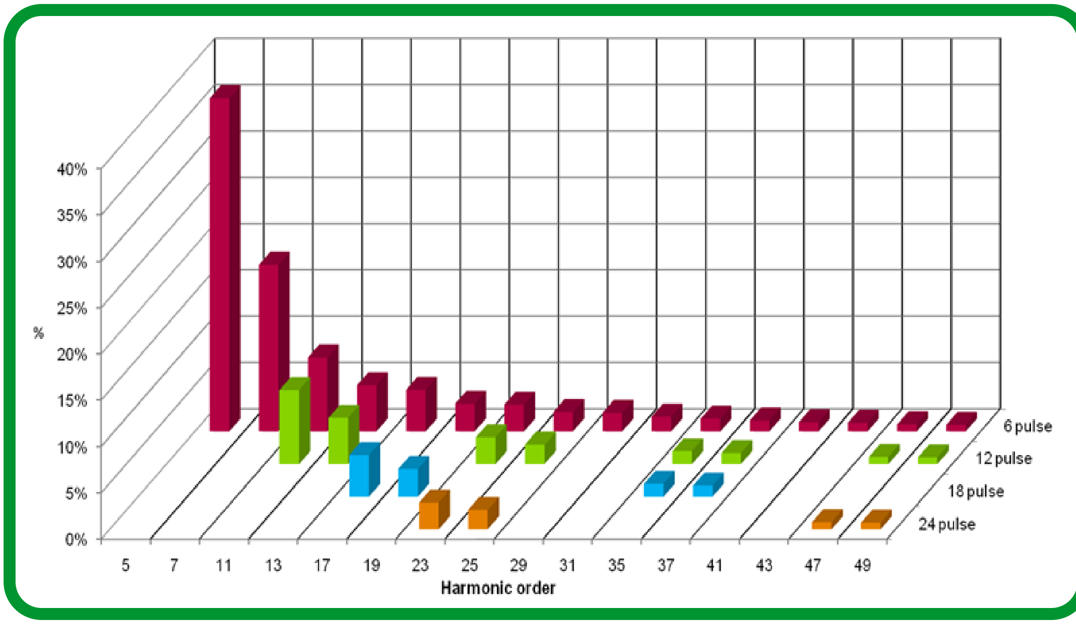

Figure 6
Harmonic spectrum for multi-pulse implementations

Passive Filter

A passive filter consists of reactors (electronics component consisting of one or more inductors wired in series with a power source and an electrical load) and capacitors (small devices that can be charged up with electrical energy, store it and then release it) set up in a resonant circuit configuration. The configuration is then tuned to the frequency of the harmonic order to be eliminated (see **Figure 7**). A system may be composed of a number of filters to eliminate several harmonic orders.

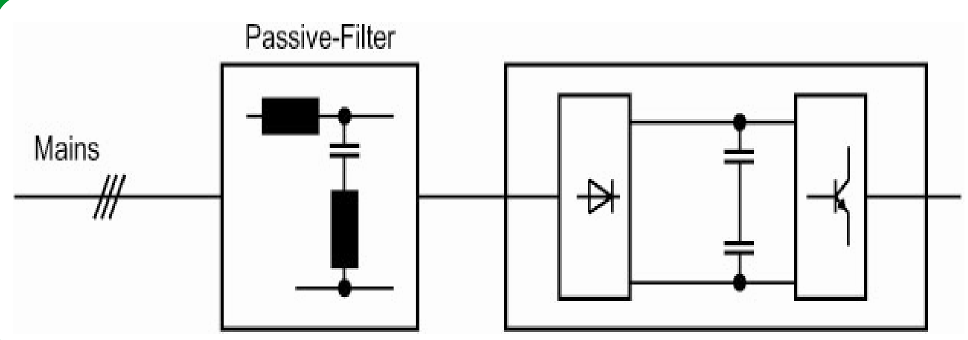

Figure 7
Simplified diagram of an inverter configured with a passive filter

Passive filters only address one operating point at a time and therefore are low cost solutions. Passive filters are not efficient at partial loads. Furthermore, passive filters are characterized by low power factor (a measure of how effectively the current is being converted into useful work output).

Active Filter

The active filter is based on the principle of measuring the harmonic currents and using this measurement on a real time basis to generate a harmonic current spectrum in phase opposition to the measured spectrum. This has the effect of canceling the original harmonic currents. Usually, an active filter is switched in parallel to the inverter. In other words, the active filter can be seen as a generator of harmonics. It produces the opposite harmonics of the measured distortions to compensate all harmonics in sum (see **Figure 8**).

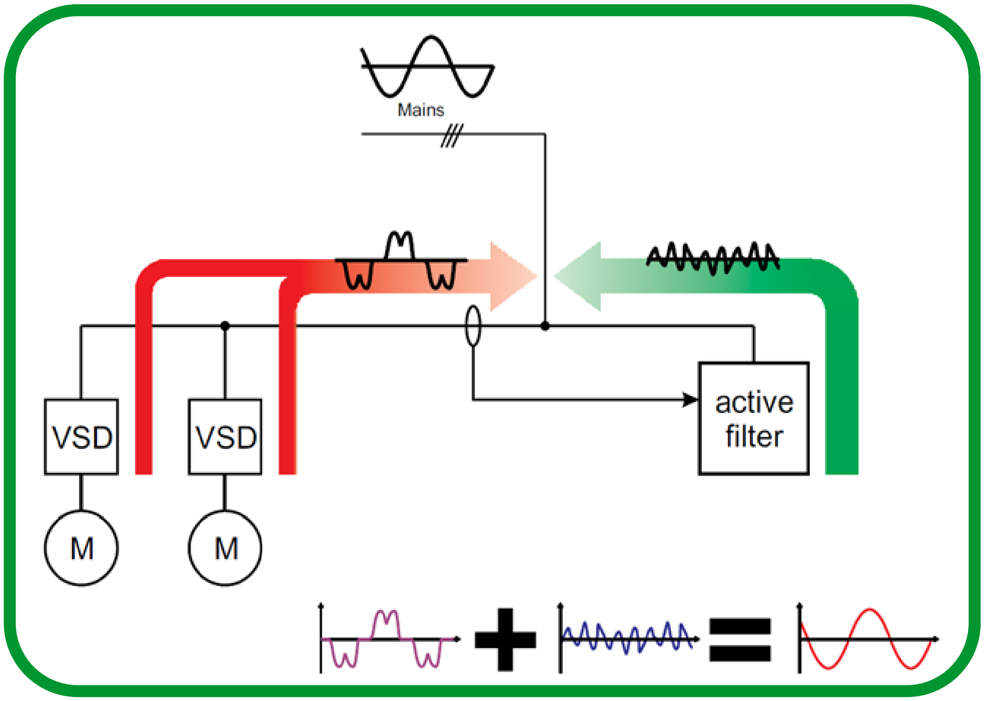

Figure 8
Simplified illustration of an active filter

Active filters are available in different supply voltages (three-phase with and without neutral) and can be used for filtering networks (several drives up to 3000A with parallel operation). A cancellation of up to the 50th harmonic is possible as well as a correction of individual harmonics. Oversizing of active filters is necessary in order to compensate for decreasing power factor.

Low Harmonic Drive

Within a variable frequency drive, if the diode rectifier (device which allows current to flow in one direction converting alternating current to direct current) is replaced by an active insulated gate bipolar transistor (IGBT) converter, it is possible to consume energy like a normal inverter (converts DC power to AC power). This configuration, called a low harmonic drive, allows the system to adjust the waveform of the mains current (see **Figure 9**). Usually the nominal waveform of the line current is sinusoidal. In the case of the low harmonic drive, the impact on the mains due to harmonics and idle power can be avoided.

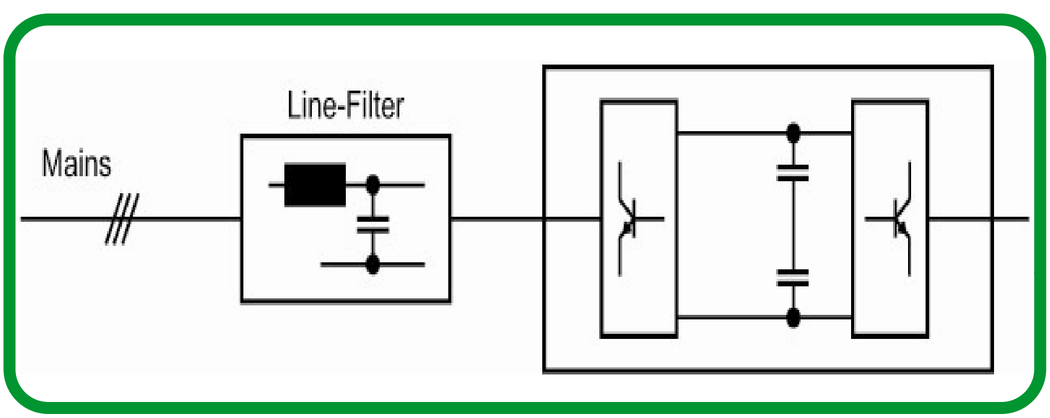

Figure 9
Simplified illustration of a low harmonic drive

Selection factors to consider

Over the last several pages, this white paper has described and compared several harmonic mitigation solutions. Each solution offers a different set of advantages and disadvantages (see **Table 1**). The table compares five of the main criteria involved in making the decision on which implementation makes the most sense for a particular industrial environment. The five criteria include the following:

- Compactness or overall space required - This answers the question of which solution requires less space relative to the other.
- Simplicity - This identifies which solution is the easiest to operate relative to the others.
- Harmonic mitigation / THDi - This compares the solutions to each other in terms of their harmonic mitigation.
- Efficiency - This reviews the energy efficiency level of the solutions.
- Price performance / value for money - This analyzes the solutions in terms of cost / benefit.

The comparisons in **Table 1** are general and do not account for exceptions that might be unique to a particular solution. For example, an active filter is often used to mitigate the harmonics from several drives. The 12-pulse solution is the only approach where a transformer is included in the comparison. The passive filter has the unique disadvantages of low power factor at partial load, and the risk of causing resonances within the grid.

In **Table 1** relative comparisons in each category are made on a scale of 1 through 5. **A rating of 1 for example, is the lowest (worst) rating, while a rating of 5 is the highest (best) rating in each of the categories.**

Table 1
Comparison of harmonic mitigation methods

	Link choke / line reactor	12 pulse	Passive Filter	Active filter	Low harmonic drive
Harmonic mitigation (THDi)	30-48% Rating = 1.0	6-15%* Rating = 3.0	5-16%** Rating = 4.0	3-20%** Rating = 5.0	2-5% Rating = 5.0
Energy efficiency	96-97% Rating = 4.0	97-98% Rating = 5.0	95.5%-96.5%*** Rating = 4.0	95-96.5%*** Rating = 3.0	95-96% Rating = 3.0
Overall space required	Rating = 5.0	Rating = 3.5	Rating = 3.0	Rating = 2.5	Rating = 2.5
Overall simplicity	Rating = 5.0	Rating = 2.5	Rating = 4.0	Rating = 2.5	Rating = 4.0
Overall price performance	Rating = 5.0	Rating = 4.0	Rating = 3.0	Rating = 2.5	Rating = 3.5

* View on the MV side
** Compensation rate depending on settings and sizing
*** Efficiency depending on compensation rate

Notes on comparison categories

In regard to the data presented in **Table 1**, the numerical ratings in the last three categories (space required, simplicity, and price performance) all consist of an average of several subcategories. The category of "overall space required" includes an average of space calculations for additional installation, additional components, and additional drives.

The "overall simplicity" category includes an average of the design effort required before the system is built, the additional workload needed during installation (such as additional wiring and additional components for an inverter without any harmonic mitigation solution) and the level of complexity of service and maintenance.

The calculation for "price performance" totals up the cost of all parts, such as transformers, supply cables, and the whole drive. It ultimately depends on the specific solution and the planning associated with it to determine the list and the dimensions of components required. Therefore, some costs are often visible right from the start. As an example, a seemingly economically priced solution for harmonic mitigation may not include the projected costs of energy or installation. A rating was performed to identify the solution offering the best value for money. The projected costs of energy supply, installation and the drive itself were reviewed and evaluated by experts.

Regarding the "harmonic mitigation" category, the disassembling of the line current into shares of frequency shows the fundamental and the harmonics. After the inductive idle power, the harmonics cause the second largest distortion in the mains. The total harmonic distortion (THD) is a specification that qualifies the rate of non-linear deformation of the current or voltage.

In the category of "energy efficiency", only the losses of each solution are observed. Savings resulting from reduction of losses on other consumer loads (with harmonic mitigation) or a power factor = 1 as an indicator for real power are not accounted for in **Table 1**.

In order to further illustrate the comparisons in **Table 1**, a series of net diagrams have been created (see **Figure 10 and 11**). They illustrate the ratings distributed over five axes. For each comparison category a separate axis exists. The same orientation for all axes is important. In this case, the higher values lie consistently further out. The highest value of five points is marked on the outer edge. The diagrams are based on the average scores from each evaluated category.

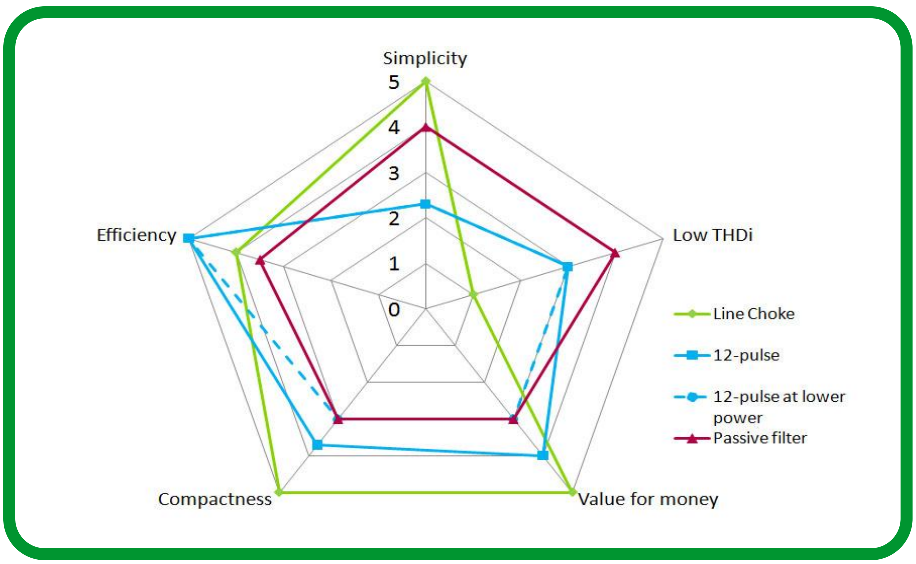

Figure 10
Net diagram for passive solutions

The net diagram of the passive solutions in **Figure 10** shows that the line choke is the most reasonably priced and compact solution but that it does not do a good job of mitigating the THDi. The 12-pulse solution is superior in regard to efficiency and harmonic mitigation but it is not simple to implement. Therefore it also has to be mentioned that the THDi of the 12-pulse solution is valued on the MV-site of the transformer. The dashed line shows the degradation of the 12-pulse solution at lower power.

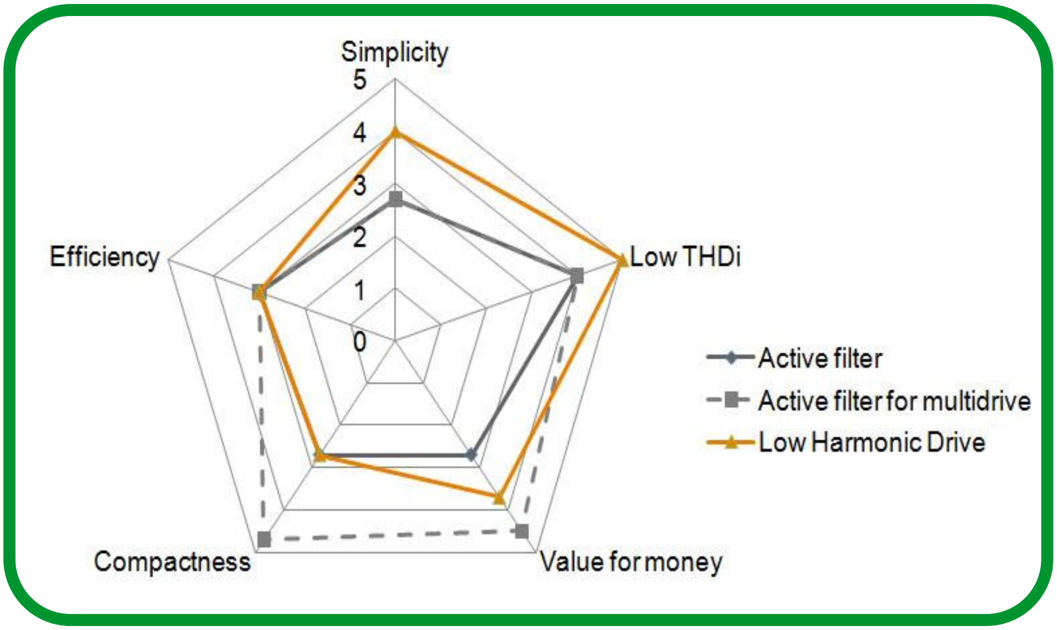

Figure 11
Net diagram for active solutions

The net diagram of the active solution in **Figure 11** shows that the active filter provides a good harmonic mitigation solution. However, the low harmonic drive provides a better value for the money and more simplicity. The dashed line shows the improved variant of the active filter for a multi-drive solution.

The results presented by the net diagrams have been summarized in the following bar diagram (**Figure 12**):

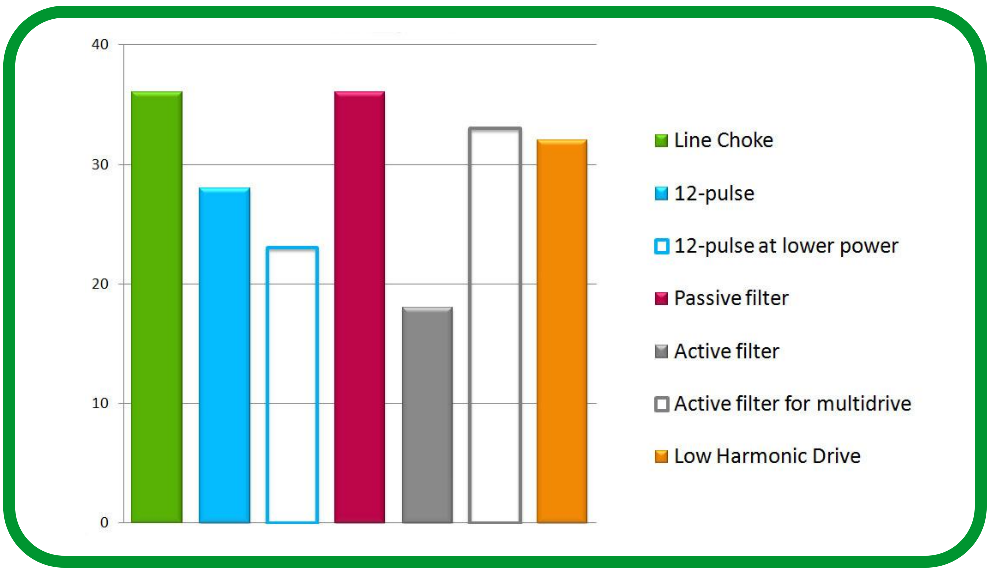

Figure 12
Bar diagram for overall scores

Conclusion

The line choke solution is the best solution for applications where the heaviest distortions should be filtered but where harmonic mitigation is not the first priority. The active filter is a good solution to mitigate the harmonics of several drives in parallel operating on one point of coupling. The 12-pulse solution has the best efficiency but is the most complex version and mitigates the harmonics on MV-site.

For applications where harmonic mitigation is very important, the low harmonic drive is the most effective option. It covers all relevant categories and offers the best harmonic mitigation solution.

About the author

Karl Kaiser is Director of Low Voltage Drive Systems Offer Management at Schneider Electric. His responsibilities include offer marketing, application support, offer training, and Global Help Desk for low voltage drive systems. He holds several patents related to drives and power electronic structures. He received his degree of graduate engineer of electronics from the University of Technology in Vienna, Austria where he worked for several years as an assistant professor. During this time he authored several publications and issued his thesis on the analysis of various power electronic architecture efficiencies.