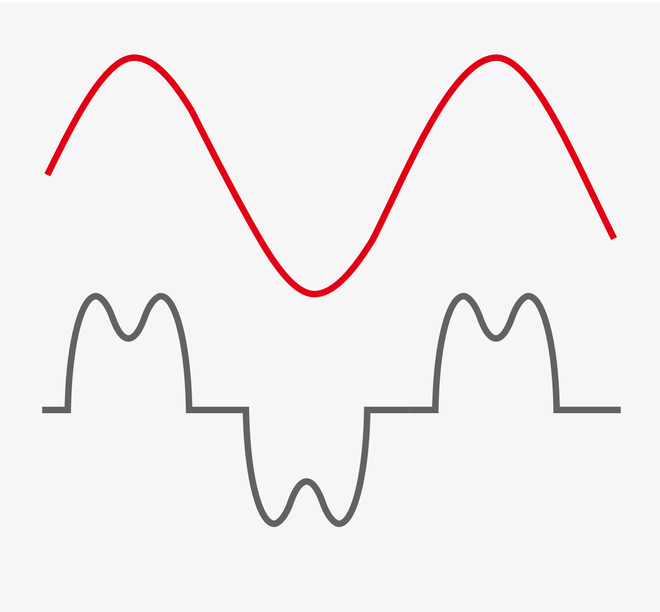
WHITE PAPER

Ultra-low harmonic and regenerative drives for increased efficiency and reliability of processes and systems

What are electrical harmonics and why do they matter?

Electrical equipment runs most efficiently and reliably when it is supplied by a clean, disturbance-free electrical power. However, often power networks are subjected to continuous or transient electromagnetic disturbances due to multiple reasons. The most frequently seen continuous disturbances present in almost any network are often harmonics, which can have a significant effect not only on power network efficiency, but also reliability.



In an ideal world, electrical supply has a pure sine waveform (top). However, in reality, it is often distorted (bottom) due to unwanted harmonics.

Harmonics are electromagnetic pollution in the power network resulting in current and voltage waveform distortion, which makes it different from the pure sinusoidal waveform generated by the electrical supplier. Harmonics are generated by non-linear loads like LED lighting, uninterruptable power supplies, computers or variable speed drives (VSDs) as a result of the constant switching of power electronics elements in their design.

The presence of harmonic content is measured as a percentage value known as the total harmonic distortion (THD) which is the relationship between all the current or voltage harmonics and the fundamental current or voltage. Where no voltage or current harmonics are present the THD is 0%.[1]

Harmonics negatively affect power networks and connected equipment. The higher the harmonic content, the higher the line current, which means higher losses in the network including its components like transformers, switches, circuit breakers and cables. Increased line current also means that power network equipment overheats which causes premature failure. And because a current with harmonics in it is a distorted current there is a risk of connected equipment malfunctioning and failing.

Harmonics may not cause immediate issues, malfunctions may take time, or may only happen when certain combinations of equipment come “on line”. Often, site issues are not even attributed to harmonics by the users. But it’s important to understand that in mission critical facilities like data centers harmonics can lead to serious consequences causing significant financial and reputational damage, and in hospitals threaten patients’ lives. Therefore, when selecting equipment, it’s crucial to make sure it does not have an adverse effect on the power system or connected devices, which in turn ensures higher process reliability and efficiency.

Considering harmonics when working on new projects can also have a significant effect on electrical equipment sizing and project sustainability as a result.

Variable speed drives and the importance of their harmonic performance

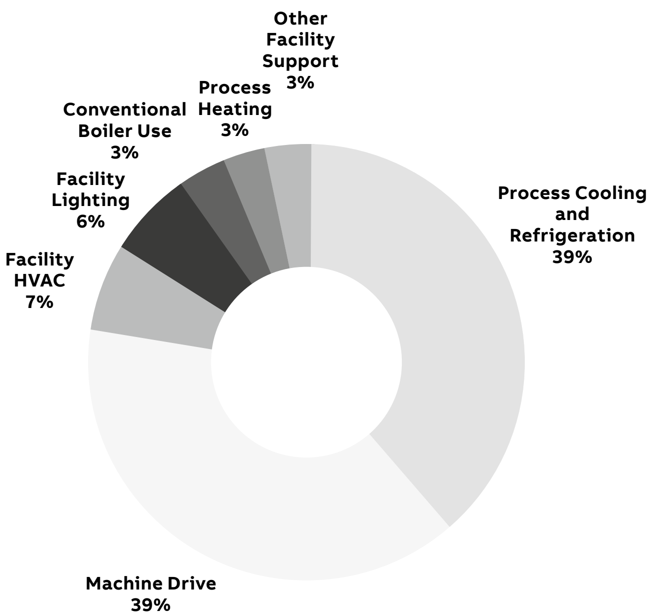
Variable speed drives help to save a tremendous amount of energy in processes with varying loads, and they do this by adjusting application motor speed to the exact process need. However, their possible effect on the power network and connected equipment should still be considered.

The role of variable speed drives in industry
It's been reported that heating, ventilation and air conditioning (HVAC) systems account for about 50% of energy consumed by an average commercial building.[2] As commercial building occupancy changes with time of the day, the need for HVAC changes as well. Based on ABB's extensive experience, drives can cut the energy consumption in HVAC processes by 20 to 60%, reducing a building's carbon footprint and bringing substantial operational savings to facility owners.

Another good example is in dairy plants where up to about 40% of the energy is consumed for process cooling and refrigeration, while another 40% can easily be used in automated production and other 10% for facility HVAC.[3] All these processes have fluctuations in the load and therefore variable speed technology offers massive energy saving potential.

At the same time, it is important to remember that, just like with other non-linear loads, drives generate harmonics in the power line which, as already mentioned, can potentially have an adverse effect on the network and the connected equipment when they exceed certain limits. Hence, the VSD harmonic content level needs to be considered at the project stage to evaluate its effect and its consequences for the facility.

Electricity use in the dairy industry, by activity



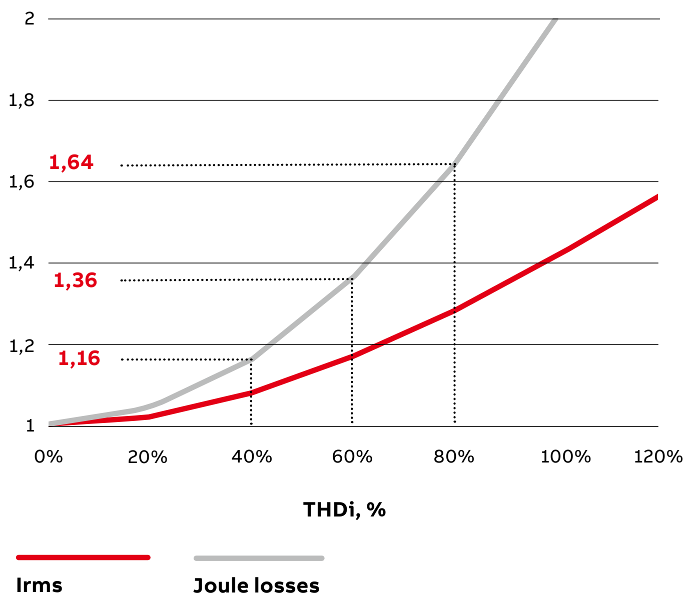
The effect of VSDs on power network efficiency
While you can save energy with VSD-controlled processes, it's important to understand how drives affect the efficiency of the power network they are connected to. Referring to theory, the passage of an electric current through a conductor produces losses resulting in heat (so-called Joule losses):

$$P = I^2 \cdot R$$

where P is heat losses, R is the resistance of the conductor and I is the line current. The total current containing harmonics and called root mean square current Irms is greater than the fundamental current I1 and can be described by the equation:

$$Irms = I_1 \cdot \sqrt{1 + THD_i^2}$$

Based on the formulas above, it can be calculated by how many times harmonics content increases line current losses. E.g. Irms current losses at 40% THDi increase by 1.16 times in comparison to a system with no harmonics. This translates to lower network efficiency and higher energy usage to cover the process needs.



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Total line current Irms and relative Joule losses as a function of the THDi.

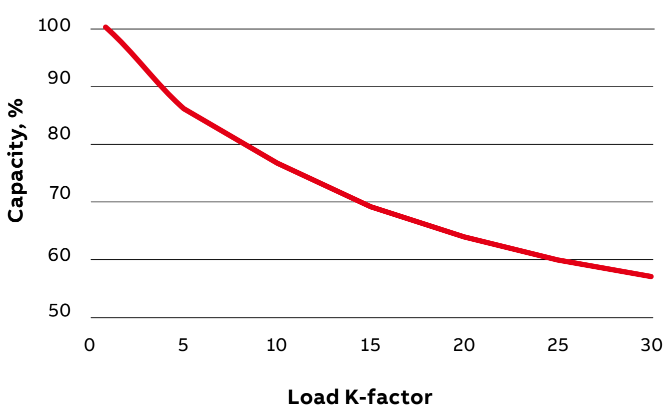
The effect of VSDs on project costs
In addition to the aforementioned, an increased line current also requires the power system to be over dimensioned to carry the excess current, which means increased material usage because of increased component size and a lower facility sustainability factor, as a result.

Low harmonic content means no oversized cables are needed. With a high THDi cables need to be oversized due to the increased line current – oversizing prevents the cable overheating and insulation damage which could potentially cause a fire. There are certain recommendations for cable sizing which take into account network THDi. Thus, a THDi below 10% does not require any additional oversizing, while with the 40% THDi typical for standard 6-pulse drives with built-in impedance oversizing of about 10% is required, and for 70% THDi – over 20% oversizing is needed.

Another important oversizing aspect is the transformer, which is often one of the most expensive power network components in a project. When a non-linear load (like a drive) is supplied from a transformer, it is necessary to derate the transformer capacity to avoid overheating and failure as a result. For a THDi close to 40% it is recommended that transformer equipment is oversized by about 40%, and for a THDi below 10%, oversizing of about 10% is recommended.

The K-factor was established by Underwriter Laboratories to define the ability of a transformer to serve varying degrees of non-linear load current without exceeding the rated temperature rise.[4] The K-factor ranges from 1 to 50. A K-factor of 50 is utilized for the harshest harmonic conditions possible. Standard transformers have a K-factor of 1.0 and are only assigned to linear loads that do not generate harmonics. From the diagram of typical transformer derating, it can be seen how various types of loads affect transformer capacity, and which derating is required at the THDi levels typical for standard variable speed drives.

Typical transformer derating



The effect of VSDs on process reliability
The presence of harmonics can also cause a more serious issue than increased energy use or the higher project costs associated with oversized components and lower facility sustainability. This serious issue is reliability, which includes, in particular, the reliability of the power supply that keeps a facility's systems and processes alive. Power supply failures can lead to serious consequences in mission-critical facilities like hospitals where they can risk patients' lives, or on production lines where they can cause massive financial damage. In the case of data

Estimating K-factor loads

Load	K-factor
Motors, incandescent lighting, resistance heating, motor generators (without solid state drives)	K-1
HID lighting, induction heaters, welders, UPS with optional input filtering, PLC and solid-state controls	K-4
Multiple receptacle circuits in health care facilities, UPS without optional input filtering, production or assembly line equipment, schools and classroom facilities	K-13
SCR variable speed drives, circuits with exclusive data processing equipment, critical care facilities	K-20
Multiwire receptacle circuits in commercial, industrial, medical and educational laboratories	K-30
Other loads identified as producing very high amounts of harmonics	K-40

centers, on average, downtime costs 5 600 USD per minute and the resulting reputational damage is even higher.[5]

Therefore, generators which provide these kinds of facilities with back-up power must be prepared for the issues they may experience when they feed non-linear loads with high harmonic content. A rule of thumb is that a generator which supplies 6-pulse drives needs to be oversized 2 to 2.5 times. If a generator is not oversized, its automatic voltage regulator might not operate properly due to excessive harmonics, and under these conditions the generator might trip.

Another aspect of process reliability is the ability to deliver nominal power to the application controlled by a variable speed drive. This can be a real challenge, for example, in long tunnels, where motor cables run for several hundred meters, which can cause a significant voltage drop that results in a lower voltage on the fan motor end. In a regular operation this can lead to a higher concentration of vehicle fumes and poorer visibility inside the tunnel during rush hours, but in the case of an emergency smoke exhaust fans may be unable to extract smoke at the rated flow, creating a risk to the tunnel users' safety.

One solution to the lower voltage is to utilize intermediate step-up transformers. However, this increases project costs and also negatively affects project sustainability because of the increased number of components. Another option is to use active front end (AFE) drives with DC bus capacitors for the process control. This technology allows the voltage to be boosted to its nominal level at the application end and deliver nominal power to the motor regardless of the voltage drop over the cable length.
The technology will be reviewed in the next chapter.

Active front end drive technology and its benefits over other solutions

There are many drive technologies present on the market today, with very different power quality performance. When a low harmonic content is critical for an application, the drives for the project should be selected carefully to avoid costly additional components like harmonic filters and to prevent any negative effects on the process's reliability.

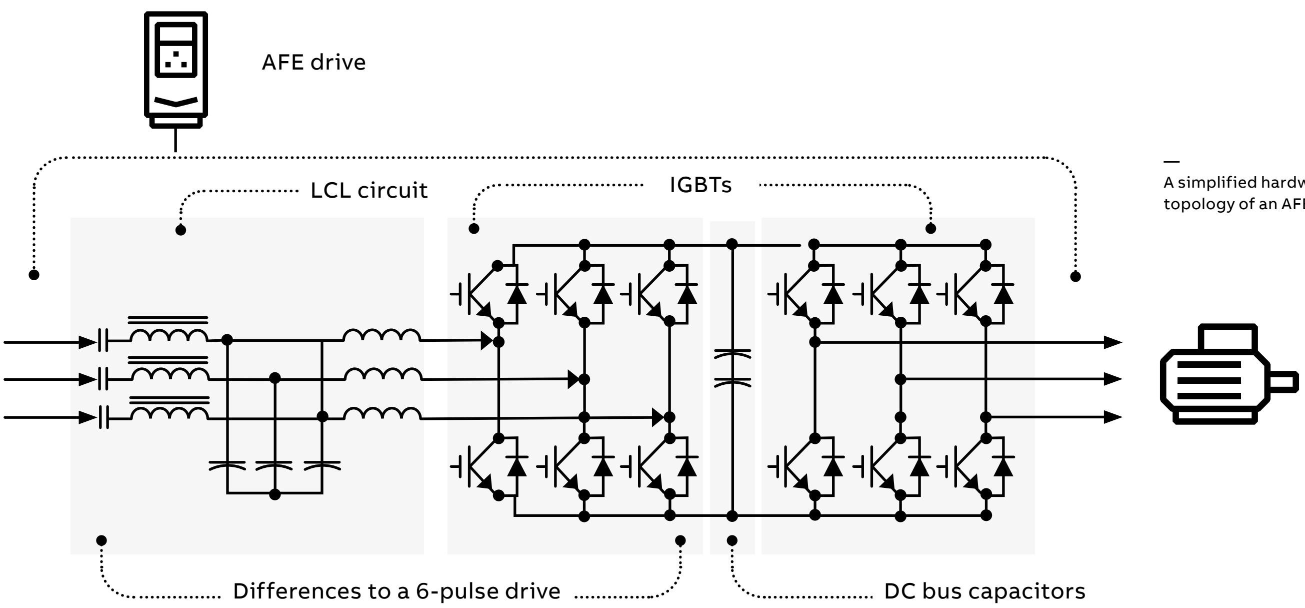
What is AFE drive technology with DC bus capacitors?
This paper focuses on active front end (AFE) drives with DC bus capacitors and their benefits, and the technology will be reviewed in more detail here.

Drives control AC motor speed and torque to match the application needs by changing the motor input frequency and voltage. Drives are installed between the electrical supply and the motor, and they regulate the power fed to the motor. Inside the drive, the power first flows through a rectifier which converts the incoming AC power to DC power. After that, the DC power flows into the drive capacitors, which make the electrical waveform smoother. In the next step, an inverter changes the inflowing DC power back to AC power before it reaches the motor. The inverter adjusts the current frequency and voltage supplied to the motor, meaning that the motor will run not with the nominal speed and torque, but at a speed and torque tuned exactly to the process needs. This saves large amounts of energy and increases process reliability and final product quality.

An AFE drive also converts alternating current (AC) to direct current (DC), and then switches the direct current back to AC like a traditional 6-pulse variable speed drive. The difference between a 6-pulse drive and an AFE drive is in the way the drives convert the AC to DC, and the electronics that allow this conversion.[6]

In AFE drives, insulated gate bipolar transistors (IGBTs) replace a traditional 6-pulse drive's diode-based rectifiers (AC to DC converters). VSDs have been used to control motors for many years using output IGBTs to generate a sinusoidal current for the motor. In AFE drives, precise control of the input IGBTs results in the sinusoidal current waveform drawn from the grid.

Another difference between AFE drives and 6-pulse drives is that they include an LCL (inductive-capacitive-inductive) circuit integrated before the front end IGBTs. The LCL circuit also eliminates harmonics above the IGBT switching frequency. All this leads to a current harmonic content in



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A simplified hardware topology of an AFE drive.

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ABB's family of ultra-low harmonic industrial ACS880, HVAC ACH580 and water ACQ580 drives is based on active front end technology with DC bus capacitors.

the network of below 3% compared to a traditional 6-pulse solution with THDi of about 40%. Active front end drives with DC bus capacitors do not produce harmonics in the first place, while other variable speed technologies may require costly additional solutions to decrease harmonics to a minimum.

The benefits of ultra-low harmonic drives

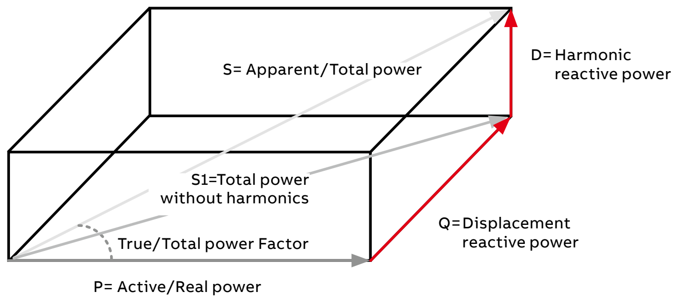
ABB has a wide portfolio of industrial and industry-specific ultra-low harmonic drives (ULH) for HVAC, water and wastewater applications based on active front end technology, which offers multiple benefits to industry.

With a THDi of 3%, facilities can avoid massive oversizing of power network components like generators, transformers, switchgear and cables in new projects, while also making the projects more sustainable due to their decreased material usage.

In retrofit projects, with an already established power network infrastructure, AFE drives allow facilities to prevent power network equipment from overheating and premature failure – this can happen when the harmonic content is too high and exceeds the network's carrying capability. AFE drives also allow existing transformers and generators that are at "full capacity" to have additional VSD load added, without needing to replace them with larger ones.

Besides harmonics, which are the distortion component of reactive power, ULH drives also take care of the displacement component of reactive power. While current and voltage distortion is the result of power electronics switching in electronic devices, current and voltage displacement means their waves are not in phase. This happens due to inductive and capacitive loads in the network. Typical inductive loads include motors running various applications, while computer servers are a good example of capacitive loads. Reactive power doesn't do any actual work but needs to be supplied to inductive or capacitive loads to maintain the voltage stability in the network.

To estimate how much reactive power is present in the network, a value called power factor is used. This indicates the relationship between the active power that does work, and the total power supplied to the circuit. The closer the power factor is to 1, the less reactive power is present in the network, the lower the line current and the more efficient and reliable the network is.



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The true power factor (PF) is the relation between two components of reactive power – power factors of distortion and displacement.

The PF of distortion is the relation of fundamental current and total current containing harmonics: $1 / \sqrt{1+THD_i^2}$

The PF of displacement is the relation of active power to total power without harmonics, also called cosϕ: P/S1.

The true PF is a multiplication of PF distortion and PF displacement: $\cos\phi \cdot 1 / \sqrt{1+THD_i^2}$

If there are no harmonics (THDi = 0) and no reactive power caused by inductive or capacitive loads, the current and voltage are in phase meaning $\phi = 0^\circ$ and $\cos\phi = 1$, total PF = 1.

Utilities often penalize consumers for a low power factor because it requires them to provide increased power generation and distribution capacity, and also means higher losses along the power line.

Standard VSDs that feature DC capacitors in their design are generally good at compensating for the reactive power of the inductive loads they control (the motors). Drives use their capacitors to feed reactive current to the motors and protect the supply utility from being the source of the reactive current itself.

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ABB's ACS880 ultra-low harmonic regenerative drives bring additional benefits to applications where energy recovery is possible.

However, more sophisticated drives with an active front end and DC capacitors, such as ABB's ULH drives, can go a step further by also compensating for other network reactive loads, potentially allowing end users to save on installing standalone reactive power compensators on their site.

ULH drives are also beneficial to the reliability of facilities and operations. Because they have a minimal harmonic content, they eliminate process interruptions from network overloads caused by increased line current. Malfunctions in connected devices due to a distorted current are also eliminated.

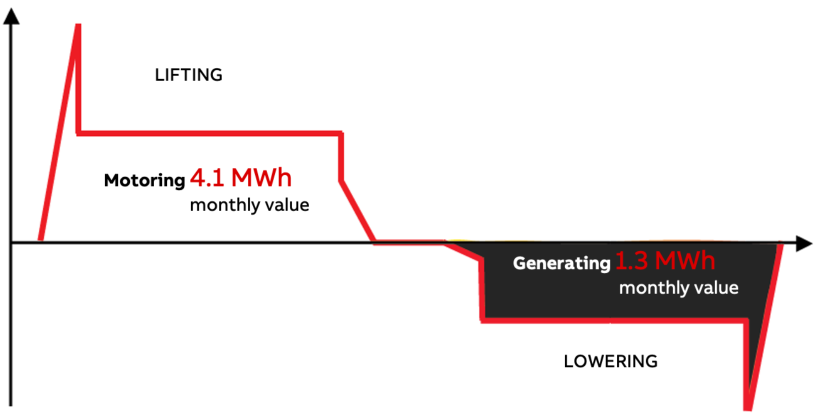
The voltage boost feature in ABB's ULH drives ensures nominal voltage at the motor terminals, even with the long motor cables and weak networks typical not only in tunnels but also in, for example, remotely located water and wastewater plants. In remote water facilities, delivering nominal pumping capabilities may be critical to ensuring a continuous fresh water supply to urban areas, as well as to the removal of sewage and storm water. Interruptions to this kind of service can cost millions of USD and have a devastating impact on the communities they serve.

A ULH drive variant with regenerative capability, in addition to all the aforementioned benefits, allows energy to be recovered from system mechanics, for example, during application braking, instead of losing it as heat through braking resistors or mechanical brakes. These can be used in crane or elevator applications, for example. Drives with a regenerative unit built-in enable active braking when an application motor is run as a generator and then feed the energy back into the network or an accumulator for later use.

Another type of application is occasional braking where the goal is not to save energy during regular braking but to stop the application as soon as possible when needed. This kind of braking can be used with tunnel ventilation where, in the case of fire, emergency fans may need stop as soon as possible e.g. to limit the spread of smoke.

There are various ways to brake an application, including brake choppers and resistors, external regenerative braking units, and matrix drives, but ULH drives with regenerative capability are considered to be preferential for several reasons[7]. In addition to minimizing harmonic content and energy regeneration, these include:

- higher system efficiency because the regenerative unit is an integral part of the drive and not a standalone component
- lower system complexity because no drive-external components are needed, like brake choppers, brake resistors or standalone regenerative units
- a smaller installation footprint because all the components are built-in
- reduced need for control room air conditioning compared to resistor braking, because no energy is wasted as heat



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A practical example of a waste handling crane with a 55 kW hoisting motor, 9 kW long travel motor, 4.5 kW trolley motor and 25 kW grab motor shows that a 32% reduction in annual energy cost resulting in 2 300 € savings can be made at power cost 0.15 € / kWh when ABB regenerative drives are used.

Alternative technologies to mitigate harmonics

There are many different approaches to reducing harmonics in power networks with 6-pulse drives and all of them have different effects on network power quality, resulting in better or worse energy efficiency, cost-effectiveness and reliability. Active front end drive technology with DC bus capacitors is considered to be advantageous for several reasons. The main reason is that it doesn't introduce harmonics in the first place, meaning no additional harmonic mitigation methods are needed.

One important aspect is harmonic mitigation performance at partial loads, which is where applications with variable speed control operate most of the time. ABB's active front end drives provide low harmonic content even at partial loads, while, for example, passive filters have certain limitations.

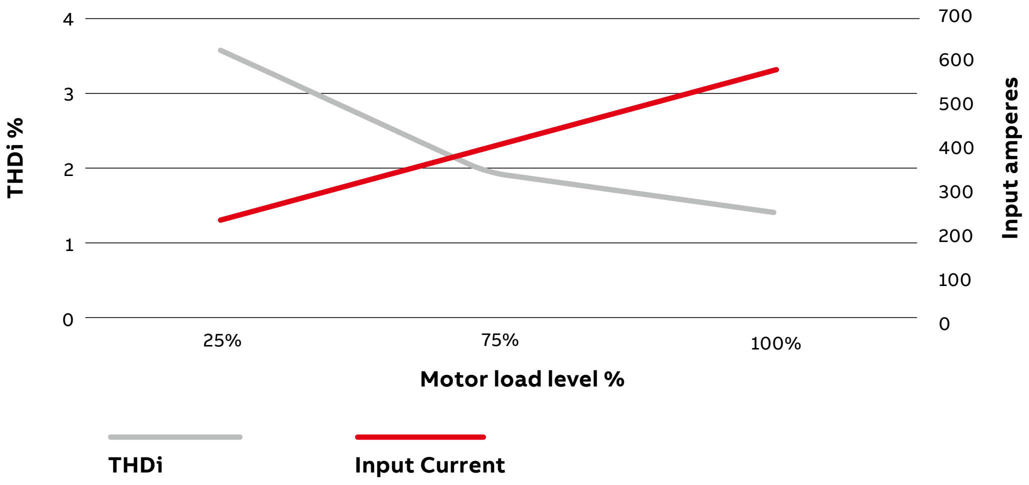
Passive harmonic filters are tuned to the specific harmonic frequency that needs to be eliminated. Several passive filters can be installed in parallel to reduce significant distortion caused by multiple harmonic frequencies, but this means a bigger installation footprint and a higher cost. Passive filter systems are designed to match the load, and if the load profile changes, then the passive filters installed must be changed too.

It is also good to remember that at loads below 20% to 30% passive filter capacitors need to be disconnected to avoid negative effects on the facility power factor and issues with the generator supply – and this spoils their harmonic reduction capabilities.

Active harmonic filters offer much better harmonic reduction in comparison to passive filters, as they detect multiple harmonic frequencies present in the network, and thanks to the IGBTs in their design they produce counter-harmonic currents to cancel the harmonics produced by non-linear loads. However, their harmonic reduction performance significantly changes with the load as well – at 50%, THDi can easily be 12-14%.

Multi-pulse drives are another alternative for harmonic mitigation. In these, the harmonic distortion is minimized significantly using a number of additional diodes in the rectifier – they use more diodes than a standard 6-pulse drive – but the installation complexity, massive footprint and need for phase-shifting transformers are significant drawbacks of the technology.

There are several active front end drive technologies present in the market. Besides active front end drives with DC capacitors, there are also AFE drives without DC capacitors available, called matrix drives.[6] Removing capacitors from a drive may lower the cost, but it negatively affects its performance, creating significant limitations on drive output voltage, harmonic performance, power factor and power-loss ride-through functionality.



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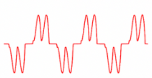
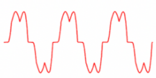
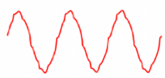
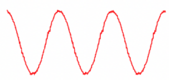
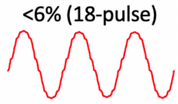
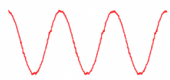
ABB's AFE drive harmonic performance in a 400V network with 20 RSC. A 650 ampere / 400V motor and ACS880-34-650A-3 drive were used.

Harmonic content at nominal load with different solutions

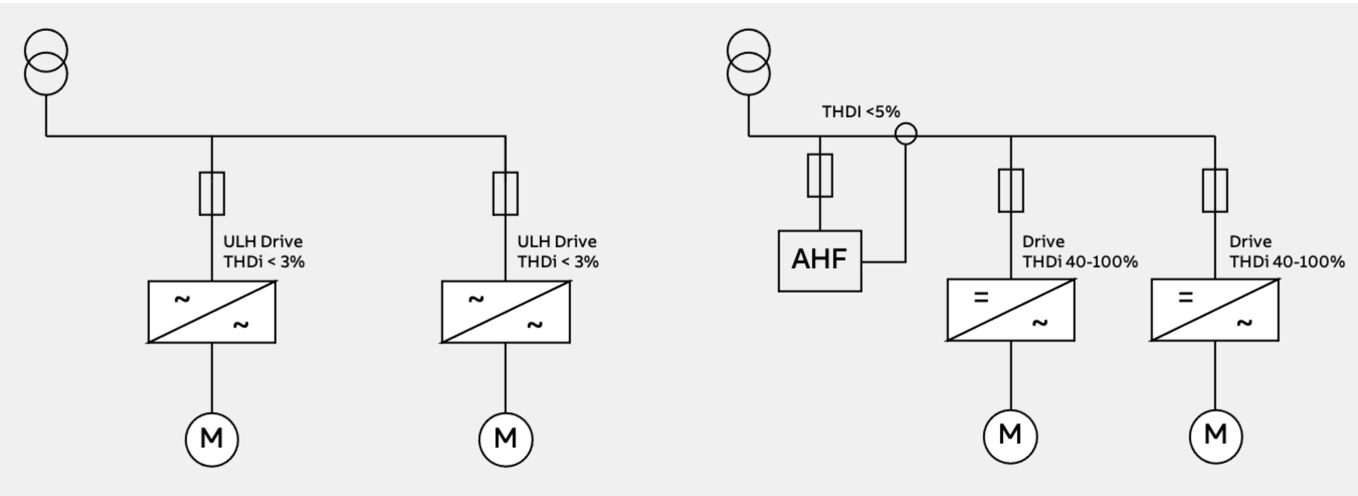
	6-pulse rectifier without choke	6-pulse rectifier with choke	6-pulse drive with passive filter	6-pulse drive with active filter	Multi-pulse drive	Active front end drive
THDi and respective current waveform	>100% 	~40% 	<10% 	<7% 	6 to 10% (12 pulse) <6% (18-pulse) 	<3% 

For example, a capacitor-less AFE drive may only produce 92% or less output voltage when operating in low harmonic mode with a THDi of about 5%. Motors that do not receive full voltage are not able to produce the rated torque at full speed unless they draw extra current to compensate for the lack of voltage. However, this makes the motor run hotter which shortens its operational life. And when matrix drives operate in maximum output voltage mode, the harmonic content in the current can reach 10%. This is above the broadly accepted industry standard benchmark for low harmonic drives, which is 5% THDi, based on applying the stringent IEEE 519 system standard directly to the drive.

AFE drives with DC bus capacitors in their design do not have this problem, and they deliver full motor voltage, while mitigating harmonics to a minimum.

When comparing different harmonic mitigation technologies, it's also important to look at how they affect system efficiency. Active front end drives naturally have lower efficiency than traditional 6-pulse solutions due to the additional active supply unit (IGBTs) in their design, but the losses to the system caused by harmonic filters that provide the same low harmonic performance are often overlooked. In reality, overall losses in systems with ultra-low harmonic drives are the same or lower, and they have the added advantages over standalone harmonic filters of a unity power factor and eliminated voltage drop at the motor terminals.

Using active harmonic filters for group installations (with one filter for several drives) is often encouraged because it makes installation more cost effective. The fact that active filters only mitigate harmonics upstream, towards the utility, while a high THDi is present in the system all the way from source of harmonics to the active filter is sometimes neglected. This means increased energy losses in the downstream part of the system and lower system reliability, plus the risk of system overload from excessive harmonic content in cases of centralized AHF failure. With active front end drives, harmonics are simply not produced by the drive, so the drawbacks of other multiple harmonic reduction technologies are avoided.



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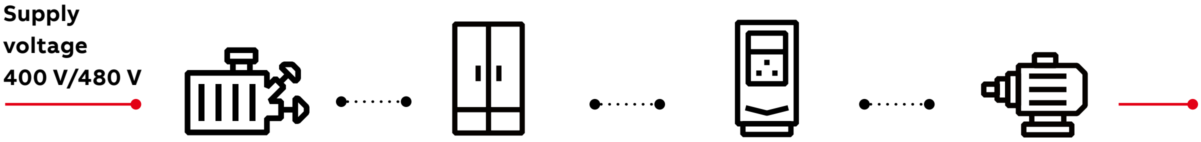
Harmonic mitigation in systems with ULH drives and an active harmonic filter (AHF).

Harmonics mitigation with passive filter

Harmonics content at nominal load = 10%

System efficiency = 87%

Supply voltage 400 V/480 V



Motor voltage after system losses ~370V/450V

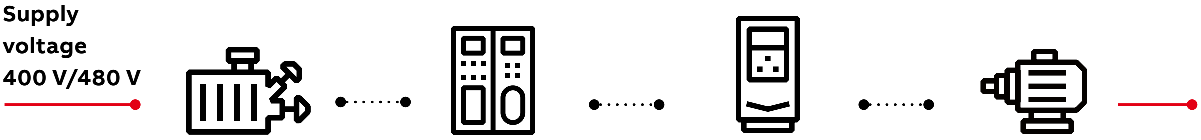
Network **efficiency**	Passive filter **efficiency**	6-pulse drive **efficiency**	Actual motor **efficiency**
~98%	**98.5%**	**98%**	**92%**

Harmonics mitigation with active filter

Harmonics content at nominal load = 5%

System efficiency = 85.7%

Supply voltage 400 V/480 V



Motor voltage after system losses ~ 380V/460V

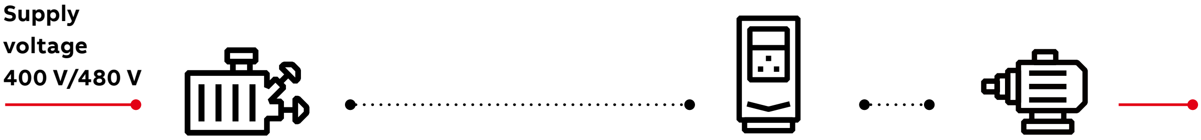
Network **efficiency**	Active filter **efficiency**	6-pulse drive **efficiency**	Actual motor **efficiency**
~98%	**97%**	**98%**	**92%**

Harmonics mitigation with active front end drives

Harmonics content at nominal load = 3%

System efficiency = 87.9%

Supply voltage 400 V/480 V



Motor voltage after system losses ~ 400V/480V

Network **efficiency**	ABB AFE drive **efficiency**	Actual motor **efficiency**
~98%	**97%**	**92.5%**

Conclusion

Variable speed drives are able to save substantial amounts of energy by adjusting motor speed to the application need. But it's crucial to evaluate the effect of VSDs on the power system before making the final choice, because some variable speed technologies can have an adverse impact on the power quality in the network, resulting in lower system efficiency and reliability, and higher project costs.

For systems which require minimal harmonic content as is typical in mission critical facilities, variable speed drives based on active front end technology with DC bus capacitors, like ABB's ultra-low harmonic drives, are the optimal solution. They ensure not only process efficiency itself, but also power network efficiency, while contributing to controlled process reliability. The substantial reduction in capital and operating costs from ultra-low harmonic drives with an active front end makes them a preferred choice for business and utility owners.

(1) Technical guide No. 6 Guide to harmonics with AC drives, ABB Drives 2017.

(2) Commercial Buildings Energy Consumption Survey, EIA 2016.

(3) Manufacturing Energy Consumption Survey – Dairy industry, EIA 2010.

(4) Proposed requirements and proposed effective dates for the first edition of the standard for dry-type general purpose and power transformers UL1561, Underwriters Laboratories 1991.

(5) The Cost of Downtime, Gartner Research 2014.

(6) Active front end drive technologies, ABB Drives 2019.

(7) Technical guide No. 8 Electrical braking, ABB Drives 2018.

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