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TOMORROW

Clean Grid Solutions

How to secure the quality of your mains supply. **Planning and designing** solutions for **better power quality**

8%

mains harmonic voltage distortion is the upper limit for reliable plant operation.

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Increase energy efficiency with power electronics – will it suffocate our mains supplies?

Rising energy prices are forcing customers to use energy efficiently, leading to a broad spectrum of solutions to reduce energy consumption. Perhaps the best known example is energy-efficient lamps, which are now widely used in both household and commercial areas. In addition, speed control of motors using frequency converters has become common practice in building automation and industrial production, since this helps to drastically reduce energy consumption in the vast majority of cases. But just like power electronics in televisions, computers, switching power supplies and the like, they also have a drawback: they burden the mains network with harmonic distortions, also known simply as harmonics. In the medium to long term, the increased use of such devices in all realms of daily life poses a considerable threat to the safety of power supply of our distribution networks.

And that's not all – harmonics can also lead to malfunctions, lower availability or even total failure of equipment in buildings or plants, without the cause of the problem being clearly recognised. This is because mains harmonics are everywhere, but they cannot be detected without suitable measuring equipment. The real problem is not that single devices generate mains harmonics, but rather that the number of these devices is constantly and dramatically increasing.
However, this is an unavoidable consequence of the demand for higher energy efficiency. Only suitable countermeasures can prevent the total collapse of the supply networks.

From a technical perspective, mains harmonics come under the realm of electromagnetic compatibility (EMC). In contrast to the generally more familiar phenomenon of highfrequency radiated interference from radio signals and the like, the effects described above are due to lowfrequency conducted interference.

This brochure is divided into two parts: one part covers the fundamentals, providing a comprehensive and largely manufacturer-independent overview of how harmonics are generated, their hazards and suitable countermeasures, and the second, solution-oriented technical part presents the broad spectrum of Danfoss VLT® and Vacon® products.

The fundamentals part starts by defining and classifying harmonics in the realm of EMC and describes how mains harmonics are generated. In further it explains the hazards to mains networks and connected devices, describes the procedure for carrying out a cause analysis, and presents an analysis method for practical use. The fundamentals part concludes by presenting possible countermeasures and outlining the economical and technical need to take suitable measures.

The technical part presents individual solutions and provides general technical data to facilitate the selection and comparison of potential solutions. It should be noted from the outset that there is no single, all-purpose solution.
There are many ways to tackle the problem, and general conditions such as plant structure, available space and economic factors all affect the selection of the right or ideal components for a specific case.

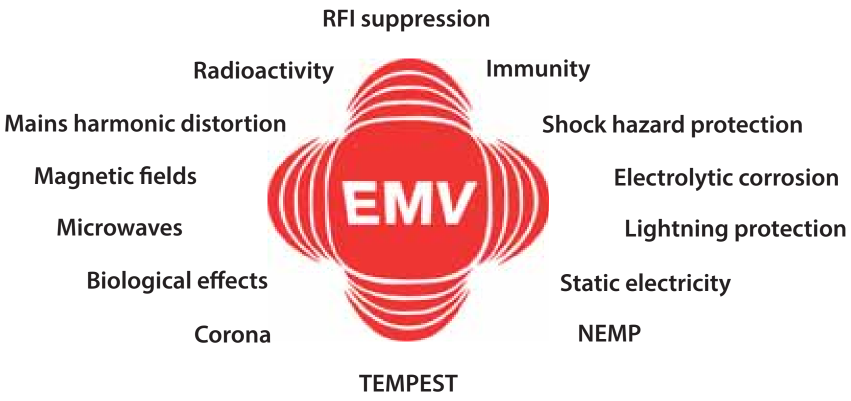
Understanding electromagnetic influences

Electrical devices and their influence on the environment
Every electrical device produces electrical and magnetic fields that affect its immediate environment to a greater or lesser extent. The magnitude and effect of these factors depend on the power and construction of the device.
In electrical machines and systems, interactions between electrical or electronic components can impair or prevent reliable, trouble-free operation. For this reason it is important for plant operators, designers and plant engineers to understand the mechanisms of these interactions. Otherwise it is not possible to take suitable and costeffective measures in the planning stage. Remember that the longer you leave it before taking measures, the more expensive they become.

Electromagnetic factors work in both directions
The components of a plant or system affect each other: each device generates emissions and is exposed to others emissions. Accordingly, a key characteristic of each component is not only the nature and scope of its emissions, but also its immunity to emissions towards the environment from neighbouring devices.

System responsibility rests with the operator
Manufacturers of devices or components for electrical drives must take measures to ensure compliance with statutory guideline values.
With the product standard EN 61800-3 dedicated to the application of variable speed drives, this responsibility has been additionally restricted to the drive unit only, while the overall plant and installation responsibility has been clearly dedicated to the end user or plant operator. Manufacturers must offer solutions that ensure use in compliance with the standard, but the responsibility for eliminating any interference, and the ensuing costs, rests with the operator.

Two options for mitigation
Two means for ensuring electromagnetic compatibility are available to users or plant engineers. The first is to suppress noise at the source by minimising or eliminating disturbing emissions. The second is to increase the immunity of the devices or systems suffering from disturbances by preventing or significantly reducing the reception of interference.



Electromagnetic compatibility (EMC) encompasses a wide range of phenomena. In drive technology, the main focus is on mains harmonics, RFI suppression and immunity.

Distinguishing between conducted and radiated emissions

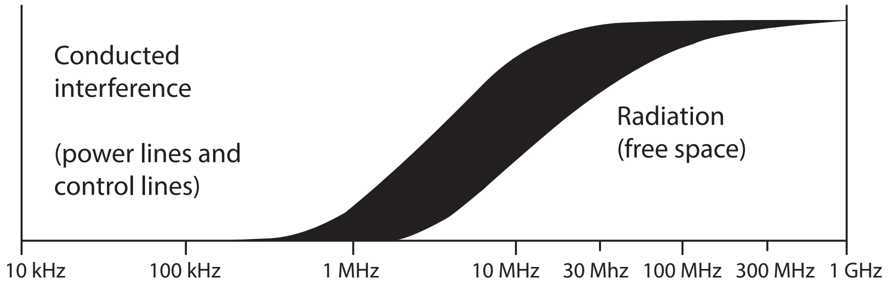
Basic principle of interference effects
There is always an interaction between several systems. In this regard, specialists distinguish between the interference source and the interference sink, or in other words, the device that causes interference and the device that suffers interference. Interference can be caused by any sort of electrical or magnetic quantity that causes an undesirable effect. This may take the form of mains harmonics, electrostatic discharges, rapid voltage variations, high-frequency interference voltages or interference fields In practice, mains harmonics are often referred to as harmonic distortions or simply "harmonics".

Transmission paths of interference
But how is interference transmitted? As a form of electromagnetic emission, it can basically be transmitted by conductors, electrical or and/or capacitive fields, or electromagnetic waves. Specialists refers to these modes as galvanic, capacitive, inductive or radiative coupling. In practice, these different phenomenas occur either individually or in various combinations.

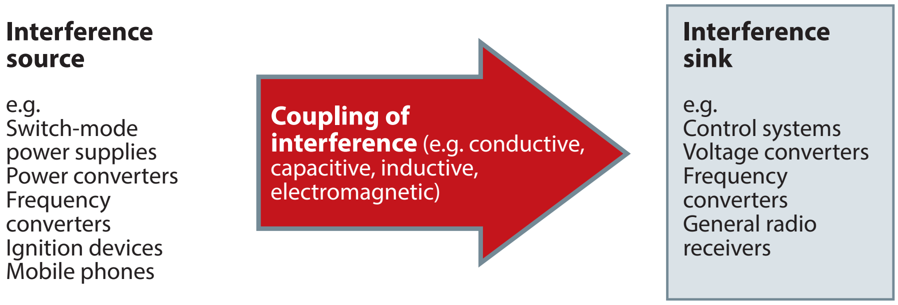
Coupling mechanisms between electrical circuits
In daily practice, coupling always means interaction between different electrical circuits with the transfer of electromagnetic energy between the circuits. There are four possible paths for this:

- Galvanic coupling is present when two or more circuits are joined together by a common conductor (for example, a potential equalisation cable)
- Capacitive coupling occurs when there are voltage differences between different circuits (for example, capacitors)
- Inductive coupling occurs between
- two current-carrying conductors (for example, a transformer)
- Radiative coupling is present when the interference sink is
- located in the far-field area of the radiation field generated by an interference source. (for example, a radio transmitter)

In many practical situations, the boundary between conductive coupling and radiative coupling is at 30 MHz, which corresponds to a wavelength of 10 metres. Below this frequency, interference propagates primarily over conductors or via electrical or magnetic field coupling. Above 30 MHz, wires and cables act as antennas and radiate electromagnetic energy or receive it over the air.



Electromagnetic interference occurs over the entire frequency spectrum, but with different forms and propagation paths.



Overview of coupling paths for electromagnetic interference and typical examples

The operating site is decisive
First and second environment

The limit values for the particular environment are specified by the relevant standards. But how are the various types of environment classified? For electrical drive systems and components this information can be retrieved from the EN 55011 and EN 61800-3 standards.
The EN 61000 standards provide further informations and also distinguishes various power ranges.

First environment: residential, commercial and light industrial areas
All operating sites that are connected directly to the public low-voltage power grid are considered to be residential, commercial and light industrial environments. They do not have own dedicated high-voltage or medium-voltage distribution transformers for separate supply.
The environments apply both inside and outside the buildings: business premises, residential buildings or residential space, food and entertainment facilities, car parks, recreational and sports facilities.

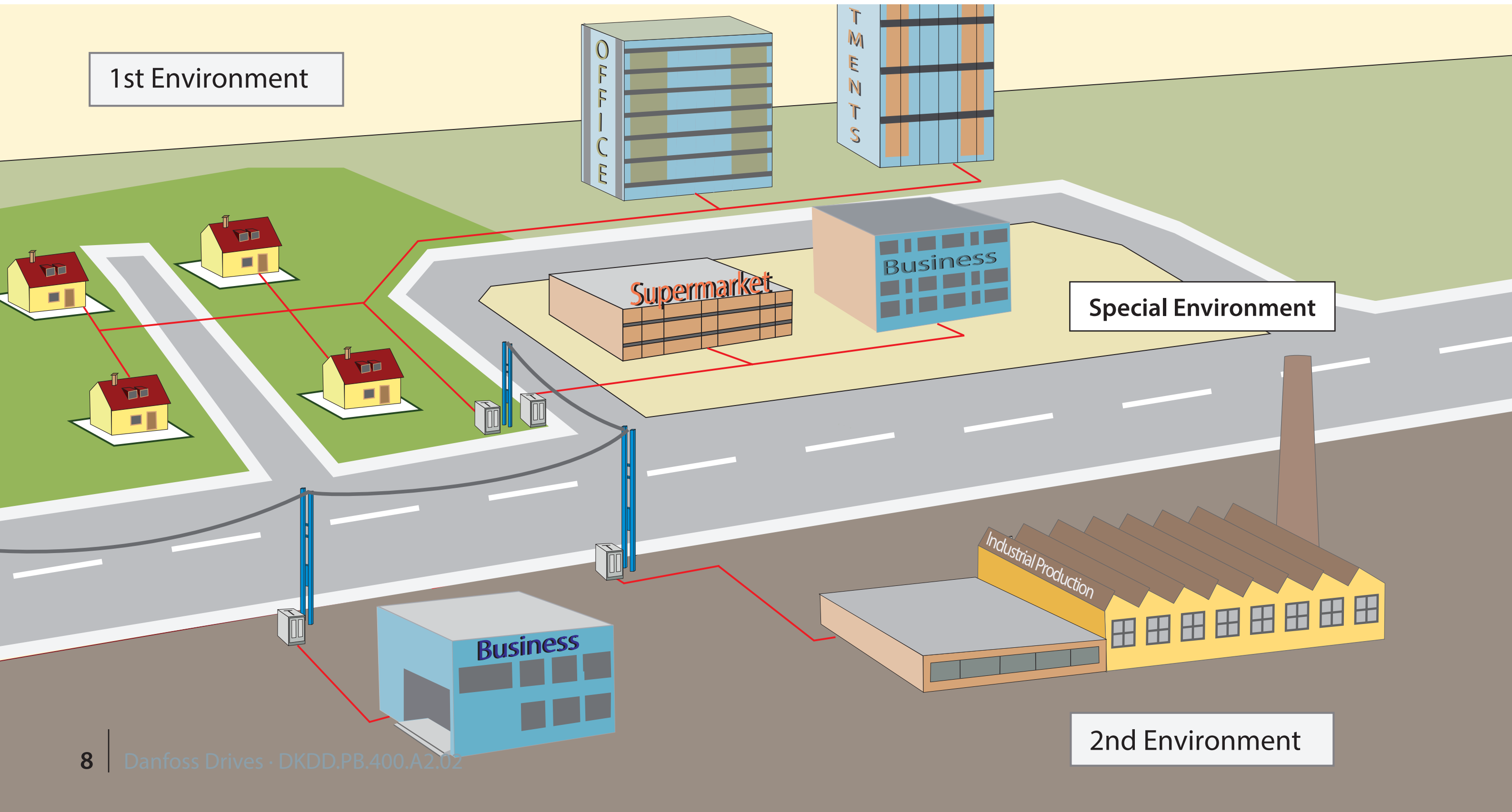
Second environment: industrial environment
Industrial environments are operating sites where the electrical devices are not connected directly to the public low-voltage power grid, but instead have their own high-voltage or medium-voltage distribution transformers. They are also defined as such in the cadastral register and are characterised by specific electromagnetic circumstances following:

- Presence of scientific, medical and industrial devices
- Switching of large inductive and capacitive loads
- Presence of strong magnetic fields (e.g. due to large load currents)

The environments apply both inside and outside the buildings.

Special environments
In these environments the user can decide on the environmental classification of the plant. The prerequisites are an own medium-voltage transformer supply and a clear demarcation relative to other environments. Within the operator's environment, the operator is directly responsible for the electromagnetic compatibility measures necessary to ensure the trouble-free operation of all devices. Some examples are the building services areas of shopping centres, supermarkets, gas filling stations, office buildings and warehouses.

Classification of operating areas in the first and second environments, and special environments in which the operator has freedom of choice.



High-frequency radio interference – limit values depend on the operating site

Radio frequency interference
Frequency converters use rectangular voltage pulses with variable width to generate variable-frequency rotating fields at corresponding motor voltages. The steep pulse edges contain high-frequency components. These components are radiated by the motor cable and the frequency converter and conducted to the mains via the supply cable. To reduce the effect of this interference on the mains feed, manufacturers use radio frequency interference suppression filters (also known as RFI filters or mains filters). They serve to protect the device against high-frequency conducted interference (interference immunity) and to reduce the amount of high-frequency interference emission from the device that is conducted or radiated by the mains cable.
The filters are intended to reduce interference emissions to a legally specified level, for which reason they should be fitted as closely as possible to the power entry point of the device. As with line reactors, the quality of the RFI filters to be used must be clearly defined. Specific limits for interference levels are defined in the standards, including the product standard EN 61800-3 and the generic standard EN 55011.

Standards and directives define limits
What are the applicable limits for assessing electromagnetic compatibility (EMC) in an installation with variable speed drives?

Two standards must be taken into account for a comprehensive assessment of high-frequency radiated interference. The first is the EN 55011 standard, which defines the limits according to the underlying environment; classes A1 and A2 for the industrial environment or class B for the residential environment.
The second is the product standard EN 61800-3 for electrical drive systems, which took effect in June 2007 and defines own categories (C1 to C4) for the operating site of the variable speed drive. Although they are comparable to the previous classes in terms of limits, they have a larger scope within the context of the product standard.

In intereference situations, inspectors will base their recommendations for interference mitigation following the generic installation standard, such as the limits for classes A1/A2 and category B of the EN 55011 standard. The user is ultimately responsible for the appropriate classification within the context of these two standards.

Product standard EN 61800-3 for electrical drive systems

Allocation by category	C1	C2	C3	C4
Sales channel	Generally available	Restricted availability	Restricted availability	Restricted availability
Environment	First environment	First or second environment (operator decision)	Second environment	Second environment
Voltage / current	< 1000 V			> 1000 V Nominal current > 400 A Connection to IT mains
EMC expertise	No requirement	Installation and commissioning by an EMC competent person		EMC plan necessary
Limits according to EN 55011	Class B	Class A1 (with warning notice)	Class A2 (with warning notice)	Values exceed Class A2

Classification of the categories C1 to C4 of the product standard EN 61800-3

Assessing and securing power quality

The perfect mains voltage

Electrical energy is now the most important resource for households, industry and commerce. But it is an unusual one: it must be constantly available, it can hardly be stored, and QC before use is practically impossible. On top of that, it is generated at some distance from the point of use, and fed into the grid together with the output from a large number of other generators. The energy reaches users via several transformers and many kilometres of overhead lines and underground cables. The network equipment belongs to a large number of different bodies, and responsibility for this equipment is also distributed among many different bodies. Ensuring the quality of the product for the end user is therefore difficult, and it is not possible to withdraw, repair or recall an insufficient supply voltage quality easily.

Statistical data about the quality of the supply voltage mostly originates from the suppliers themselves. The tolerable level of distortion from the supplier's perspective may be quite different from what customers find acceptable. It appears that the only situations that constitute deficient quality for the customer are dropouts (for anything from a fraction of a second to several hours) or shortterm voltage sags. Many processes are sensitive to such interruptions. Some example are:

- Continuous or parallel processes in which machines running in synchronisation become unsynchronised
- Staged processes in which a power interruption destroys the results of all previous stages, such as food manufacturing
- Power outages in the data processing systems of banking businesses can cause enormous financial losses

Even in everyday life we have come to depend on the greatest possible security of the energy supply.

Power quality – what are the key factors?

To be perfect, the electricity supply would have to be constantly available, remain within the defined frequency and voltage tolerances, and have a pure sinusoidal waveform. Every customer has a different view of how much deviation from the ideal is tolerable, depending on their specific requirements.

There are five factors for assessing mains power quality:

1. Waveform distortion, e.g. due to harmonics or flicker
2. Total outage lasting from seconds to hours
3. Undervoltage or overvoltage in the form of long-term deviations outside the 10% tolerance range
4. Short dropouts and surges, e.g. as a result of unbalanced mains voltages or switching operations in the network
5. Transients – high peak voltages in the kilovolt range with a duration in the millisecond range

Standardised measurement methods for voltage quality verification

Parameter	Measurement method	Interval	Observation period
Voltage variations	Average of 20-ms RMS value	10-minute intervals	1 week
Voltage sags	Duration and amplitude	Recorded as a single event	1 day
Voltage interruptions	Duration	Recorded as a single event	1 day
Harmonic voltage and interharmonic voltage	Average of 200-ms RMS values (in accordance with the IEC1000-4-4 standard)	10-minute intervals	1 week
Flicker	Short-term flicker (Pst values) over 10 minutes (in accordance with the IEC 868 standard)	Average of 12 Pst values (2-hour intervals)	1 week
Voltage unbalance	Average ratio of reverse and forward components	10-minute intervals	1 week
Signal voltages	3-second averages are classified	3-second intervals	1 day
Frequency	10-second averages are classified	10-second intervals	1 week

Each of these power quality problems has a different cause. For example, a transient resulting from a blown fuse can cause problems for another customer. Harmonics can be generated by devices within an endcustomer site and distributed over the network to other users.

The electricity companies take the position that customers with critical requirements on power supply quality must take the effort and cost of power quality assurance themselves, rather than guaranteeing all customers very high availability everywhere and at all times. Ensuring the supply of power at all times under all conditions in the overall network is economically unfeasible and virtually impossible. This would require suppliers to also take into account exceptional weather conditions in the vicinity of overhead transmission lines or accidental damage to cables during excavation work. It is therefore the responsibility of customers themselves to take suitable measures to ensure that the supply of power for their own needs is reliable and sufficient to meet their requirements.
This means that they can also set a higher quality standard than the supplier provides or guarantees.

Technical solutions for the reliable supply of good power
In light of the above, customers must decide for themselves on the nature and scope of additional equipment and resources required to achieve the necessary supply quality. The problem is that the information they need is not always available. There are few statistics on mains outages. This makes it very difficult for customers to determine the cost of preventive measures. However, a relatively high availability of around 99.98% is the highest that can be achieved economically without considerably increasing the price of electricity.

Short interruptions in the range of 0.2 to 5 seconds occur relatively often. Among other things, they can be caused by trees falling on overhead lines during storms. In most cases, the electricity supplier is not directly responsible for these faults. The supplier simply offsets the resulting losses in the level of costs for outages in the supply of electricity.
However, the customer experiences a loss of income resulting from the interruption of production.

Longer interruptions can also result from faults on the part of the supplier or faults in the supply network, such as damage to the transmission lines due to outside factors. The only remedy for this is redundant systems, such as backup generators or uninterruptable power supplies.
As these redundant systems (UPSs) are complex and expensive, careful planning at the earliest possible stage is necessary. This is the only way to precisely define weaknesses and plan the necessary redundancies into the structure of the overall supply system.

Assessing and securing power quality

Problems with harmonics almost always fall under the responsibility of the user. They result from non-linear input currents in electrical loads.

As a result of the mains impedance, the higher frequency components are superimposed on the mains voltage and can be distributed through the network. The most common causes of these non-sinusoidal input currents are rectifier and phase control circuits. These circuits are very widely used and can be found in energy-efficient lamps, computers, monitors, frequency converters, battery chargers, and other systems with power electronics. This means that interference due to harmonics can occur in a system as a result of harmonics generated in the system itself. Solutions can be implemented in the devices themselves or at the point of common coupling. The plant operator must determine which solution makes the most sense in economic terms.

Transients are high-frequency events with a duration less than one mains cycle. They can be caused by switching operations, blown fuses, tripped circuit breakers, or lightning strikes in the network. Transients reach levels of several kilovolts and cause considerable damage in the absence of suitable countermeasures. Device manufacturers must provide a certain amount of protection against transients, with the number of events based on the frequency of lightning strikes and the lifetime of the device. If transient events are significantly more frequent in a particular section of the network, the protective devices age considerably faster and device protection is lost after a relatively short time. Lightning protection schemes are based on protecting the network against transients in plants by means of surge protectors and varistors, so that the mains voltage at the load is limited to the specified maximum peak voltage.

How good is good enough?

Problems with mains power quality repeatedly confront planners with this question, for which there is no simple answer. We recommend that you consult national or international standards in this regard. They define individual phenomena and specify compatibility limits that serve as the basis for device manufacturers and network suppliers. However, they do not take into account a concentration of these events or the cumulative effect of several incidents occurring at the same time. These need not necessarily arise only from the electricity provider.

The key question is:
Is the operating equipment and the electricity supply mutually compatible?

For this purpose, the end user must define the required power quality and implement the measures necessary to assure this quality. This requires good planning, effective countermeasures, cooperation with the electricity supplier, frequent monitoring and ongoing maintenance.

Mains disturbances and their hazards

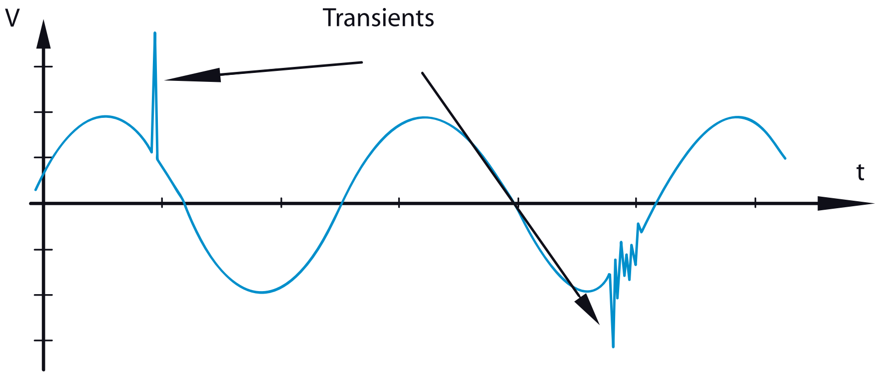
Supply networks in danger
With the coming of the integrated European power grid, higher grid utilisation and lower investments, mains power quality does detoriate with increased tendency. Deviations from the ideal sinusoidal waveform are therefore unavoidable, and they are allowable within certain limits. Planners and operators have an obligation to minimise this mains distortion. But what are the limits, and who defines them?

Legal basis ensures quality
Standards, directives and regulations are helpful in the debate on clean, high-quality mains power.
In Germany for instance, the basis for the objective assessment of mains power quality is the directive regarding the Electromagnetic Compatibility of Devices (EMVG). The European standards EN 61000-2-2, EN 61000-2-4 and EN 50160 define the limits to be maintained for the mains voltage in public and industrial distribution networks. The EN 61000-3-2 and EN 61000-3-12 standards regulate the harmonic current emissions of devices connected to the mains. In the overall assessment, system operators must also take into account the EN 50178 standard and the connection conditions of the electricity company.
A basic assumption is that compliance with these levels will enable troublefree and proper operation of all devices and systems in power distribution networks.

How mains harmonics are generated
As already mentioned, harmonics are generated by nonlinear loads such as frequency converters, energy-efficient lamps, and switch-mode power supplies in television sets, monitors and computers. All of these devices, as well as many others, have pulsating input currents.
The specialist term for the distortion of the sinusoidal waveform of the supply network resulting from the pulsating input currents of the connected loads is „low-frequency harmonics“ or „harmonic distortion“. Based on the Fourier analysis of the waveform, specialists also describe this in terms of the harmonic content of mains power, which they analyse at frequencies up to 2.5 kHz, corresponding to the 50th harmonic of 50 Hz. As a result of feedback to the mains supply network, these harmonics cause more or less severe distortion of the voltage waveform, depending on the mains impedance.

The input rectifiers of frequency converters also generate this typical form of harmonic distortion on the mains. In the case of frequency converters on 50-Hz networks, the main focus is on the third (150 Hz), fifth (250 Hz) and seventh (350 Hz) harmonics. They produce the strongest effects. The total harmonic content is given by the total harmonic distortion (THD) factor. As a rule, at a given site the level of mains distortion rises with the number of installed devices with integrated power electronics.

In the ideal case, the mains supply has a pure sinusoidal waveform with a fundamental frequency of 50 or 60 Hz. All electrical equipment and devices are designed to work best at this frequency.



Lightning strikes are among the most common causes of mains transients in HVAC systems.

Effects of mains harmonic distortion

Mains distortion such as harmonics and voltage fluctuations is classified as low-frequency conducted mains interference. This sort of interference has a different appearance at the point of origin than at any other load connection point in the network.

The combination of mains infeeds, mains topologies and loads must be taken into account in the assessment of mains distortion.

Excessive harmonic distortion of the mains supply means the mains voltage is composed of not only the 50 Hz or 60 Hz frequency, but also other frequencies. These harmonics cannot transmit electricity to electrical devices, but they have considerable detrimental effects:

- Restriction of supply and mainscapacity
- Higher losses
- Increased heating of transformers, motors and cables
- Reduced device lifetime
- Expensive, undesirable production downtime
- Interference to instrumentation and control systems
- Pulsating and reduced motortorque
- Acoustic noise

In simple terms, harmonics reduce reliability, impair product quality and increase operating costs.

Note: Excessive harmonic levels stress power factor correction systems and damage or lead to the failure of such systems. For this reason power factor correcting capacitors should always be used in combination with detuning reactors.

Does this mean that every frequency converter causes problems with harmonics?

Problems generally do not arise from individual frequency converters, but instead from the total number of devices with power electronics in the system and the usually large number of small electronic devices.

VLT® and Vacon® frequency converters are almost all equipped as standard with harmonic suppression reactors to reduce harmonic emissions.

In many cases this is sufficient to keep mains voltage distortion within allowable limits.

In some cases, however, additional harmonic mitigation is desirable or necessary.

For this purpose, Danfoss offers a broad range of specific solutions for harmonic mitigation, including Danfoss VLT® and Vacon® frequency converters with 12-pulse input rectifiers, low harmonic drives and stand-alone active or passive harmonic filters. Active filters can also take other mains loads in the network into account and compensate for their harmonic emissions.

In straightforward situations, you can use the free VLT® or Vacon Harmonics software tools to determine the level of harmonic emissions in your system, or you can use the HCS Harmonic Simulation Software for more complex systems.

These programs help you decide whether you need additional measures reducing harmonics.

They take the current standards into account and are able to calculate mitigation solutions.

Are there any frequency converters with zero harmonic emissions?

Every frequency converter generates mains harmonics. However, the present standard only considers the frequency range up to 2.5 kHz.

Even though there are presently no binding limits between 2 till 9 kHz and from 9 till 150 kHz, it is adviseable to keep as well an eye on the existing disturbance in this frequency range of the installation and also on tendencies for resonance. Future limiting levels for this frequency range are currently being discussed within international standardization groups.

Mains power analysis and countermeasures

How do you select the optimal solution for mitigating harmonics?

There are various ways to mitigate harmonics. They all have their pros and cons. There is no single solution that is ideal for all combinations of applications and mains conditions. To find the optimal solution for harmonic mitigation, users must consider a number of parameters. The factors can be divided into four groups:

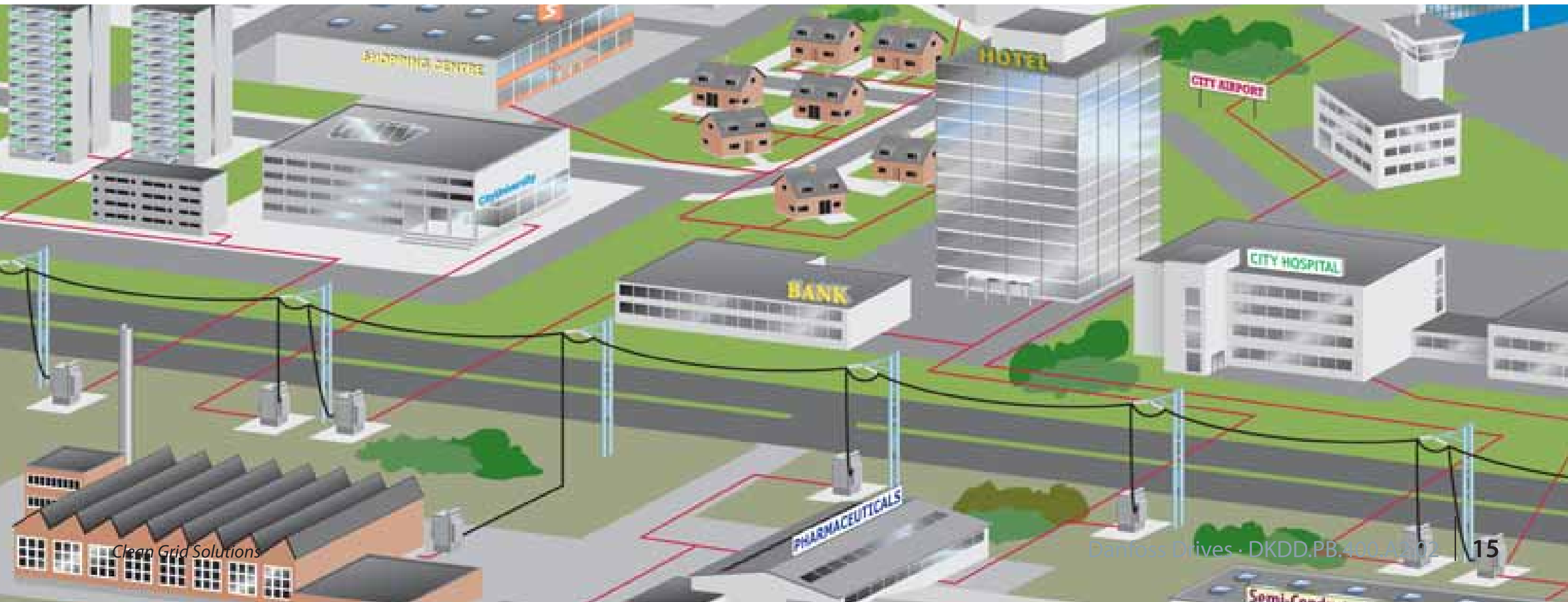
- Mains conditions, including other loads
- Application and processes
- Regulatory compliance
- Cost-effectiveness of the solution for the application

How do mains conditions affect harmonic distortion?

The key factor for determining the harmonic distortion of a supply network is the network impedance. It depends primarily on the size of the transformer relative to the overall power consumption of the installed loads. The larger the transformer relative to the loads producing harmonic emissions, the lower the effect of the emissions.
The electrical supply network is a system composed of mains infeeds and connected loads, all joined together by transformers. All loads with non-sinusoidal input current contribute to the harmonic distortion of the mains network – not only in the low-voltage distribution network, but also at higher voltage levels.
This means that when you make measurements at a connection point, there is always a certain amount of existing distortion, which specialists call "background harmonics". As the loads connected to the network may be single-phase or three-phase devices, the harmonic distortion of the individual phases is different. This results in different voltage levels on the individual phases, and thus phase imbalance.
The various solutions for harmonic mitigation differ in their sensitivity to background harmonics and imbalance. It is therefore necessary to estimate these factors when deciding on the most suitable solution to be used for harmonic mitigation.

Which application aspects must be taken into account?

The absolute harmonic content rises with the amount of power consumed by nonlinear loads. For this reason, both the number of installed frequency converters and their individual power ratings and load profiles have a considerable effect on harmonic content. The total number of frequency converters and other nonlinear loads in a network segment determines the total harmonic current distortion (THDi) in that segment, which is the ratio of the total harmonic content to the fundamental frequency.
The load factor of the frequency converters is important because the percentage value of the THDi increases under partial load conditions. This means that overdimensioning frequency converters increases mains harmonic distortion. In addition, users must take into account general conditions such as available wall area, cooling air (pollution degree), vibration, ambient temperature, elevation, relative humidity and so on, since the various solutions differ in their suitability for use in particular environmental conditions.



Mains power analysis and counter measures

Compliance with applicable standards
To ensure a minimum level of power quality, electricity suppliers demand that their customers conform to applicable standards and regulations. Specifications vary depending on the country and the installation environment, but they all have the same goal: limiting the harmonics distortion of the mains network. The way the specifications are fulfilled depends on the network conditions. It is therefore not possible to ensure compliance with the standards and limits without knowledge of specific network structures and conditions. None of the standards define specific solutions for harmonic mitigation. For this reason it is important to be familiar with the standards, regulations and recommendations and to know the present harmonic distortion level of the network in order to find the optimal solution for a particular situation.

Economic factors for the selection of reasonable measures
Users should naturally consider all procurement and operating costs in order to ensure that they have found the most cost-effective solution. The procurement costs of the various solutions for harmonic mitigation depend on the power level concerned. The solution that is the most cost effective at a particular power level is not necessarily the most economical over the entire power range. The operating costs arise from the losses engendered by the measures themselves over the entire load profile and the maintenance costs over their entire lifetime. Unlike active solutions, passive solutions often do not require periodic maintenance. On the other hand, active solutions are able to keep the power factor close to 1 over the entire power range, resulting in better power utilisation under partial load conditions.
In addition, users should include future development plans for the plant or facility in their planning, since a solution that is optimal for a system in the planning stage may have drawbacks for a foreseeable extension. In such cases, a different measure may prove more flexible and thus more advantageous, and therefore be less costly in the long term.

Calculating harmonic emissions
To ensure power quality, there are various methods available for mitigating, preventing or compensating for harmonic emissions from plants or devices. Mains harmonics calculation programs, such as HCS (Harmonic Simulation Software), allow calculations to be made for plants or systems in the planning stage. This allows the system operator to examine and consider specific measures in advance. Selection of suitable measures increases and secures the availability of the plant.

Practical aspects – selecting the right measures

Options for mitigating harmonic emissions

Generally speaking, harmonic emissions can be reduced by using electronic power conditioners to reduce pulsating currents by means of amplitude limiting. This also improves the power factor λ (lambda). Various methods are available for mitigation, avoidance or compensation:

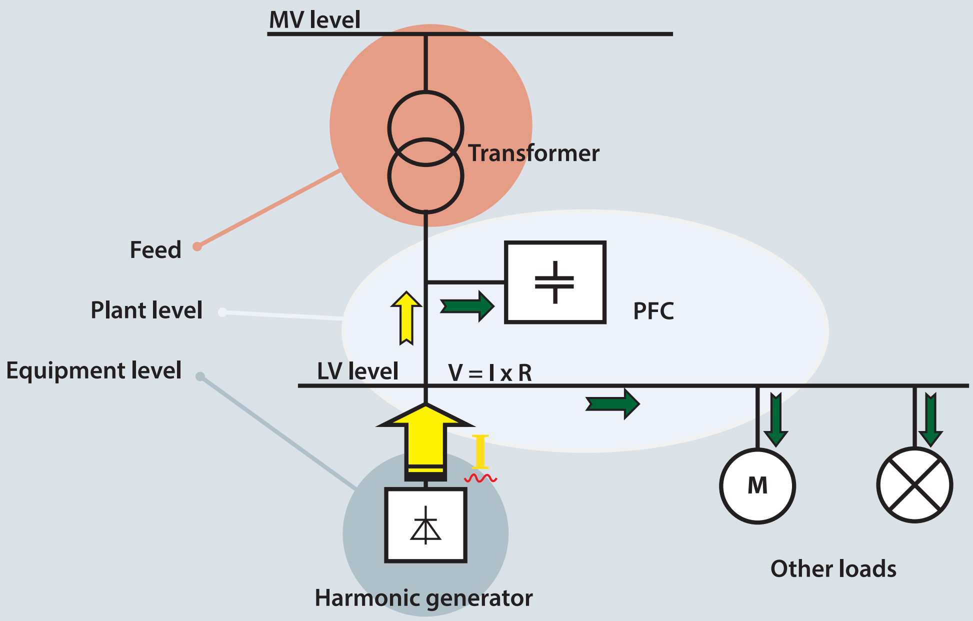
- Chokes at the inputs or in the DClinks of frequency converters
- Slim or reduced DC links
- Rectifiers with 12, 18 or
- 24 pulses
- Passive filters
- Active filters
- Active front ends and active infeed converters
- So called "Low Harmonic Drives", having integrated one of the before listed technologies

The measures can be classified as either passive or active, and they differ particularly with regard to project engineering. In some cases provisions for a specific measure must be made in the project engineering stage of a plant or system because later retrofitting would further increase the cost of measures that in part are already expensive.

No basic recommendation is possible
It is not possible to make any basic recommendation for any of the harmonic mitigation measures described here. What's important is to make the right choices during the planning and project engineering phases in order to obtain a drive system with high availability, low harmonic emissions and low RFI.
In any case, before deciding on which of the mentioned measures will be used, you must carefully consider the following factors:

Consideration
THDu need
Internal/external standards
Mains voltage & tolerance
Max voltage unbalance
Grid pre-distortion
Generator run/back-up
Standby need
Displacement PF / Reactive control
Amount of loads to be corrected
Application/load dynamics
Enclosure protection
Cooling air segregation need
Max ambient temperature
Physical space available
Efficiency target
Initial cost vs running expenses
Acoustical noise
Power regeneration need

Various solutions for harmonic mitigation.

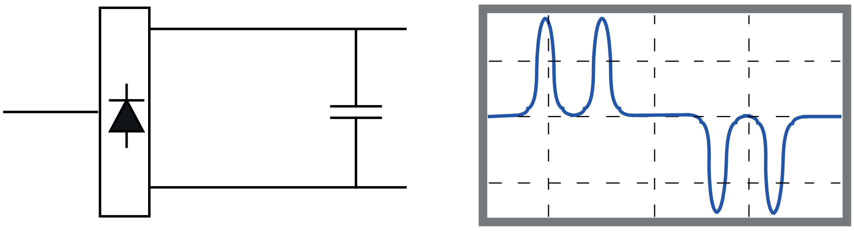


Mains or DC link chokes

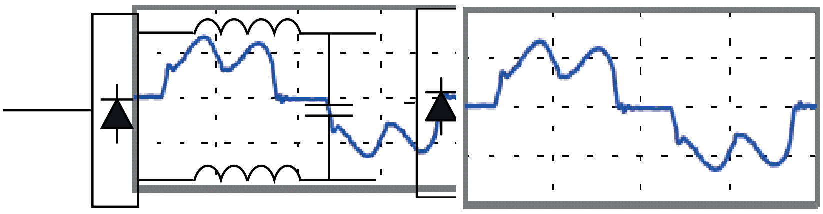
Certain frequency converter models are supplied without any chokes. Operating these devices without any harmonic mitigation measure causes severe distortion of the current waveform on the mains side due to the strong intermittent charging currents of the DC link capacitors. The desired RMS current for recharging the capacitors consists of short current pulses with high crest factors. The crest factor can even be higher than 10, resulting an extremely large total harmonic distortion level (THDi) of the current waveform with a total harmonic distortion level (THDi).

Chokes (inductors) reduce mains harmonic distortion from the rectifier, thereby improving the power factor λ (lambda). For example, the total harmonic distortion (THDi) of a frequency converter without a line reactor equals around 80%. This value can be reduced to less than 40% with internal or external chokes. Users can purchase line reactors separately and fit them externally. This expense is not necessary if the chokes are integrated in the device as standard. In addition, a DC link choke with the same effect is smaller and lighter, and therefore cheaper.

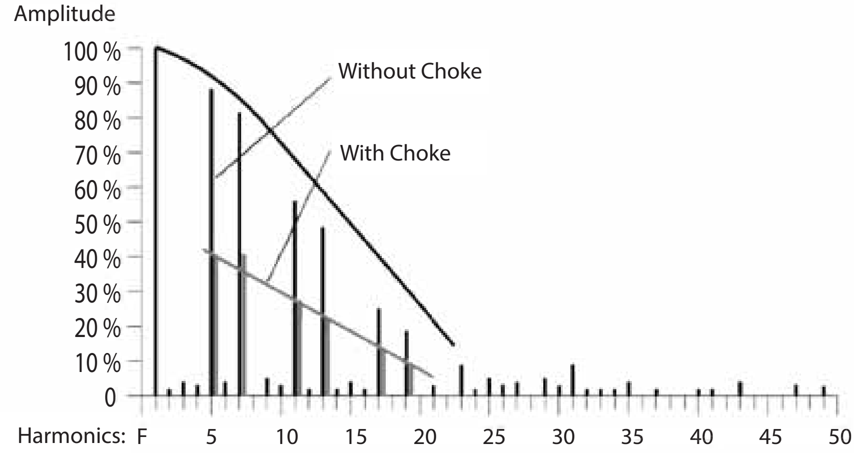
The level of background harmonics in the supply network that a frequency converter should be able to tolerate is specified in the EN 60146-1-1 standard (general requirements for semiconductor rectifiers). A choke in the converter input circuit can provide additional protection in situations with high background harmonic levels.



Converter without choke (THDi >100%).



Converter with DC link choke (THDi ~40%).



Mitigating harmonic emissions from frequency converters.

Slim DC link

Another way to reduce harmonic emissions from frequency converters is to use a slim DC link. Conventional converters have capacitors connected after the input rectifier to smooth the rectified voltage. This smooth DC voltage comes at the expense of harmonic emissions.
To mitigate harmonic emissions, some manufacturers reduce the capacitance of the DC link capacitors or eliminate them entirely. The advantages of such converters are that they allow less costly, the design of more compact devices and also result in reduced harmonics in the frequency range up to 2 kHz compared to conventional types without chokes. However, the harmonics in the range above stronger than with a comparable conventional architecture.

The frequency spectrum of converters with slim DC links is relatively difficult to estimate. Even though, manufacturers can specify the interference emissions of a specific model over the entire frequency range. Prior calculation of the distortion level in the mains network will be hardly possible, if if different devices with Slim DC links are used in a given application. The harmonics from the different devices may augment each other, or they may cancel each other. The larger the frequency spectrum of the harmonics, the higher the probability of exciting a resonant frequency of another component.

What resonances will be created in the mains network cannot be determined in advance. The broad frequency spectrum of harmonic emissions from these devices can also increase the risk of resonances with other components in the network, such as fluorescent lamps, transformers or capacitors in power factor correction systems.

Harmonic emissions become a problem for users when they cause interference or malfunctions in their systems. With increasing levels of mains distortion resulting from various nonlinear loads, the effort necessary to reduce mains distortion rises. It might rise even more when the generated frequency spectrum is very broad.

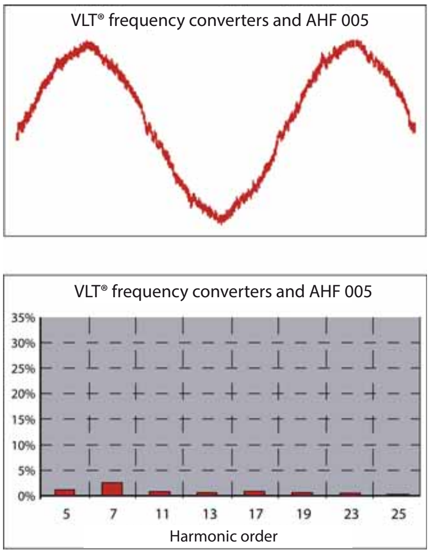
Along with mains distortion resulting from their input currents, converters with lean DC links burden the mains with the switching frequency of the motor-side inverter. This is clearly visible on the mains side, due to the low or non-existent capacitance of the DC link. This frequency is usually fixed and can therefore be attenuated easily with filters if necessary. However, users who adopt this measure should not use functions that vary the switching frequency, such as acoustic management of the motor or automatic derating.
Below table shows a comparison of drives with slim and conventional DC link. There are also variable speed drives with so called „reduced DC link", which are in their behaviour in between both technologies.

	Slim DC link	**Conventional DC link**
Mains harmonics below 2 kHz	Low content	Medium content
Mains harmonics above 2 kHz	Medium content	Low content
Capacitor size	Low	Medium
Capacitor price	Low	Medium
Inverter switching frequency	Clearly measurable on mains side	Hardly measurable on mains side
Cost of filters	High	Usually low
Combination of different products	Can cause problems	No problems
Motor heating	Generally warmer	Within range of normal tolerances
Motor smoothness	Instantaneous ripple causes mechanical stress	Standard load
Mains failure	Minimum buffering	Buffering up to 10 times longer
Load characteristics	Tendency to oscillation with load changes	Settles down quickly
Step load changes / load shedding	Sensitive	Robust
High-inertia loads	Difficult	Robust

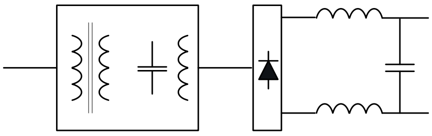
Passive filters – robust and efficient

Passive filters essentially consist of inductors and capacitors not being tuned to individual frequencies like an absorption circuit, but working like a bandstop filter, reducing all low harmonics up to the 50th significantly. They are connected between the mains and the frequency converter, and they reduce harmonic distortion on the mains much more effective than inductors alone.
Typically passive filters are added to frequency converters with (integrated) AC or DC coils to reduce the total harmonic current distortion further down to desired levels. As passive filters generally distort the voltage waveform at the frequency converter input, it is risky to use filters from another manufacturer with a frequency converter, due to the possibility of interference or damage to the frequency converter. Passive filters produces a nearly sinusoidal current waveform, resulting typically in THDi below 10% or 5%, depending on the passive filter design.
As a rule, this sort of filter can be also be used with several small frequency converters connected in parallel. This reduces costs. Filters may also be retrofitted ahead of the frequency converters. In many cases it is sufficient to simply fit filters on the large units in a plant.
However the capacitive reactive current of the filter under partial load conditions must be taken into account. This capacitive current can be as high as 30% of the nominal current.
Modern drive systems with dedicated passive filter technology allow, for applications where too high reactive current is not acceptable, to disconnect the capacitor bank at a defined part load level through a magnetic contactor.

In general the performance of passive filters is load dependent, which usually is no problem, as the total effect of the harmonics on voltage distortion is as well reduced with the less load current given.
Solutions with passive components represent in general a quite robust, highly efficient (η>98 %) and easy to handle technology. In addition they do not load the mains with additional switching frequencies as some of the active solutions sometimes do.



Passive filters reduce harmonic current distortion to under 5% or under 10%.



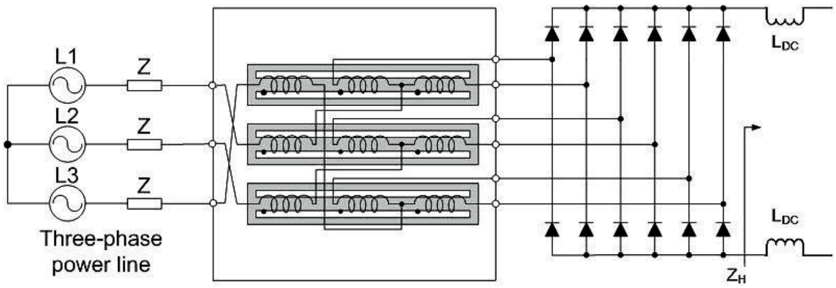
Passive harmonic filters at the frequency converter input.

Passive filters can also be connected in parallel for compensation at relatively high power.

Multipulse rectifiers
12 pulse or more

Harmonic cancellation or compensation, which reduces mains distortion, can occur not only between devices with different switching schemes, but also between different transformer vector groups.
For large drives, a Dy5d6 threewinding transformer is a proven way to cancel fifth and seventh harmonics. Here the primary winding in D configuration supplies the total power, while each of the secondary windings is designed for half of the total power. This arrangement results in 12-pulse rectification due the 30° phase shift between the d and y secondary windings. Their fifth harmonics have a phase shift of 150° (5 x 30°), resulting in cancellation due to the net 180° phase difference.

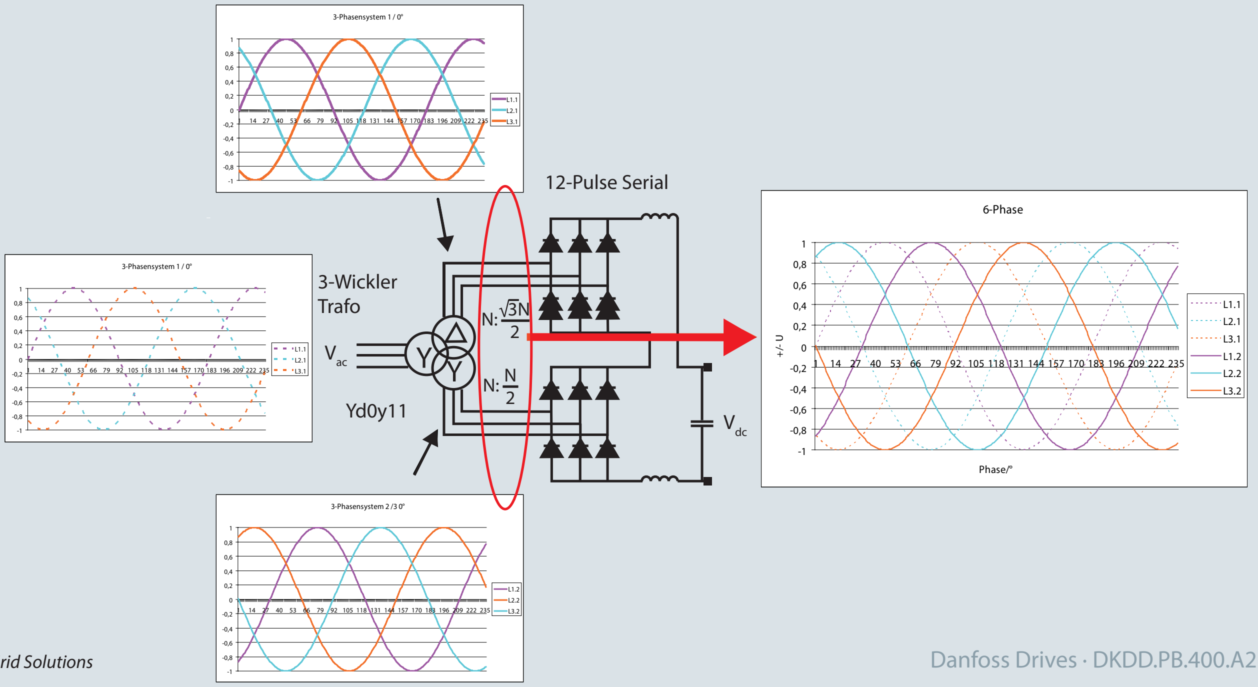
This circuit yields a harmonic content of approximately 10…15% on the mains side. Even lower THDi values can be achieved with higher order pulse rectifiers, such as approximately 5…8% THDi with an 18-pulse circuit. However, in this regard it must be borne in mind that using multi-winding transformers is a special approach that incurs additional costs for the transformer and extra wiring. As a result, this approach is only cost effective at high power levels.



12-pulse rectifier (THDi 14.1%).

12-Pulse rectifiers in parallel or series circuit
A 12-pulse rectifier can be configured as a parallel circuit or as a series circuit. The parallel circuit requires less transformer power capacity than a 12-pulse series circuit. As the secondary windings are floating, a series circuit is advantageous for tristate or three-level inverters with a high DC link voltage that is balanced relative to earth and generates more sinusoidal motor voltages.
It is also possible to connect several conventional (6-pulse) voltage converters to the secondary windings.

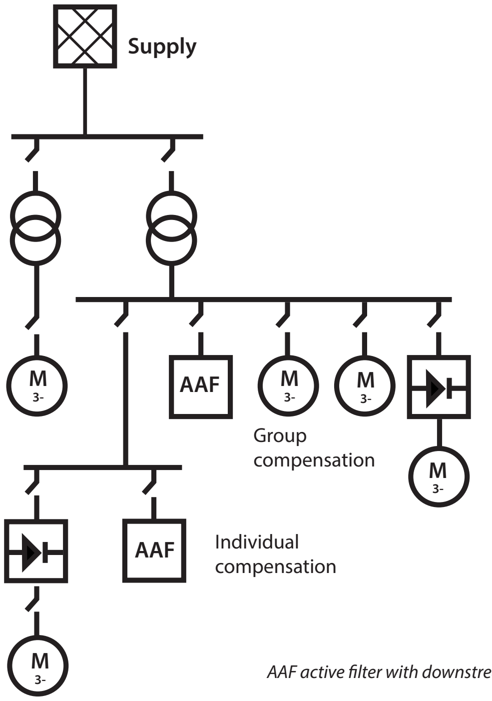
In this case the user must ensure that the converter loads are balanced, if the aim is to minimise harmonic emissions.



Active filters
– precision filtering and flexible installation

Active harmonic filters are a modern approach to mitigating harmonics. Compared to conventional passive filter technology, they are smaller and lighter, especially in the higher power range.
With an extremely short response time in the range of microseconds, active filters eliminate interference before it can cause damage.
Active filters are basically modified frequency converters that are able to feed power back into the mains, They sense harmonic currents present in the network and feed antiphase currents back into the network. Typically harmonics up to the 50th order can be reduced either in their total average or by selection and tuning of individual orders. In addition active filters can control the cos phi. These devices usually operate with a switching frequency in the range of 4 to 16 kHz. They are available for the low-voltage level with compensation currents of 30 A to 500 A, and they are extensible.

The operating principle of an active filter is based on purposefully injecting current as necessary instead of absorbing current. The distortion reactive power is compensated by the addition of antiphase harmonic currents. The currents needed to offset the harmonic currents are calculated by constantly monitoring the power quality. An active current source is used to feed in current so that the net result is a sinusoidal current waveform. The injected current has exactly the same order of harmonics, with the same amplitudes, but the injected current is 180° out of phase with the load current. The sum of the current from the load and the injected filter current cancels the harmonics. As a result, the mains only has to carry the fundamental frequency.



AAF active filter with downstream loads.

Flexible installation
Active filters can supply more or less compensation current, depending on the load. This makes them very flexible with regard to changes in harmonic levels, load currents and network structures. The filter is connected in parallel with the network to be attenuated, rather than in series. This gives users more freedom in choosing the installation location, and it is not essential to place the filter right next to the device that generates the harmonics. The filter can be physically installed where sufficient space is available. The filter can be operated continuously at its maximum rated load. Several active filters can be connected in parallel to increase compensation capacity. Resonance effects with the network impedance are practically excluded.

This type of filter has of course a more complex structure then a passive one. It requires fast, highresolution data acquisition for the measured values and high computing power in the control section, as well as power electronics with high switching speeds. An active filter essentially consists of an inverter that feeds power into the mains network stabilized by a DC link. A capacitor is used for energy storage. The connection to the mains is done via a so called LCL filter. This prevents the transfer of noticeable interference at the switching frequency to the mains network.
The better the LCL filter, the better the suppression of mains interference arising from the switching frequency of the filter.

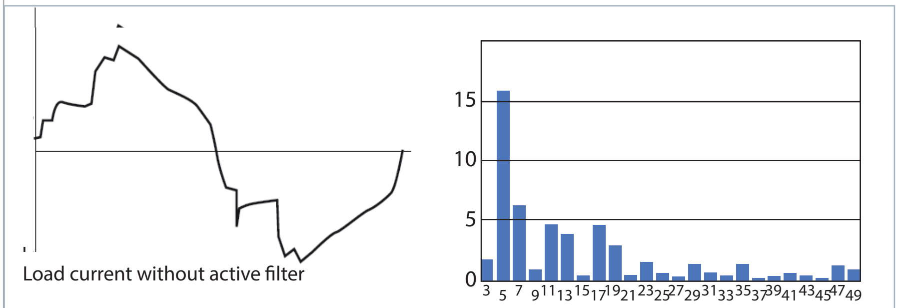
Selecting active filters
When selecting an active filter, you need to know at least the total harmonic distortion current required to be compensated. Preferably it is also known which frequency spectrum is present to assure that the filter has enough reserves in each order harmonic. The spectrum can be found out by means of a mains analysis service. Complete mitigation of the interference source is only possible if the full harmonic spectrum is sufficiently attenuated, in particular the higher order harmonics.
The figure shows that even with compensation up to the 13th harmonic, a considerable amount of distortion is still present. The wider the compensation spectrum, the closer the resulting waveform approaches the ideal sinusoidal waveform.

The filter can also be operated continuously at its maximum power rating. However, harmonic compensation is reduced at maximum rated power. To increase compensation capacity, several active filters with different power ratings can be connected in parallel at the same network connection point.

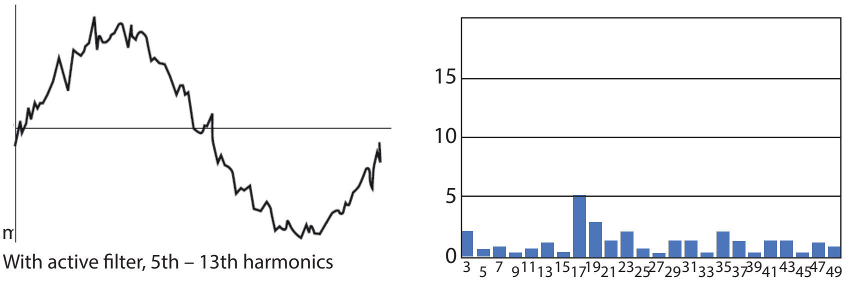
Active filters can be integrated into control systems using built-in interfaces. This makes it possible to externally activate the filter when compensation is necessary. However, it is also possible to simply exchange signals between the plant control centre and the filter. Fault indications or operating status indications can then be processed in the control centre.

Active filters are power electronics devices and can generate highfrequency emissions. The switching frequency superimposes highfrequency noise on the mains network, which must be attenuated by a passive LCL filter.
However a certain amount of residual noise will always be detectable on the mains side.

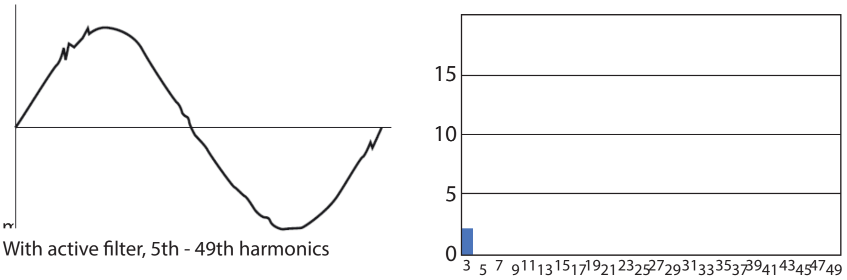
Caution is adviseable whe several active filters are connected in parallel, especially if those are from different manufacturers, as they could build parallel resonant circuitries.
Plants in which chokeless phase correction systems are installed should not be operated together with active filters, since as well severe resonancephenomena are possible.
Using a filter increases the virtual network short-circuit power. The mains voltage waveform becomes more sinusoidal.
The network becomes harder and more stable, which allows the current consumption of the loads to be increased. With central compensation, the harmonic currents at the service point (point of common coupling; PCC) are reduced, but inside the plant the harmonic distortion may rise.



Load current without active filter



With active filter, 5th – 13th harmonics



With active filter, 5th - 49th harmonics

Active Front End and active infeed converters

Variable speed drives with active front end (AFE) or active infeed converter (AIC) consist of an inverter bridge, connected via an LCL filter to the supply. The IGBTs in the inverter bridge are controlled, so that a sinusoidal current can be drawn from or supplied to the mains. So AFE/AICs can potentially also regenerate power back into the supply. Even though this feature is quite useful in vertical movement or applications which require frequent braking, some manufacturer lock this function in their AFE-based low harmonic drives.

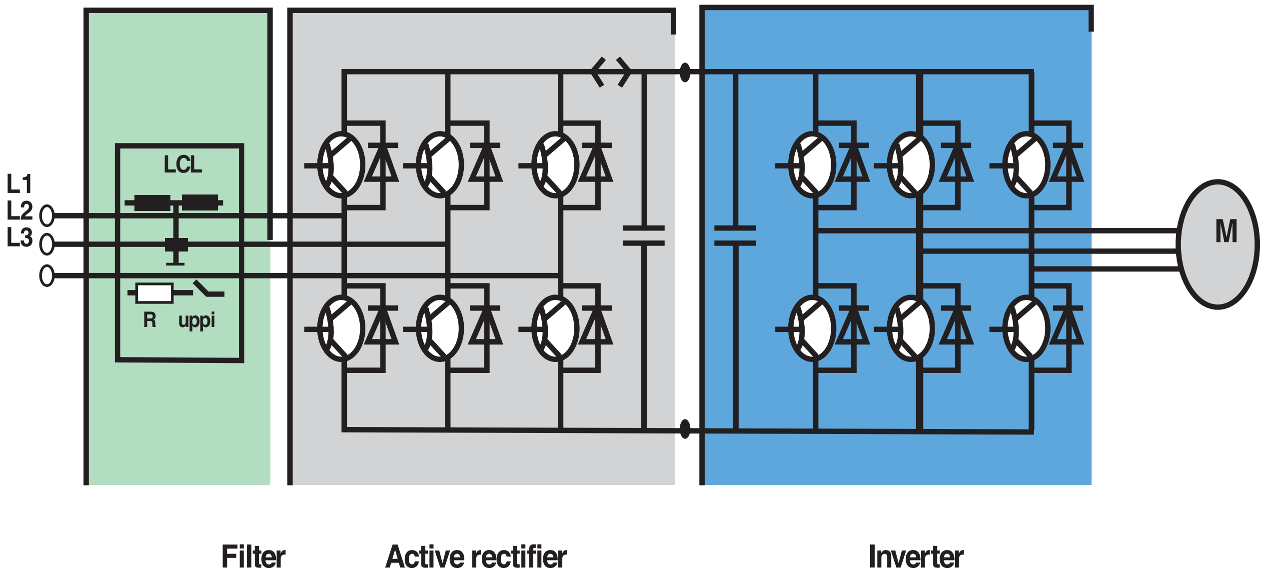
Similar to active filter technology, the power factor of the input current can also be changed, so an AFE can also be used to compensate phase shifts caused by other loads on the supply- within its current rating. Compared to an active filter an AFE always requires to be sized for the full load current which results in a usually worse energy efficiency.

Benefits of drives with AFE/AIC technology

The harmonic current content drops to a THDi value of less than 5% in the range of the 3rd to 50th harmonics. Four quadrant operation is possible, if the drives manufacturer has opened up for this feature.

AFE Drives are capable of raising ("boosting") the DC link voltage, which can be very useful for applications with low mains voltage in combination with long motorcables and motor filter requiring to achieve the rated voltage at the motor terminals. Operating the motor beyond it´s rated voltage can result in increased motor current, additional motor heat-up and reduced motor efficiency.

Conventional AFE devices essentially consist of two frequency converters, with one feeding power to the motor and the other to the mains.
Due to the additional transistors and LCL magnetics on the input side, the efficiency of the whole device is lower in motor driven mode.
As the DC link voltage of AFE drive can be boosted, there should be taken care that the motor winding insulation is suitable, especially if the motor is directly connected without any output filter. Good, relatively complex devices filter out
this switching frequency before feeding power back to the mains.



Active front end

Special aspects: transformer capacity utilisation and backup generator

Maximum transformer capacity utilisation

Plant operators can use speedcontrolled drives rated up to several MWs on low-voltage mains (400 V, 500 V and 690 V).

A transformer converts the voltage from the medium-voltage grid to the necessary voltage.

On the public power grid (first environment: residential area), the electricity company deals with this.

On industrial grids (second environment: industrial area; usually 500 V or 690 V), the transformers belongs to the end users, who are then directly responsible for feeding power to their plants.

Transformer load

In the case of transformers that supply power to frequency converters, it must be borne in mind that frequency converters and other rectifier loads generate harmonics that increase the reactive power load on the transformer. This leads to higher power dissipation and additional heating. In the worst case this can lead to transformer failure. Intelligent vector groups (circuits with several transformers) may however cancel harmonics under some conditions.

Power quality

A question that arises in connection with ensuring power quality in accordance with applicable standards is: how many frequency converters can the transformer handle?

Power network calculation programs, such as the HCS software *www.danfoss-hcs.com*, provide awareness on about how many frequency converter loads a transformer can supply in a given plant.

Operation from a backup generator

Plant operators use backup power systems when they must be able to operate connected devices even in the event of mains voltage dropout.

They are also used when the available mains connection cannot supply enough power. Operation in parallel with the public power grid is also possible in order to obtain more mains power. This is common practice when there is also demand for the heat generated by combined heat and power plants. This allows users to benefit from the high efficiencies that can be achieved with this energy conversion technology.

When backup power is supplied by generators, the mains impedance is usually higher than for operation from the public power grid. This leads to higher harmonic content. With proper design, generators can operate in a network with harmonic generators.

In practice, this means:

- Higher harmonic distortion can usually be expected when switching from mains operation to generator feed.
- Planners and plant operators should calculate or measure the increase in harmonic distortion in order to ensure that the voltage conforms to specifications and thereby avoid malfunctions and failures.
- Imbalanced loading of the generator must be avoided, since it results in higher power dissipation and may lead to higher harmonic content.
- A generator winding with a 5/6 pitch factor attenuates the fifth and seventh harmonics, but increases the third harmonic.
  A 2/3 pitch factor attenuates the third harmonic.
- Operators should disconnect power factor correction systems if possible, to avoid potential resonances in the mains network.
- Harmonics can be attenuated by chokes or absorption filters. Resistive loads operating in parallel also have an attenuating effect, while capacitors operating in parallel cause additional distortion due to unpredictable resonance effects.

If these factors are taken into account, a mains network fed by a generator can handle a certain number of frequency converters while still complying with power quality standards. Still a precise calculation of the situation during generator operation, i.e. with the HCS software, is advisable.

www.danfoss.de/hcs.com

B2 and B6 rectifiers ➞ max. 20% generator loading
Choked B6 rectifier ➞ max. 20–35% generator loading depending on characteristics
Controlled B6 bridge ➞ max. 10% generator loading

The maximum load figures above are recommended guideline values for trouble-free plant operation based on experience

HCS software for harmonic calculations

Current situation
The power supply network must be monitored for increasing harmonic distortion. This results from the increasing use of modern electrical and electronic devices, more and more of which have rectifier input circuits that typically generate harmonic currents. As a result of these high-frequency harmonics on the mains, distortions values close to the allowable limits are presently being reached. In critical cases, this results in noticeable effects on connected electricity consumers, which can lead to malfunctions and failures.

Simulating mains distortion with and without filters
Plant designers and engineers, planning firms, power distributors and electricians are responsible for observing specific limits on mains harmonic distortion. This duty includes knowledge of the relevant standards (EN 50160, the EN 61000 series, etc.) and the responsibility to ensure compliance to them.
In order to achieve this properly, it is essential to analyse the generation of harmonic currents by the individual device types and to determine the distortion of the supply voltage based on this information. This requires sound technical knowledge, since the amplitudes and phase angles of the harmonic currents depend on the mains voltage waveform.

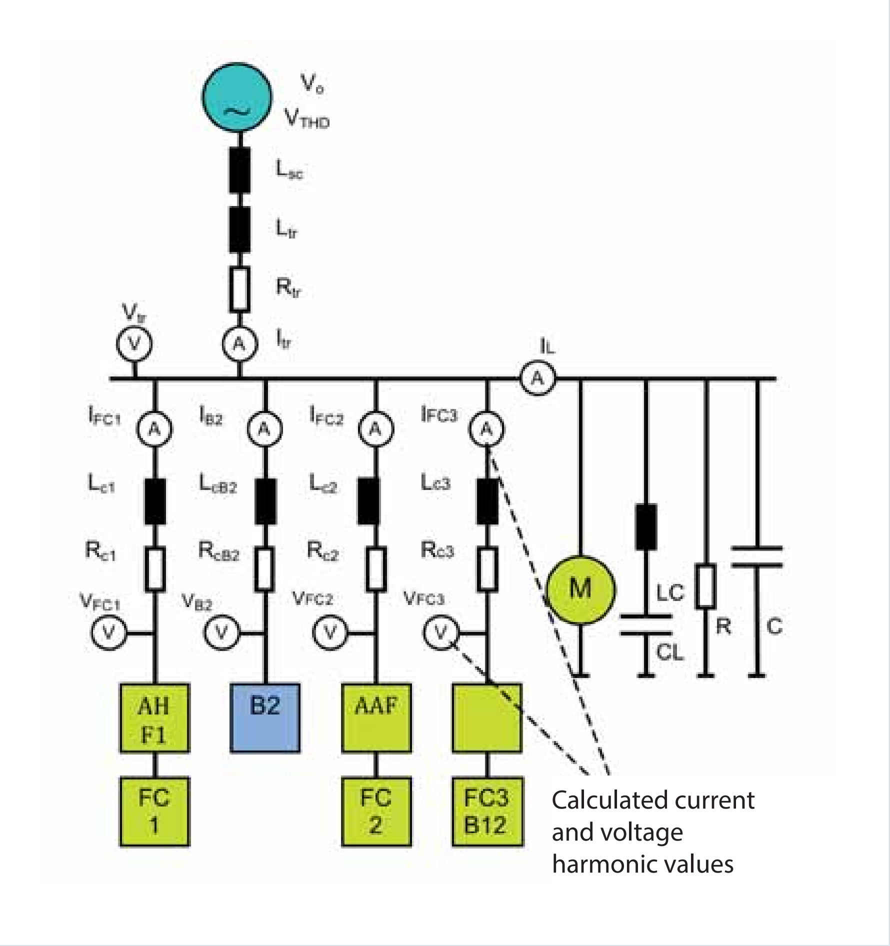
To avoid excessive impairment of mains power quality, a variety of mitigation, prevention or compensation methods can be used for plants and devices that generate harmonic currents. Calculating this is a practical task that can be done quickly and easily. With the HCS network simulation software, you can consider specific countermeasures as early as the planning stage and thereby ensure the availability of your plant. Harmonic emissions from electronic devices can be calculated, taking into account the plant configuration and standard limits up to 2.5 kHz. Plant operation using generator supply can also be simulated reliably. Switching the mains to generator operation is possible and the software takes the backup power supply situation into consideration. Current standards (EN 50160, EN 61000 and IEEE519) are included in this evaluation.

Online calculation on the Web

At *www.danfoss-hcs.com* you can obtain the latest version of the HCS calculation software quickly and easily. The Windows-compatible user interface makes this highperformance software intuitive to use. Simply enter electronic power devices (such as frequency converters), mains supply components (transformers and backup generators), cable and overhead connections, other loads, motors or power factor correction systems in a calculation worksheet.

Various calculation levels

When the calculation starts, the internal software calculation program imports data via the Internet link, processes the calculations, and displays the results in tables, bar charts and diagrams. The program compares the calculated results with your selected standard limits. If the harmonic levels are too high, you can perform the calculation again after changing some of the data and then compare the results.
Unlike previous programs that utilise tabular data for harmonic currents that is only valid under laboratory conditions, HCS can take the phase angles of the harmonics and commutation processes into account for the entire system. For example, the HCS software shows voltage and current curves for major network nodes.
HCS can be used worldwide; instructions and help are also available in English, as well as for 60 Hz mains frequency. For easy use, it is available at various levels, from Basic for simple situations to Expert for complex mains loads.



Calculated current and voltage harmonic values

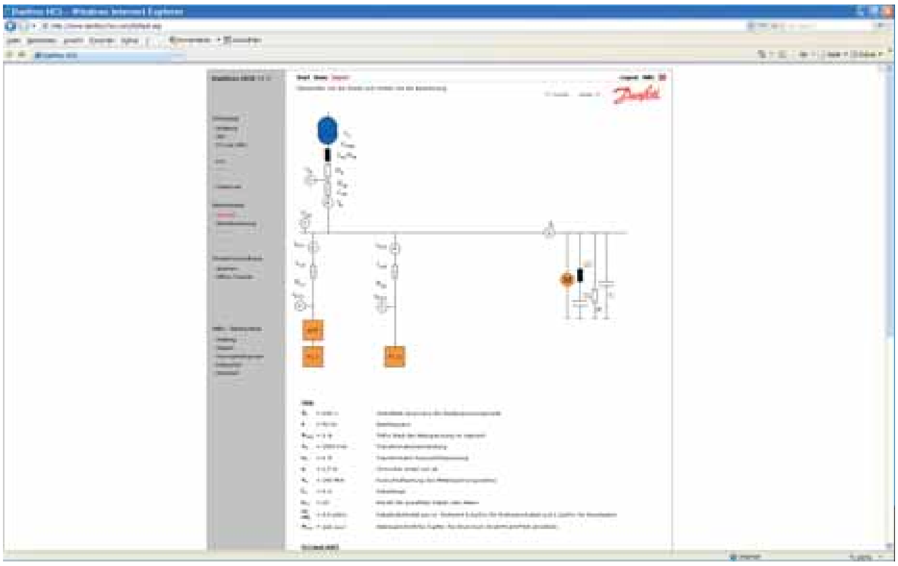
Basic level

At this level you only need to enter the voltage, frequency, nominal power and impedance of the mains transformer or the generator. VLT and Vacon frequency converters frequency converters can be selected from a list by type, quantity and load level. Alternatively, you can also enter motor shaft power, load factor, mains commutation inductance and/or DC link smoothing choke inductance to enable a free choice of devices.

Expert level

At the Expert level HCS can provide even more exact calculations, but it requires more input data.
For instance, it can determine the voltage drop in wiring from the values entered for cable lengths and wire sizes. The short-circuit power or harmonic distortion level of the medium-voltage grid can be specified, and other linear network loads can be taken into account.
Using this information, HCS correctly simulates the attenuation by resistive

and motor loads and the resonance effects due to phase correction capacitors with and without chokes. Harmonic cancellation with respect to single-phase converters and singlephase electronic office equipment is also taken into account. The software can additionally perform simulations for harmonic mitigation measures. This can be done by using line reactors, incorporating an advanced harmonic filter (AHF) or advanced active filter (AAF) in the mains supply line, or using low harmonic drive (LHD) converters. Another option is to use converters with 12-pulse rectifiers.



After entering the values, you can check all the values in the overview before performing the calculation.

Convenient documentation

All entered data can be grouped by project, saved and recalled. At the push of a button, the software documents all calculated projects in a detailed and easily understandable manner. The results are presented in tables and bar charts for various, predefined measurement points in the system. Values exceeding limits are clearly marked with warnings. Along with the harmonic currents, the harmonic voltages and if necessary the current and voltage waveforms are shown. To complete the documentation, an overall record is provided which includes the circuit diagram, subject to specification of the desired EN standards.

Achieving energy efficiency by mitigating harmonic emissions

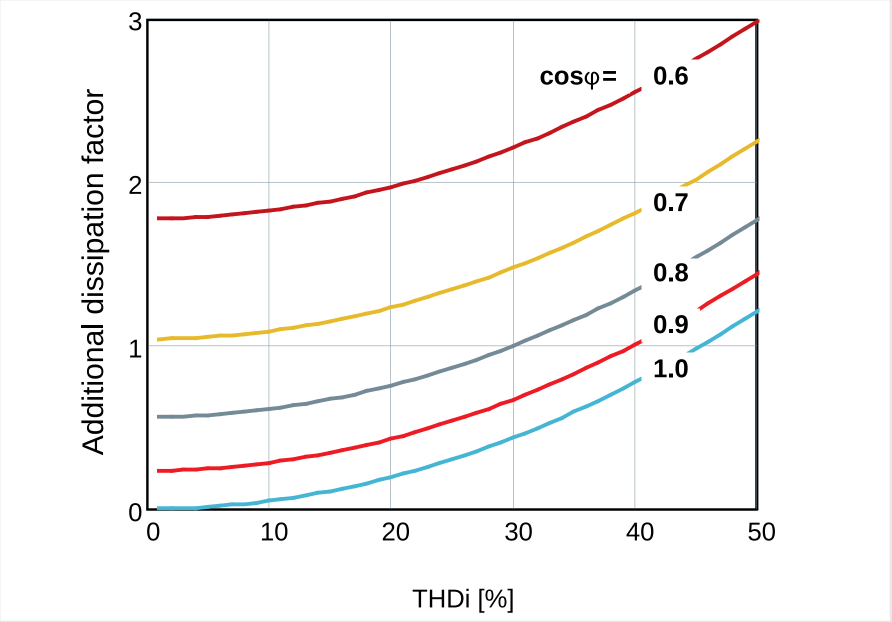
In the past, drive products usually boasted higher power ratings or higher accuracy as unique selling features. However, today's users are focussing on yet another key performance feature: the energy efficiency of the overall drive system. Due to tenacious competition in highly competitive markets, plant operators and end users are keen to minimise total life cycle costs – the total ownership cost (TOC) – in order to improve the cost-effectiveness of the plant. For this reason, mechanical engineers and plant engineers as well as manufacturers of drive products are compelled to change their attitudes and offer system efficient solutions.

Particularly in drive systems, energy costs for the drives form the largest part of the overall TOC, making them the main factor over the service life. Over 95% of the operating costs of drives can be attributed to energy consumption. Accordingly, automation and drive specialists must strive to tailor their solutions for energy efficiency. Energy-efficient drive systems not only increase the cost effectiveness of the plant, but also reduce CO2 emissions thanks to lower energy consumption.

Reducing additional losses
Mitigating mains harmonics and reactive power in a mains network causes a significant decline in additional network losses, and therefore a reduction in energy costs. Higher-frequency current components cause increased heating and higher power dissipation in wiring and devices.

Mitigating mains harmonics and reactive currents reduces reactive power and increases the share of active power in the apparent power. In other words, the devices need less mains current for the same drive power. The net result of harmonic mitigation measures is a significant reduction in additional losses in the power network.
Additional losses due to reactive currents (cos φ) and harmonic currents, defined by the total harmonic distortion THDi can be assessed using the diagram in the adjacent figure.

Diagram for assessing additional loses in the power network due to reactive and harmonic currents. From the figure it can be seen that a load with a THDi of 30% and a cos φ of 0.8 nearly doubles the losses in the network.

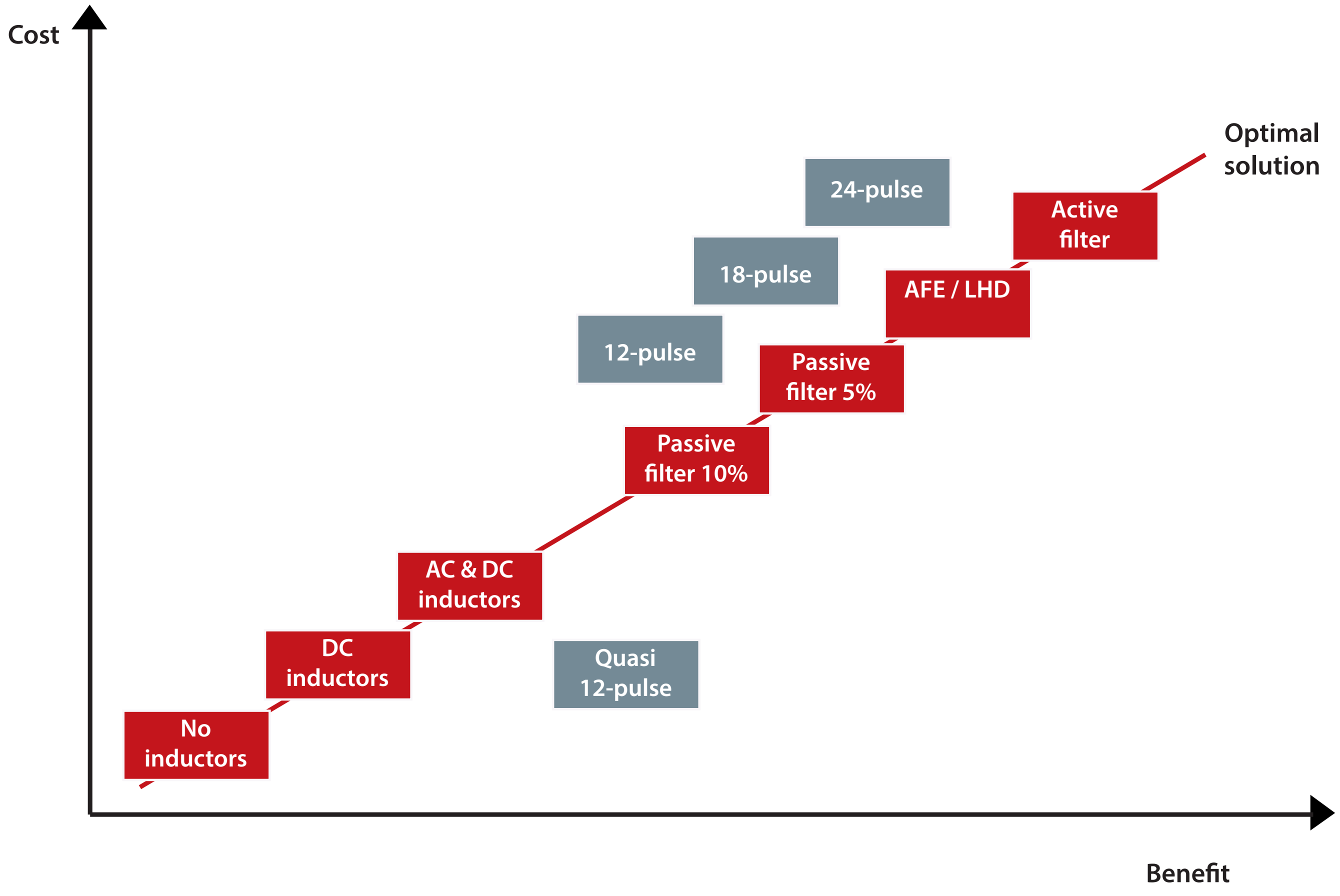


Summary:
There is no single best solution

Each of the previously described options is suitable for specific application areas and provides effective protection against excessive harmonic distortion in the supply network under suitable conditions. The methods are equally proven and robust, but most of them have the disadvantage that retrofitting is relatively costly.

Modern technologies such as active filters, active front-end rectifiers and low harmonic drives apparently fulfil the demand for simple, lowcost solutions. However, a shift to the higher frequency range up to 20 kHz can be seen with these technologies. No standardised values have been specified as yet in this range, but detrimental effects will occur with increasing intensity if these technologies are not examined critically with regard to their effects on the mains. Suitable filters or protective measures must be considered in all cases. This device technology will become increasingly common in future, and it must be taken into account in project engineering.

Overview of measures for harmonic mitigation.



From theory to practice

In practice, it is clearly evident that the increasing use of rectifier loads aggravates the occurrence of harmonic emissions. Rectifiers draw non-sinusoidal currents from the mains. Harmonic emissions from frequency converters arise primarily from the DC link capacitors due to their charging currents. The current only flows in short pulses near the crest of the mains voltage. These current spikes cause notching of the mains voltage and significantly distort its sinusoidal waveform.
To keep the supply network clean, it is now standard practice to limit the fifth harmonic of the current to a value of approximately 40% THD. The requirements are described in the EN 61000-3-12 standard.
All frequency converters are regarded as wideband interference sources, which means that they emit interference over a wide frequency range. Plant operators can reduce radiated interference from frequency converters by taking suitable measures. For example, they can ensure trouble-free operation in the plant by using RFI filters and line reactors. These components are built into Danfoss frequency converters as standard. The integrated chokes reduce the harmonic currents of VLT® VLT(R) and Vacon(R) devices to less than 40% THDi.

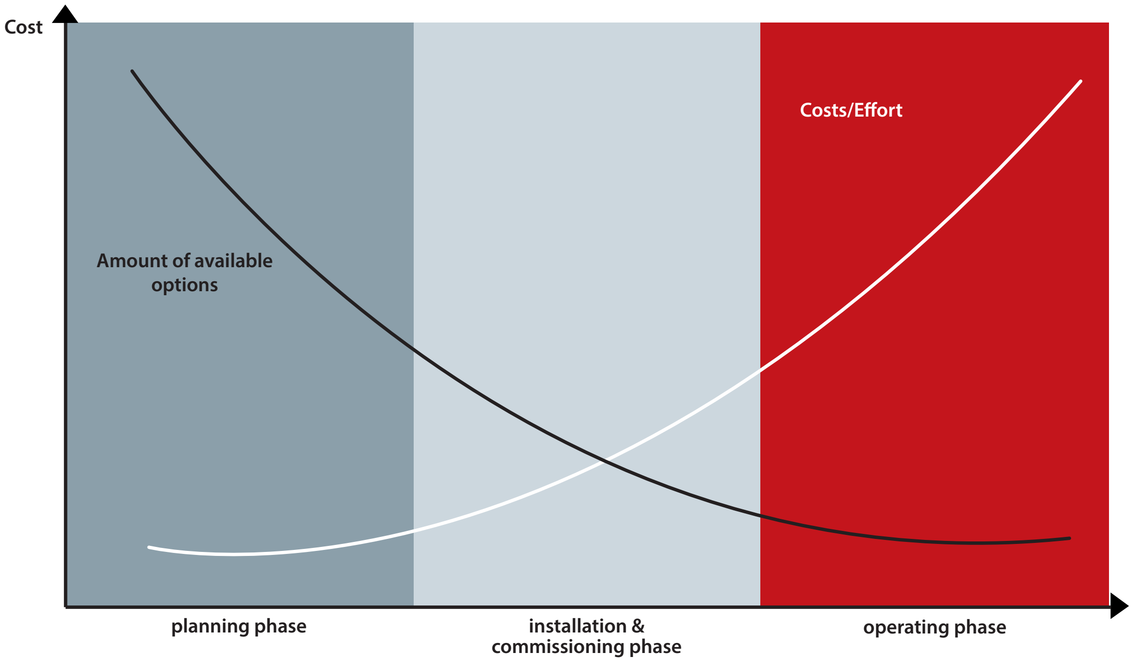
In application cases where the plant operator must mitigate harmonic emissions to less than 10% or 5% THDi, optional filters and active measures may be used to achieve virtually complete attenuation of harmonic emissions.

Mitigation measures
Various options for limiting harmonic emissions are available to plant operators, and to planners and plant engineers in the preliminary phases. They can be divided into passive and active measures, and they differ with regard to project engineering in particular, among other things.
What's important is to make the right choices during the planning and project engineering phases in order to properly configure a drive system with high availability, low harmonic emissions and low RFI. Generally speaking, the longer the user waits before addressing this issue and taking suitable measures, the more costly is the solution.

It is not possible to make any basic recommendation for any of the harmonic mitigation measures described here. In any case, before deciding on which of the described mitigation measures will be used, the user – who is ultimately responsible for compliance with the limits – should carefully consider the following aspects:

- Perform a network analysis
- Generate precise overview of thenetwork topology
- Check the space situation in theavailable electrical equipment rooms
- Determine the extension possibilities for main distribution and subdistribution panels

Effort and costs for harmonic mitigation measures



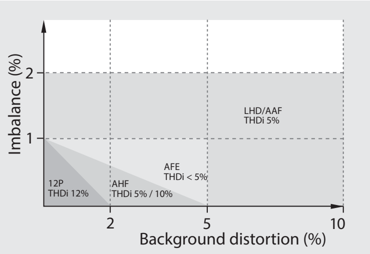
The way to cost-effective mitigation

Mains conditions

Grid conditions

Before considering mitigation equipment, the system impedance has to be known.

No grid is ideal because pre-distortion and imbalance
is always present and so needs to be considered when choosing equipment.



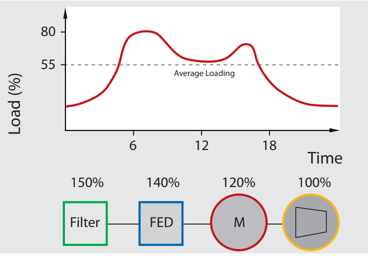
Imbalance and pre-distortion

The harmonic mitigation performance of the different solutions depends on the grid quality. The higher the imbalance and pre-distortion, the more harmonic the equipment has to suppress.
The graph shows at what pre-distortion and imbalance level each technology can keep its guaranteed THiD performance.

Application

Application

A common pitfall is over-sizing of components between load and grid. The consequence is a poor harmonic performance, low system efficiency and a higher initial cost.



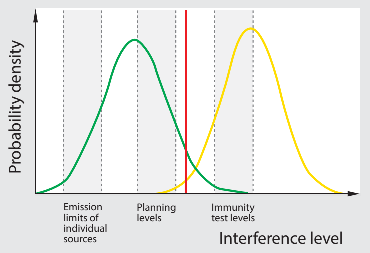
Over-sizing

Published filter data are all given at 100% loading but filters are seldom run at full load due to over-sizing and load profile.
Serial mitigation equipment must always be sized for the maximum current, but be aware of the duration of part load operation and evaluate the different filter types accordingly. Over-sizing gives poor mitigation performance and high running costs. It is also a waste of money.

Compliance with standards

Compliance with standards

A total voltage distortion of THvD = 5% is good engineering practice and will, in most cases, make the installation comply with local standards and recommendations.
It ensures that unintended tripping or component breakdown is not caused by harmonic pollution.



Standards compliance

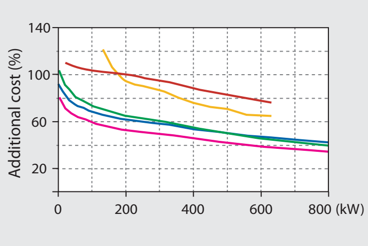
Keeping equipment immunity higher than system distortion ensures trouble free operation. Most standards set restrictions on total voltage distortion according to a planned level, often between 5% and 8%.
Equipment immunity is, in most cases, far higher: for drives, between 15-20%. However, this influences product life adversely.

Costs

Cost

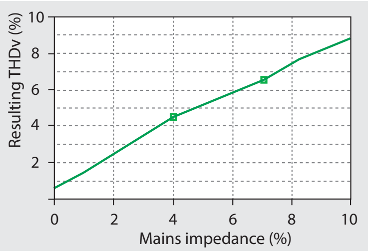
The initial cost of different mitigation equipment depends on power size.

The system efficiency determines the running expenses, but service costs also need consideration.



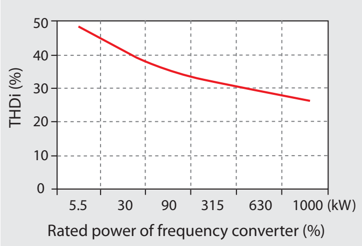
Power size vs. initial costs

Compared to the frequency converter, the different solutions have different add-on prices depending on power size.
The passive solutions in general offer the lowest initial cost and as the complexity of the solutions increase, so does the price.



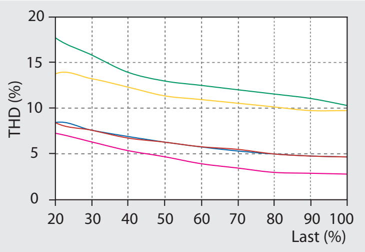
System impedance

As an example, a 400 kW FC 102 drive on a 1000 kVA transformer with 5% impedance results in ~5% THvD (total harmonic voltage distortion) at ideal grid conditions, whereas the same drive on a 1000 kVA, 8% imp. transformer leads to 50% higher THvD, namely 7.5%.



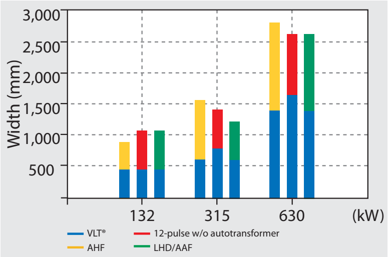
Total Harmonic distortion

Each drive generates its own total harmonic current distortion (THiD) which depends on the grid conditions. The bigger the drive is in relation to the transformer the smaller the THiD.



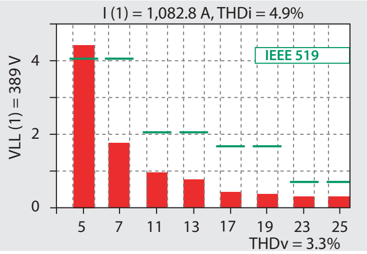
Harmonic performance

Each harmonic mitigation technology has its own THiD characteristic which is load dependent.
These characteristics are set at ideal grid conditions without pre-distortion and with balanced phases.
Variations hereof will result in higher THiD values.



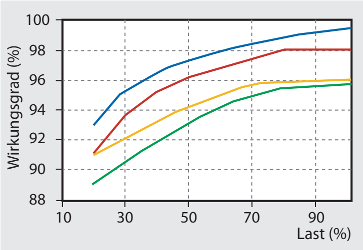
Wall space

In many applications the amount of available wall space is limited and must be utilized to the greatest extent possible.
Based on different technologies, the various harmonic solutions each have their optimum size and power relationship.



Fulfilling the standards

To determine whether or not the harmonic pollution of a given application/grid exceeds a specific standard, many complex calculations must be done. With the help from free Danfoss MCT 31 harmonic calculation software, this is made easy and less time consuming.



System efficiency

The running cost is mainly determined by the overall system efficiency. This depends on the individual products, true power-factors and efficiencies. Active solutions tend to keep the true powerfactor independent of load and grid variations. On the other hand, active solutions are less efficient than passive solutions.

VLT® Advanced Harmonic Filters AHF 005 / 010

Reliable harmonic mitigation
VLT® frequency converters fulfil the requirements of EN 61000-3-12 without additional filters. To minimise mains power distortion, Danfoss offers the advanced harmonic filters AHF 005 and AHF 010. They are specifically adapted to VLT® and Vacon frequency converters and use a patented method to achieve very high attenuation of harmonics.
Using an AHF filter reduces harmonic currents fed back into the mains network to less than 10% or 5% THDi (Total Harmonic Current Distortion), respectively. This represents a lowcost alternative to complex 12-pulse or 18-pulse input rectifier circuits.

For precise calculation of your mains harmonic distortion, Danfoss offers the Harmonic Calculation Software HCS online at *www.danfoss.de/software*.

Take advantage of the proven benefits of AHF filters:

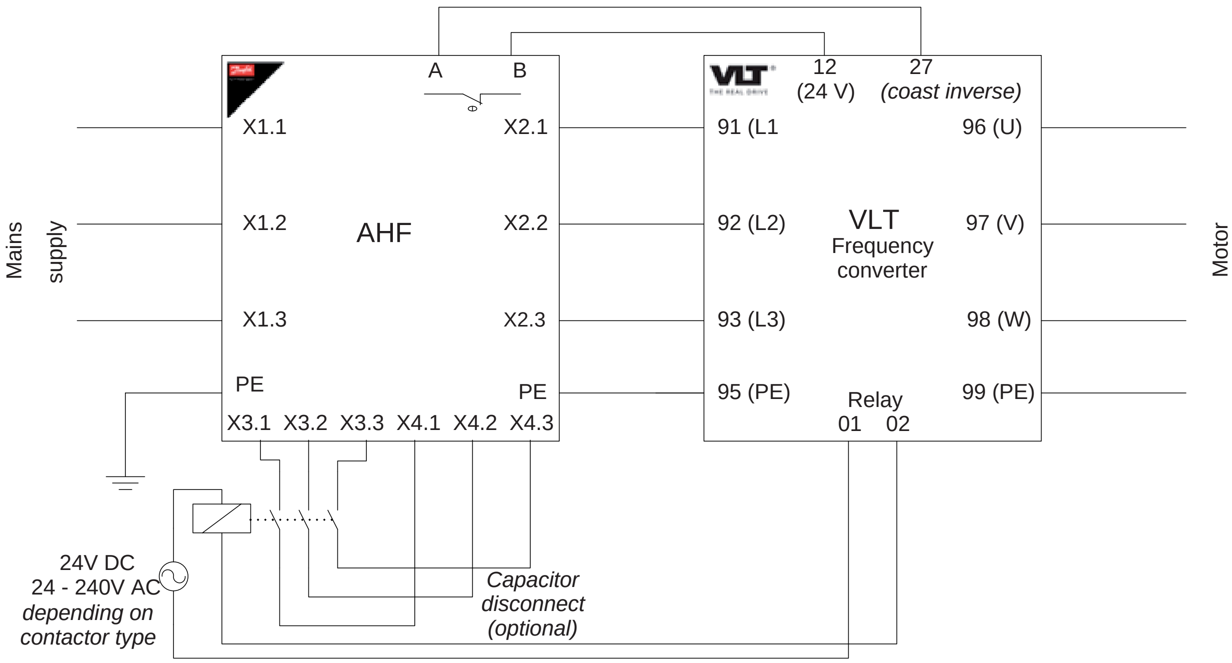
- Robust enclosure
- Easy installation and retrofit
- Fast commissioning
- A single filter module can be used for several VLT® frequency converters
- Thermal protection (switch contact)
- AHF capacitor disconnect terminals as standard
- An IP21/NEMA 1 upgrade kit with built-in capacitor disconnect contactor is available as an option

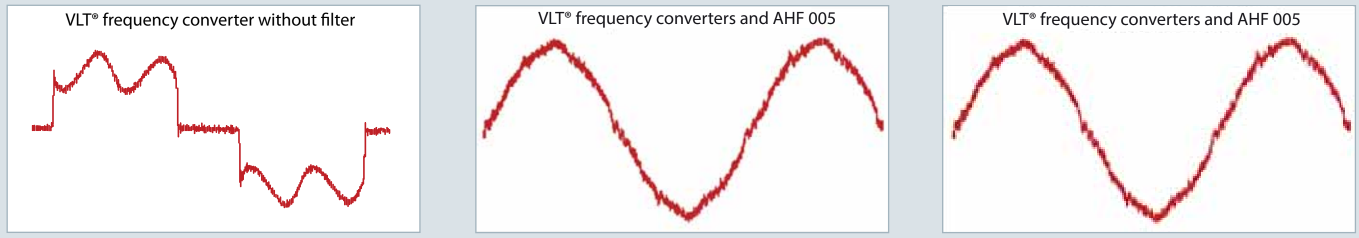
Specifications

	AHF 010	AHF 005
THiD* at: – 40% load – 70% load – 100% load	 ~ 12% ~ 11% < 10%	 ~ 7% ~ 6% < 5%
Efficiency* at 100% load	>98.5%	
True power factor* at: – 40% load – 70% load – 100% load	 ~ 81% ~ 96% > 99%	 ~ 80% ~ 95% > 98%
Ambient temperature	45° C without derating	
Cooling	For enclosures rated IP 20, forced air cooling is built in. For enclosures rated IP 00, implement separate cooling measures as part of the installation.	

** Measured at balanced grid without pre-distortion*

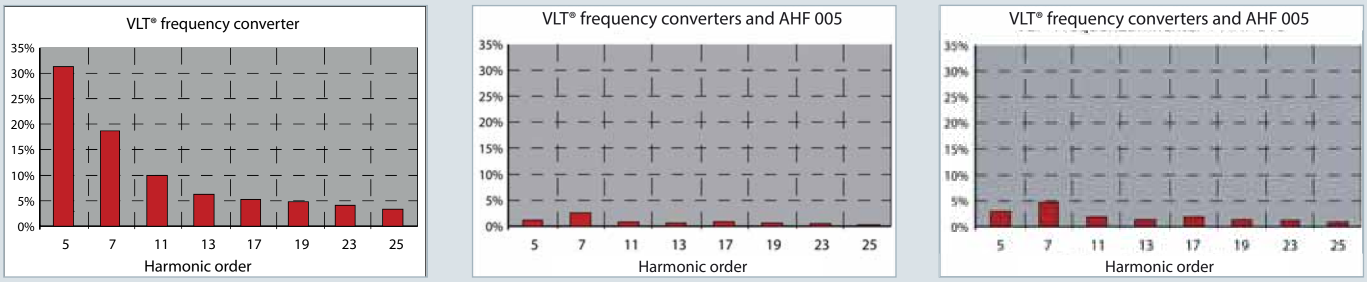
Connection Diagram




B6 rectifier drive with DC coil

B6 rectifier drive + DC coil + AHF 005

B6 rectifier drive + DC coil + AHF 010


B6 rectifier drive with DC coil

B6 rectifier drive + DC coil + AHF 005

B6 rectifier drive + DC coil + AHF 010

Passive filters reduce harmonic current distortion to under 5% or 10%

VLT® Advanced Active Filter AAF 006

Mitigate harmonics, improve power quality and enhance system availability
For more flexibility in harmonic mitigation, Danfoss offers the VLT® Advanced Active Filter AAF 006. Based on state-of-the-art semiconductor devices together with modern microprocessor technology, Danfoss has developed a new active electronic filter system. It reduces total harmonic distortion (THD) to 5%, resulting in the restoration of a good sinusoidal current waveform.

This gives users a viable alternative to complex 12-pulse or 18-pulse input rectifier circuits. Compensation for power factor (cos φ) is also included.

Stand-alone or in combination with VLT® frequency converters
The modular architecture of the VLT® Advanced Active Filter AAF 006 is similar to that of a high-power frequency converter. It offers high energy efficiency, user-friendly interfaces, rear panel cooling and high enclosure protection ratings.

This high-performance filter solution can mitigate harmonic distortion from VLT® frequency converters or act as a stand-alone solution to mitigate harmonic distortion from other interference sources. Another advantage is that it can be connected at any desired point in the concerned network.

Voltage range
- 380 – 480 V ~, 50 – 60 Hz

Power range
- 190 A, 250 A, 310 A, 400 A
- Parallel connection of up to four units possible

Specification of achievable THDi*
- 50% load <10%
- 100% load < 5%

Achievable power factor λ*
- 50% load > 0.95
- 100% load > 0.98

Ambient temperature 45°C

** Specifications apply to networks without background distortion*

Enclosure protection rating
- IP21, IP54

Suitable for:
- Increasing plant availability
- Improving power quality in soft mains networks
- Better utilisation of mains capacity
- Effective utilisation of generator capacity
- Securing sensitive environments

400 VAC (380 - 480 VAC)					
Total Current [A]	Max. Reactive [A]	Max. Harmonic [A	Frame	Dimensions H x W x D mm [inches]	Weight Kg [Lbs]
190	190	170	D14	1740 x 600 x 380 [68.2 x 33.5 x 15.0]	283 [623]
250 310	250 310	225 280	E1	2000 x 600 x 500 [78.8 x 33.5 x 19.4]	476 [1047]
400	400	360			498 [1096]

Feature	Benefits
• Power factor correction • Targeted mitigation of specific harmonics • Automatic adaptation to network changes	– Increased plant availability and operational reliability
• Low-energy mode / sleep mode	– Energy saving
• Reduced harmonic levels	– Higher transformer capacity utilisation and efficiency – Lower transformer losses – Lower wiring losses – Smaller wire cross-sections – Less cooling capacity needed in electrical room
High reliability	Benefits
• High operational reliability • High immunity to voltage fluctuations • Integrated protective functions • Maintaining operation when overloaded	– Enhanced plant availability and operational reliability
• Optional main switch, fuses and RFI filters	– Lower external component count and installation cost
• Rear panel cooling	– Lower temperatures prolong component lifetimes
• Coated circuit boards	– Enhanced resistance to aggressive ambient conditions
• Retrofit	– Saves time and money – Can be retrofitted at any desired location – No modification of existing devices necessary
High ease of use	Benefits
• Prize-winning LCP control panel	– Easy commissioning and parameter configuration
• Proven VLT® design enclosure	– Easy installation, even in confined spaces
• Modular system design	– Fast, economical installation
• Compatible with VLT® MCT10 software	– Fast commissioning, parameter configuration and data backup
• High compatibility with VLT® frequency converter system components	– Fast, easy maintenance – Fewer spare parts necessary
• Optional Profibus DP interface	– Monitoring and control of active filter parameters, i.e. cos phi reference.

Total Current A	Max. individual harmonic compensation [A]							
	I_5	I_7	I_{11}	I_{13}	I_{17}	I_{19}	I_{23}	I_{25}
190	119	85	55	48	34	31	27	24
250	158	113	72	63	45	40	36	32
310	196	140	90	78	56	50	45	40
400	252	180	115	100	72	65	58	50

VLT® frequency converters with 12-pulse front-end

Lower harmonic emissions and higher power quality
Danfoss VLT® High-Power Drives with 12-pulse front-end reduce mains harmonic distortion in plants and improve mains power quality.
To achieve this, Danfoss uses a transformer with 30-degree phase shift in the input stage of the frequency converter to combine two 6-pulse rectifiers, which cancels the 5th, 7th, 17th and 19th harmonics. This reduces mains harmonic distortion to a THDi of 10 to 12%, compared to 30–50% with conventional 6-pulse bridge rectifiers and line reactors. The advantage of this approach is that it eliminates the need for additional measures such as absorption circuits, which often require extensive network analysis in order to avoid resonances in the overall system.

The High Power devices with 12-pulse input stages are also fully integrated into the modular VLT® platform. For instance, Danfoss attaches great importance to using the proven components of the High Power Drive family. The devices also use all available extension options and have the same proven graphical control panel for easy, intuitive programming and configuration.
They also provide an STO function in accordance with EN 61800-5-2.

Cooling via rear panel cooling duct
Cooling air flows over heat sinks in a rear-panel cooling duct, reducing air circulation in the electronics compartment. This arrangement removes up to 85% of the dissipated heat directly from the enclosure. That boosts reliability and prolongs device lifetime by reducing the temperature rise and contamination of the electronic components. The rear panel cooling duct is separated from the electronic components with IP54 intrusion protection.

Power range
250 kW – 1.4 MW

Voltage range
380 – 690 V

Enclosure
IP21 / NEMA Type 1
IP54 / NEMA Type 12

Available VLT® platforms
VLT® HVAC Drive FC 102
VLT® AQUA Drive FC 202
VLT® AutomationDrive FC 302

Developed for:
- Poor-quality mains supplies
- Harmonic mitigation
- Generator-powered applications
- Step-down, step-up applications
- Galvanically isolated applications

Helps achieve standards compliance
- IEEE-519 1992
- EN 61000-2-4
- G5/4

Features	Benefits
Consistent operating concept and modular VLT® platforms	Easy operation: if you can use one, you can use them all.
Proven power electronics	Reliable operation.
Modular system design	All components can be accessed from the front by opening the doors. Faster and easier replacement of faulty components.
Rear-panel cooling duct	Reduces maintenance effort, increases drive availability and prolongs service life.
Standard Rittal TS8 electrical cabinet with IP21 or IP54 rating	Easy expansion.
Class C2 RFI filter in accordance with EN 61800-3, corresponding to EN 55011 Category A1	Mitigates harmonic emissions and electromagnetic interference without additional external filters.
Integrated DC link chokes	Reduces mains harmonic distortion in the entire network. Higher overall system efficiency thanks to no additional losses.
Fuses in DC link	Improves protection of individual converters with capacitive clamp coupling.
High-quality coated circuit boards	Enhanced protection against harsh ambient conditions and aggressive gases.
Reduced harmonic emissions	Lower risk of resonances in the system. Reliable operation of other electronic installations. Fewer device faults.

VACON® frequency converters with 12-pulse front-end

Lower harmonic emissions and higher power quality
Danfoss VACON® Enclosed Drives with 12-pulse front-end reduce mains harmonic distortion in plants and improve mains power quality.

Like the VLT Drives, the VACON drives utilize two input rectifier bridges along with a customer supplied input transformer with 30-degree phase shift. This reduces mains harmonic distortion to a THDi of 10 to 12%, compared to 30–50% with conventional 6-pulse bridge rectifiers and line reactors.

The High Power devices with 12-pulse input stages are also fully integrated into the VACON enclosed drives.

Cooling via rear panel cooling duct with VACON®100 Enclosed
Cooling air flows over heat sinks in a rear-panel cooling duct is an option with the VACON 100 Enclosed drives (FLOW and INDUSTRIAL). The rear panel cooling duct is separated from the electronic components with IP54 intrusion protection.

Front Door Control Compartment
The VACON100 Enclosed drives have a unique front door in door compartment for low voltage control electronics and options. This compartment can be access independently from the main enclosure door.

Wide power Range with VACON NXC
The VACON NXC drives with 12 pulse input are available at a in wide range of power and voltage range. At high powers (2MW) the NXC with 12 pulse provides a cost effective solution for a high power drive with harmonic mitigation.

Power range
200 kW – 2.0 MW

Voltage range
380 – 690 V

Enclosure
IP21 / NEMA Type 1
IP54 / NEMA Type 12

Available VLT® platforms
VACON® 100 INDUSTRIAL
VACON® 100 FLOW
VACON® 100 Enclosed
VACON® NXC

Developed for:
- Poor-quality mains supplies
- Harmonic mitigation
- Generator-powered applications
- Step-down, step-up applications
- Galvanically isolated applications

Helps achieve standards compliance
- IEEE-519 1992
- EN 61000-2-4
- G5/4

VLT® Low Harmonic Drives

VLT® AutomationDrive, HVAC Drive and AQUA Drive with reduced harmonic emissions.
Unlike harmonic mitigation with other technologies, which is dependent on the stability of the mains and the load or affects the motor, the new Low Harmonic Drives from Danfoss constantly regulate the mains and load conditions without impairing the connected motor.
They are designed to be especially motor friendly. Peak output voltages and ripple voltages are compatible with motors that conform to IEC 60034-17/25 and NEMAMG1-1998 Part 31.4.4.2.
VLT® Low Harmonic Drives have the same modular architecture as the VLT® High-Power Drives and the same features, including high efficiency, cooling via a rear-panel cooling duct, and user-friendly operation.
VLT® Low Harmonic Drives fulfil all harmonic requirements. They display device performance with reference to the mains and provide a graphic overview of the mains characteristics.

The ideal solution for:

- Fulfilling all harmonic requirments and standards
- Mains with backup generators
- Weak mains
- Converter installations on networks with limited short-circuit power

Voltage range

- 380 – 480 V AC, 50 – 60 Hz

Power range

- 132 – 630 kW high overload /
- 160 – 710 kW normal overload (corresponds to enclosures D, E and F)

Protection rating

- IP21 / NEMA 1, IP54 / NEMA 12

MCT 10 Parameter configuration software
Ideal for commissioning, maintenance, monitoring and logging.

HCS 2.0 software
Software tool for making harmonic calculations for VLT® Low Harmonic Drives and other products.

RoHS conformant
VLT® Low Harmonic Drives are environmentally compatible and conform to the RoHS Directive.

Options

- dv/dt filter: protects motor insulation
- Sine-wave filter (LC filter): reduces motor noise emissions

400 VAC (380-460 VAC)

Normal overload		160% overload		Enclosure	Dimensions	Weight
Power	Current	Power	Current		H x W x D	
kW	[A]	kW	[A]		IP 21 [mm]	kg
160	315	132	260	D	1780 x 1022 x 378	380
200	395	160	315			380
250	480	200	395			406
315	600	250	480	E	2000 x 1200 x 494	596
355	658	315	600			623
400	745	355	658			646
450	800	400	695			646
500	880	450	800	F	2200 x 2792 x 600	2009
560	990	500	880			2009
630	1120	560	990			2009
710	1260	630	1120			2009

VACON® NXC AFE Low Harmonic

The VACON® NXC Low Harmonic drive is the perfect choice for applications where low harmonics are required. This drive not only meets the most demanding requirements for clean power but also provides other important benefits such as regenerative braking and voltage boost for maximum output power.

Clean power saves money

The low harmonic cabinet drive offers an excellent total solution to meet even the most demanding power quality requirements. The drive also complies with the IEEE-519, G5/4 harmonic standards.

The low THDi reduces supply currents and allows supply transformers, protection devices and power cables to be dimensioned according to the actual active power. It creates savings for both new and retrofit projects as there's no need to invest in expensive 12- or 18-pulse transformers.

Features

- Clean power with total current harmonics THDi < 5 %
- Over-dimensioning of power transformer or input cables is not required
- Regenerative function available
- Reducing system complexity
- No need for special 12-pulse transformers
- Well-suited for retrofit projects
- Increased flexibility with a wide range of standard options

Benefits

- Over-dimensioning of input components is not needed, reducing the total costs
- Voltage boost function for maximum output power
- Braking energy can be fed back to network saving energy costs
- Reduces overall investment costs and optimizes the use of available space

Mains voltage	Low harmonic drive type	Loadability					Motor shaft power		Frame size	Dimensions and weight W x H x D (mm)/kg
		Low (+40°C)		High (+40°C)		Maximum current I_S [A]	400 V / 690 V			
		Rated continuous current I_L [A]	10% overload current [A]	Rated continuous current I_H [A]	50% overload current [A]		10% overload P [kW]	50% overload P [kW]		
380-500 V 50/60 Hz	NXC 0261 5 A 2 L 0 RSF	261	287	205	308	349	132	110	AF9	1006 x 2275 x 605/680
	NXC 0300 5 A 2 L 0 RSF	300	330	245	368	444	160	132		
	NXC 0385 5 A 2 L 0 RSF	385	424	300	450	540	200	160	AF10	1006 x 2275 x 605/700
	NXC 0460 5 A 2 L 0 RSF	460	506	385	578	693	250	200		
	NXC 0520 5 A 2 L 0 RSF	520	572	460	690	828	250	250		
	NXC 0650 5 A 2 L 0 RSF	650	715	590	885	1062	355	315	AF12	2006 x 2275 x 605/1400
	NXC 0730 5 A 2 L 0 RSF	730	803	650	975	1170	400	355		
	NXC 0820 5 A 2 L 0 RSF	820	902	730	1095	1314	450	400		
	NXC 0920 5 A 2 L 0 RSF	920	1012	820	1230	1476	500	450		
	NXC 1030 5 A 2 L 0 RSF	1030	1133	920	1380	1656	560	500		
	NXC 1150 5 A 2 L 0 RSF	1150	1265	1030	1545	1854	630	560	AF13	2206 x 2275 x 605/1950
	NXC 1300 5 A 2 L 0 RSF	1300	1430	1150	1725	2070	710	630		
	NXC 1450 5 A 2 L 0 RSF	1450	1595	1300	1950	2340	800	710		
	NXC 1770 5 A 2 L 0 RSF	1770	1947	1600	2400	2880	1000	900	AF14	4406 x 2275 x 605/3900
	NXC 2150 5 A 2 L 0 RSF	2150	2365	1940	2910	3492	1200	1100		
	NXC 2700 5 A 2 L 0 RSF	2700	2970	2300	3278	3933	1500	1200		
525-690 V 50/60 Hz	NXC 0125 6 A 2 L 0 RSF	125	138	100	150	200	110	90	AF9	1006 x 2275 x 605/680
	NXC 0144 6 A 2 L 0 RSF	144	158	125	188	213	132	110		
	NXC 0170 6 A 2 L 0 RSF	170	187	144	216	245	160	132		
	NXC 0208 6 A 2 L 0 RSF*	208	229	170	255	289	200	160	AF10	1006 x 2275 x 605/700
	NXC 0261 6 A 2 L 0 RSF	261	287	208	312	375	250	200		
	NXC 0325 6 A 2 L 0 RSF	325	358	261	392	470	315	250		
	NXC 0385 6 A 2 L 0 RSF	385	424	325	488	585	355	315		
	NXC 0416 6 A 2 L 0 RSF*	416	416	325	488	585	400	315		
	NXC 0460 6 A 2 L 0 RSF	460	506	385	578	693	450	355	AF12	2006 x 2275 x 605/1400
	NXC 0502 6 A 2 L 0 RSF	502	552	460	690	828	500	450		
	NXC 0590 6 A 2 L 0 RSF	590	649	502	753	904	560	500		
	NXC 0650 6 A 2 L 0 RSF	650	715	590	885	1062	630	560		
	NXC 0750 6 A 2 L 0 RSF	750	825	650	975	1170	710	630		
	NXC 0820 6 A 2 L 0 RSF*	820	902	650	975	1170	750	650		
	NXC 0920 6 A 2 L 0 RSF	920	1012	820	1230	1476	900	800	AF13	2206 x 2275 x 605/1950
	NXC 1030 6 A 2 L 0 RSF	1030	1133	920	1380	1656	1000	900		
	NXC 1180 6 A 2 L 0 RSF*	1180	1298	1030	1463	1755	1150	1000		
	NXC 1500 6 A 2 L 0 RSF	1500	1650	1300	1950	2340	1500	1300	AF14	4406 x 2275 x 605/3900
	NXC 1900 6 A 2 L 0 RSF	1900	2090	1500	2250	2700	1800	1500		
	NXC 2250 6 A 2 L 0 RSF*	2250	2475	1900	2782	3335	2000	1800		

**Max. ambient temperature of +35°C.*

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