



## Harmonic Distortion and Variable Frequency Drives

### Definitions

- **Variable Frequency Drives** (VFDs); sometimes referred to as "variable speed drives."
- **Harmonic Distortion** is a measure of the amount of deviation from a pure sinusoidal wave form that can be caused by a non-linear load (a VFD is considered a non-linear load because it only draws current from the power line as required).
- **Distorted Waveform** = fundamental (60Hz sinusoidal waveform) + multiples of the fundamental frequency, typically the 5th, 7th, 11th, 13th, and 17th, etc. (e.g.  $5 \times 60\text{Hz} = 300\text{Hz}$ ,  $7 \times 60\text{Hz} = 420\text{Hz}$ , etc.)
- **Voltage Distortion** is the deviation in the supplied voltage from a pure sinusoidal waveform.
- **Current Distortion** is the deviation in current drawn by a non-linear load from a purely sinusoidal waveform.
- **Pulse Width Modulation** (PWM) is a means by which nearly sinusoidal current can be caused to flow in a motor, at a desired frequency (40, 50, 60Hz for example), by sinusoidally varying the pulse width of a much higher frequency squarewave.
- **Point of Common Coupling** (PCC): A connection point in a power system where it is important and desirable to control the level of harmonic content and/or voltage distortion (deviation from a pure sine wave).
- **Total Demand Distortion** (TDD) is the ratio between the RMS sum of all the harmonic currents drawn and (divided by) the total fundamental current (at 60Hz in N.A.) at a point of common coupling (over a 15 or 30 minute period).

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**CONTROL TECHNIQUES**™

# Active Front End



*Clean, efficient and reliable motor control with low harmonic distortion.*

Designed to meet the demand for clean power, Control Techniques offers the latest in both microprocessor and power semiconductor technology to provide the industry with economical, compact and highly flexible active front end drive packages.

These packages integrate Control Techniques' Unidrive M Active Front End controller and EMC filtering for high performance with extremely low harmonic distortion.

## Active Front End Features

- Integral Active Front End controller and EMC filter
- 100 kA fault rating
- NEMA 1 enclosure is standard, other enclosure ratings available
- Optional easy-to-use electronic bypass control

**Nidec**  
All for dreams



## HVAC Drive H300

### Key Features

- Static and rotational auto tune
- 8 preset speeds; 8 sets of accel / decel rates
- Catch spinning motor function
- Built-in PID
- Energy savings mode
- Power metering
- Network connectivity
- Easy-to-use, plain text LCD keypad
- 3 option slots for other communication options and/or for I/O expansion
- SmartCard for parameter cloning
- FREE energy saving software and drive setup tools

### Active Front End Benefits

#### Low Harmonic Distortion

- IEEE519-2014 harmonic compliance at the drive input terminals
- Won't interfere with sensitive equipment
- Not sensitive to line imbalances
- Superior to 12- and 18-pulse solutions
- Maintains Unity Power Factor

#### Easy Installation

- Available up to 2,000 HP at 460 V
- Single package – no need for external filters or transformers
- UL508A approved
- 100 kA SCCR ratings

#### Flexible Solutions

- Wide range of I/O and communications option modules including BACnet
- Electronic bypass three contactor and soft start option

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## Harmonic Reduction Technologies

The first stage of a PWM VFD (the rectifier) creates distortion of the AC line as the rectifier charges a capacitor bank called the DC bus. Current is drawn from the AC line only when the rectified voltage exceeds the voltage level to which the capacitor is charged. Severe harmonic distortion can have several detrimental effects. Over the years, several standards have been adopted to address these potential effects in terms of recommendations for maximum allowable levels of distortion. One such standard cited frequently in North America is IEEE-519.

THDV Level	Sensitive Applications
3%	Airports
	Hospitals
	Telephone companies
THDV Level	General Applications
5%	Office buildings
	Schools
THDV Level	Dedicated Systems
10%	Factories

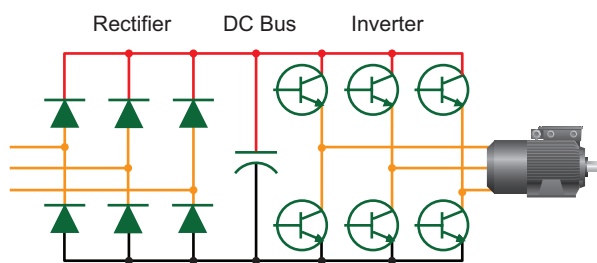


Figure 1 – Typical PWM VFD

### IEEE-519 Standard

ANSI/IEEE Standard 519, IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters, was published in 1981. It recommended maximum levels of total-harmonic-voltage-distortion (THDV) at the point that the utility connects to different types of users (point of common coupling, or PCC), shown in Figure 2. Different maximum levels were provided for different types of buildings (see Figure 3).

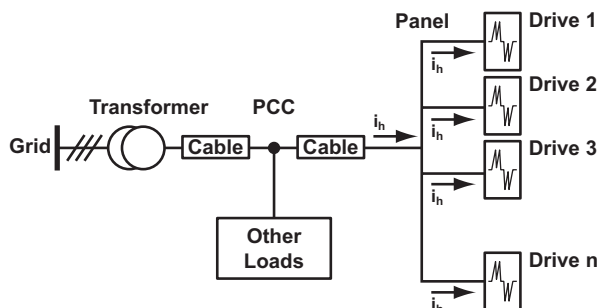


Figure 2 – Point of Common Coupling

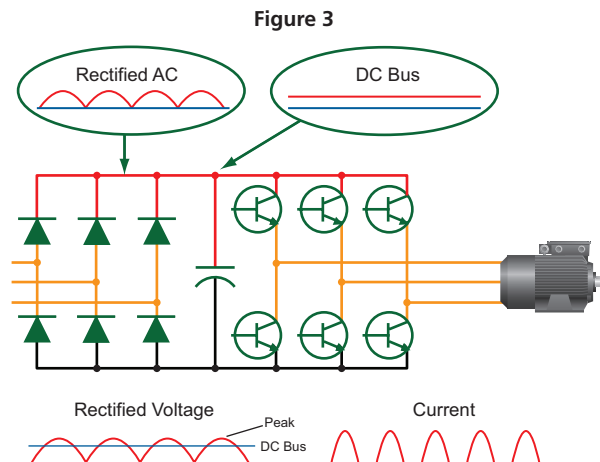


Figure 3

Figure 4

Current only flows when the rectified voltage exceeds the voltage that the capacitor is charged to. Current flow thus becomes “non-linear” (not sinusoidal).

Voltage distortion created by VFDs can cause “flat-topping” of power-system voltage waveforms which, in turn, can cause sensitive electronic equipment to malfunction. The area between the two waveforms shown in Figure 5 is the actual level of distortion and is expressed as a percent of the fundamental pure 60Hz waveform.

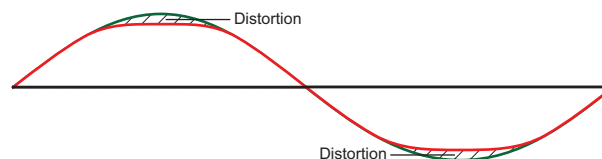


Figure 5 – “Flat-topped” power-system voltage waveform



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IEEE-519 was revised in 1992 to provide recommendations on maximum allowable levels of harmonic current distortion (see Figure 6). The new standard also defined the maximum recommended contribution of any individual harmonic. The amount of allowable distortion is based on a ratio of the short circuit current available to the distribution system (ISC – maximum short circuit current available at point of common coupling), and the maximum load current recognized by the distribution system (II – the maximum load current at the point of common coupling). Basically, a large transformer feeding a building will have more short circuit current available and the ratio becomes larger allowing for a higher level of harmonics.

ISC/II	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$
< 20	4.0	2.0	1.5	0.6	0.3
20 - 50	7.0	3.5	2.5	1.0	0.5
50 - 100	10.0	4.5	4.0	1.5	1.0
100 - 1000	12.0	5.5	5.0	2.0	1.0
> 1000	15.0	7.0	5.0	2.0	1.0

**Figure 6 - IEEE-519 recommended maximum individual current harmonics**

Also introduced by IEEE-519-1992 is the term “Total Demand Distortion” (TDD) which provides recommendations for maximum total current distortion (contribution by all individual harmonics) as a percent of the total demand load current during a 15 or 30 minute demand (see Figure 7). Again the TDD is referenced to the ratio of the load current to the short circuit current available.

ISC/II	Total Demand Distortion (TDD)
< 20	5.0
20 - 50	8.0
50 - 100	12.0
100 - 1000	15.0
> 1000	20.0

**Figure 7 - IEEE-519 Total Current Demand Distortion**

The key issue with current distortion is that it creates voltage distortion. However, current distortion can also create increased audible noise as well as additional heating of distribution transformers and the cables providing power to the equipment generating the harmonics.

IEEE-519 was subsequently revised in 2014 to provide additional clarity on the Point of Common Coupling (PCC). Frequently for industrial users (i.e., manufacturing plants) the PCC is located at the high voltage (HV) side of a dedicated transformer. For commercial users (office parks, shopping malls, etc.) the PCC is located at the low voltage (LV) side of a common service transformer.

The location of the PCC was explicitly established so that all users of a given PCC are aware that they must all work together to ensure that limits are met.

## IEEE-519 Compliance

IEEE Standard 519 states, “Within an industrial plant, the PCC is the point between the nonlinear load and other loads.” This statement has been widely misunderstood and misused. Some consulting engineers have interpreted this to mean that the current distortion is to be measured at the VFD input-power connections, a total misunderstanding of the purpose behind this standard and use of it. The drive itself is the only component in the entire electrical system that will see this level of distortion (measured at the drive input terminals). Maintaining some level of current distortion at the input of the drive will not guarantee any level anywhere else in the building. This misapplication of the standard has led to use of costly and energy-consuming reactors, passive filters, multi-pulse drives and active filters that are in many cases unnecessary. Because these devices can increase the initial cost of the drives by as much as 500%, it is important to understand the intent and purpose of this standard and use it accordingly.

A variety of information is required to determine whether or not any form of harmonic mitigation is necessary to comply with a recommended level of distortion as defined by IEEE-519:

- The transformer feeding the building must be defined (KVA and % impedance). The larger the transformer, the “stiffer” the power line resulting in lower levels of harmonic distortion.
- The total number of drives and their cumulative horsepower must be defined. A few small drives on a very large transformer will have very little effect.
- The amount of non-linear load (drives) versus the building’s linear load will, to a large degree, determine the total amount of current distortion thus determining if the drives are a big or small percentage of the load on the transformer.

Using this information, an estimate of the current and voltage distortion can be made. More accurate calculations can be made if additional information is available such as existing harmonic distortion levels and wire lengths/sizes between the drives and the PCC. As a rule of thumb, unless the drives constitute more than 30% of the load on the main distribution transformer from which they receive power, there is little need

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to be concerned about harmonics and standard 6-pulse drives should be sufficient. In most commercial buildings, the fan and pump drives being used are not more than 30% of the total load. If any doubt remains, however, a harmonic analysis of a given installation should be performed.

## Harmonic Mitigation Techniques for AC Drives

If harmonics are higher than desired after performing an analysis, there are a number of ways to mitigate the harmonic distortion. Harmonics are caused by the first stage of a VFD (the rectifier). The distortion of input current feeding this rectifier on a standard (6-pulse) VFD ranges between 70-100%.

### Reactors

AC line reactors (see Figure 8) and DC link chokes (reactors) will make the current drawn from the power line more sinusoidal (see Figure 9). With an AC line reactor or DC link choke, the distortion of the input current will typically be 30-40% compared to the 70-100% of a drive with no reactor. Reactors will increase the initial cost of the drive 10-20% and are included as standard in many drives 5 horsepower and larger.

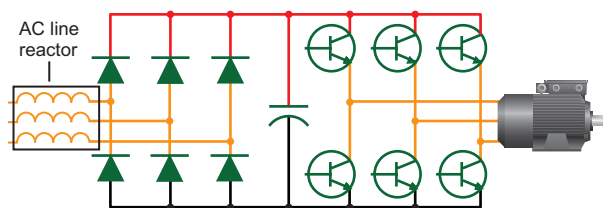


Figure 8

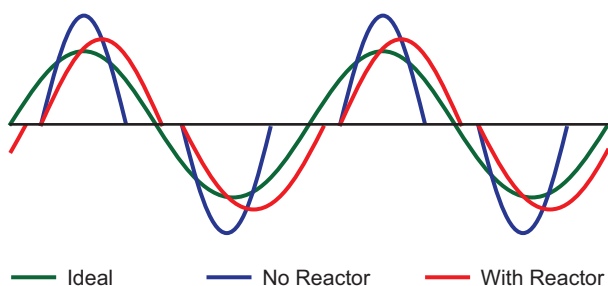


Figure 9

Blue- standard 6 pulse, Red-6 pulse with AC reactor or DC link choke, Green – pure sinusoidal current flow

AC line reactors have the dual benefit of convenience and providing additional attenuation of AC power supply disturbances such as surges or poor phase balance. They do however cause a reduction in DC link voltage so they can create voltage drop issues. An oversized AC line reactor with a low line voltage can create enough of a voltage drop that not enough output voltage can be created to provide full motor torque and horsepower.

As a general rule, the total AC reactance should not exceed 5%. This is sufficient to meet the harmonic levels required by international standard IEC-61000-3-12 for a balanced 3 phase rectifier with  $R_{sce}$  (the ratio of the drive-rated current-to-supply fault level at the point of common coupling with other supply users) greater than or equal to 120 (i.e. primarily a 5th harmonic not exceeding 40% and a THD not exceeding 48%).

### DC Link Chokes

DC link chokes can be used individually (typically on the positive DC bus) or in pairs with one each on the positive and negative bus. When two DC reactors are used on the bus, the inductance is additive. Equivalent impedances can be achieved using either one larger reactor on the positive or negative bus or two smaller reactors on both the positive and negative bus.

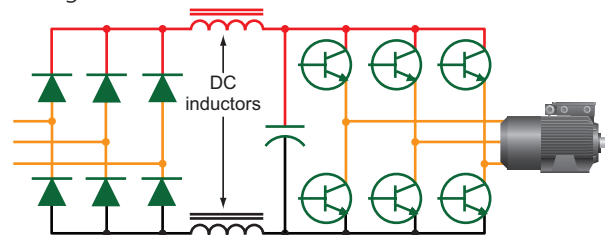


Figure 10

A key advantage of DC link inductors is the minimal drop in DC voltage with increasing load. For reactance values on the order of 4%, the benefit for harmonics is similar to that of the AC reactor but with slightly greater benefit for the lower order harmonics such as the 5th. However, the benefit is subject to diminishing returns since the harmonics can never be reduced below the levels for an infinite inductance (e.g. 20% for the 5th harmonic) and in practice, the 5th harmonic is unlikely to be reduced cost-effectively to below 30%.

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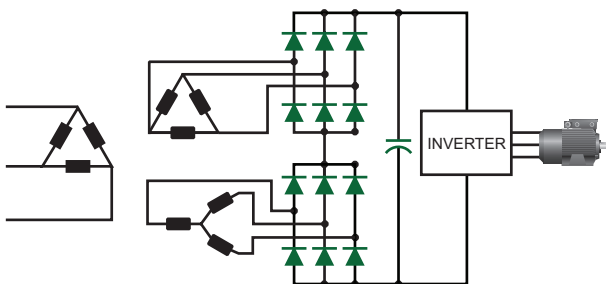
The disadvantage of DC inductors is that the rectifier becomes more susceptible to the effects of supply surges and poor balance and must therefore be equipped with adequate surge suppression. To avoid undue sensitivity to supply unbalance, it is important to choose inductor values such that the inherent resonant frequencies with the DC capacitors do not coincide with the characteristic frequencies of an unbalanced supply.

Used alone, DC inductors do not reduce the high-order harmonics significantly and may even increase them. For this reason it may be desirable to use standard AC reactors.

The use of Control Techniques VFDs with AC line reactors and DC link chokes varies based on the drive's horsepower and voltage ratings. Drives smaller than 5 horsepower have neither AC line reactors or DC link chokes since their harmonic impact is normally negligible. The equivalent impedance of the reactors used on larger drives will vary as well based on horsepower and voltage with an average of approximately 5%. Midsize drives (greater than 5 horsepower and smaller than 100 horsepower) will use DC link chokes (either one on the positive leg or one on both the positive and negative leg). Larger drives (100 horsepower and larger) will use AC line reactors.

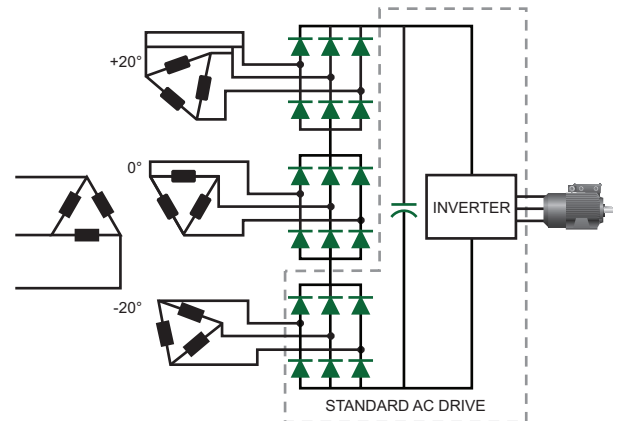
## Multi-Pulse Drives (12 and 18-Pulse)

An additional method of mitigating harmonics is the use of 12-pulse drives (see Figure 11) and 18-pulse drives (see Figure 12). These drives contain multiple rectifiers as well as an expensive transformer with one primary and multiple secondary. These configurations act to cancel some of the lower level, higher amplitude harmonic currents.



**Figure 11 - 12-pulse rectifier**

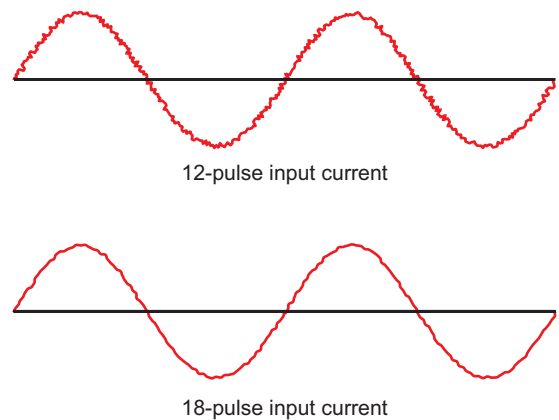
*includes transformer (1 primary, 2 secondaries) and 2 input bridges and balancing reactors*



**Figure 12 - 18-pulse rectifier**

*Includes transformer (1 primary, 3 secondaries) and 3 input bridges and balancing reactors*

Refer to Figure 13. Current distortion at the input terminals is approximately 10% for 12-pulse drives; 5% for 18-pulse drives.



**Figure 13**

These technologies have several drawbacks:

- Initial cost of a 12-pulse drive is approximately 400% higher than a standard 6-pulse drive (500% higher for 18-pulse drive)
- Input power lines must be very well balanced (1% or better); even a slight imbalance of 3% will negate nearly all of the harmonics mitigation.
- Physical size – extra bridges and custom transformers increase size requirements
- Higher operating losses create lower efficiencies

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## Passive Filters

Refer to Figure 14. Passive filters comprised of a tuned configuration of capacitors, inductors and in some cases resistors, are sometimes used to eliminate specific harmonics (typically the 5th, 7th, etc.). Depending on the level of mitigation, use of passive filters increases the total cost of the installed drives by 200-500%. These filters are slightly more tolerant of line imbalances but also have losses associated with using them.

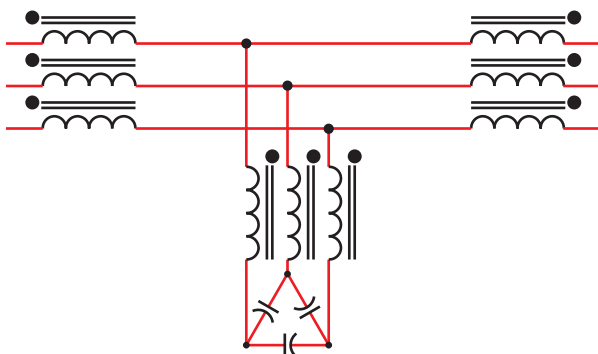


Figure 14 - passive filter

## Active Harmonic Filter and Active Front End

Newer technologies are the active harmonic filter (AHF) and the active front end (AFE) VFD. A single AHF can filter the harmonics of several VFDs or an entire facility. The AHF is in parallel with the other loads and only handles the corrective harmonics required to offset those generated by the non-linear loads. The current distortion at the input of the filter will be less than 4% and these filters are relatively unaffected by line imbalances.

The AFE is really a combination of two inverters. One inverter powers the motor and the other actively draws power from the line. The AFE handles both the fundamental current and the harmonic currents created by the load.

Both techniques act like active audible noise reduction techniques. If a 5th harmonic is detected, a harmonic of equal and opposite amplitude is generated that effectively eliminates the 5th harmonic. These techniques, while still costing as much as an 18-pulse drive, have the most promise to become lower in cost.

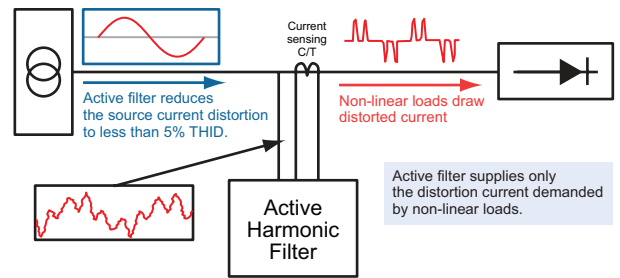


Figure 15 - active filter

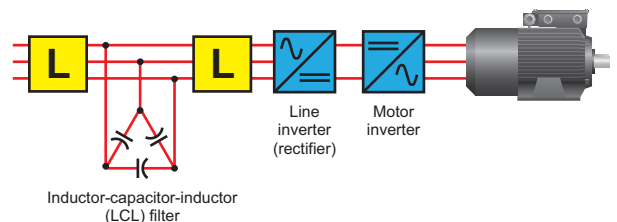


Figure 16 - active front end

## Summary

When choosing VFDs, it is important to properly compare and analyze drive manufacturers' products including a complete harmonic analysis based on individual drive sizes and quantities being used and the system to which they are connected. While one manufacturer's products may have better performance at a given frame size, the aggregate performance of all the sizes and quantities of drives being used on any individual project may indicate another manufacturer's products are the better choice.



75 HP HVAC Drive H300 AFE system



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