Danfoss Drives Harmonics Review

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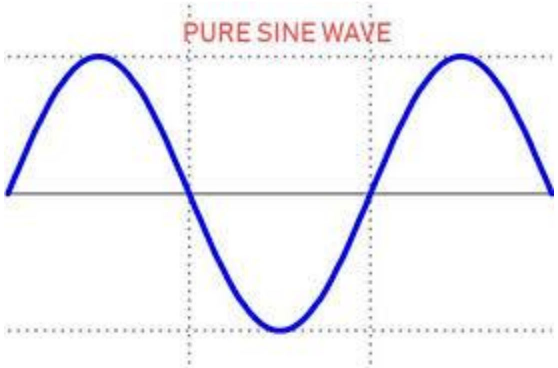
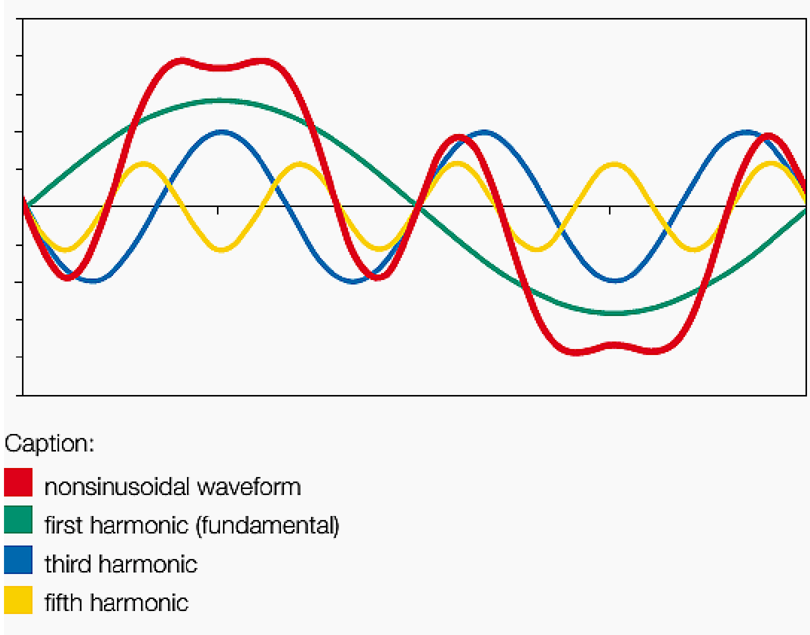
ENGINEERING TOMORROW

Agenda

- Overview of Harmonics
- Voltage Distortion VS Current Distortion
- Harmonics Mitigation Solution Options
- Passive Filter Functionality



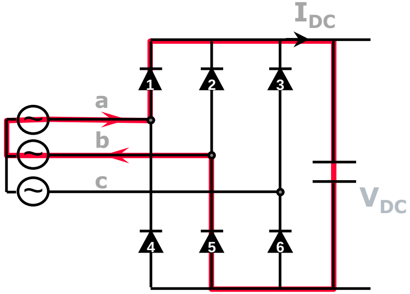


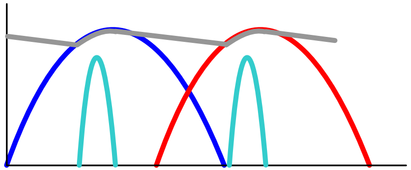
Energy efficiency

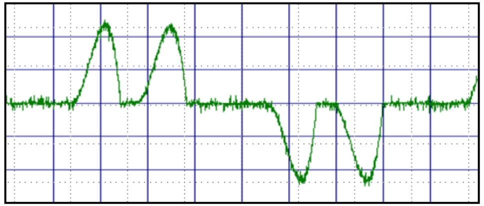
- Electronic motor control can typically **save 60% of the energy** consumption of pump and fan applications.
- Today, only 25% of all electric motors globally are frequency controlled by an AC drive. I makes sense to install drives in 40-50% of all motor-systems.
- AC drives all have the same side effect: **Harmonic Distortion.**
- Harmonics obstruct energy savings.

Harmonics: What they are…and are not

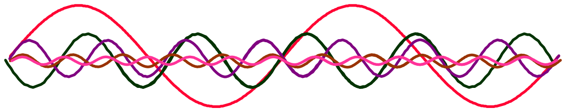
- All diode rectifier circuits draw non sinusoidal current.
- They are referred to as "non linear" load.
- Biggest contributors are:
  - Switch mode power supplies
  - Lighting
  - UPS
  - AC drives
- Different AC drives have different current waveform (harmonic footprint).

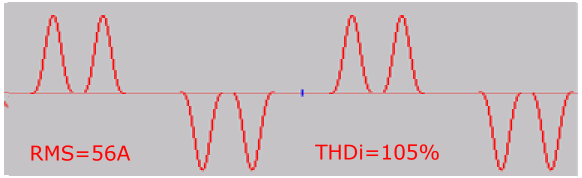


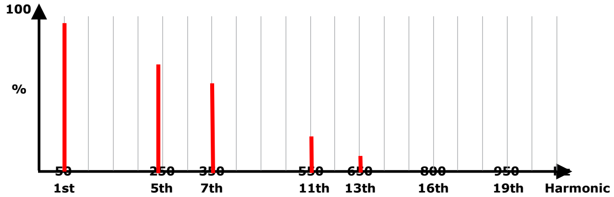




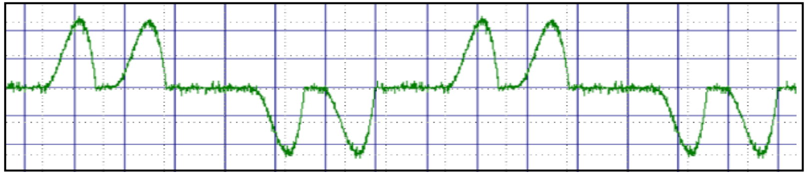
Harmonics: What they are…and are not





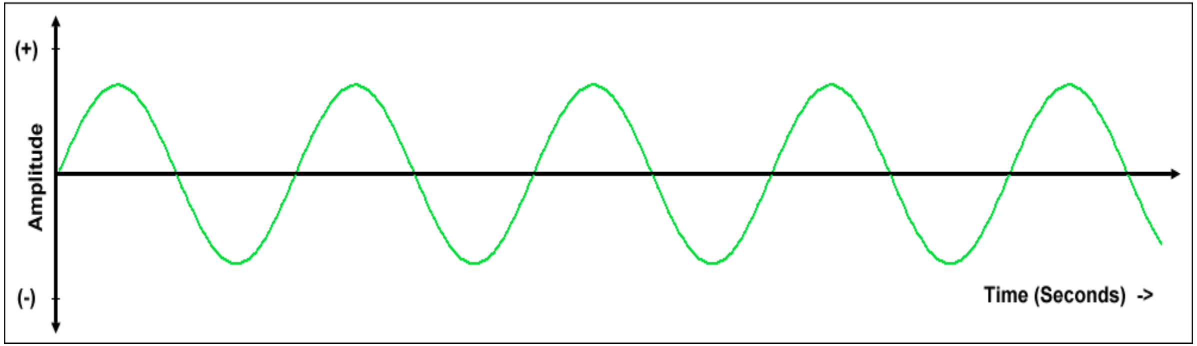


- Any periodic signals, independent of shape, can be represented as a sum of sine-waves.
- This is called a "Fourier" representation.
- Let us make a Fourier analysis of the current waveform of the AC drive below.



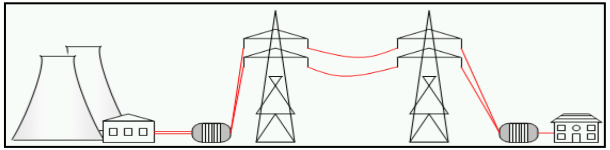
The Ideal Waveform

- In public power distribution networks the ideal undistorted AC electrical signal has a typical frequency of 50Hz or 60Hz depending on the country or region.

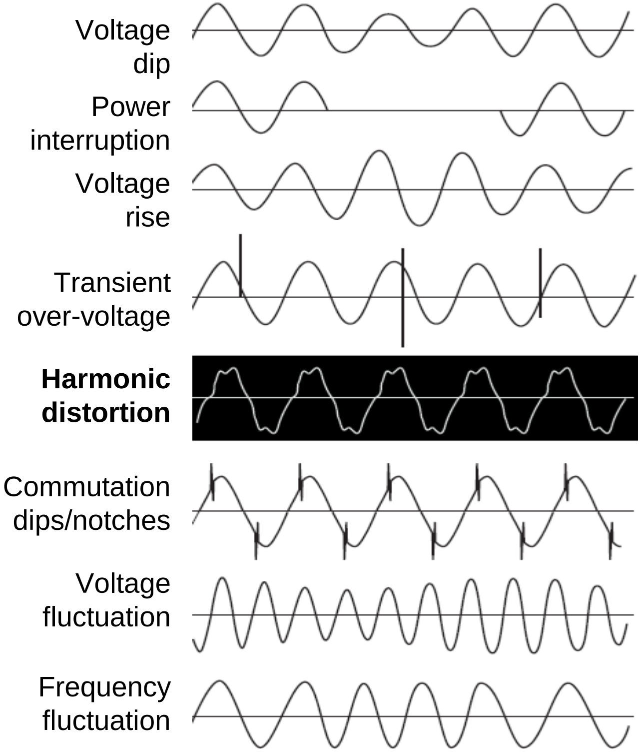


Power Disturbances

- The power grid normally experiences huge variations of load and reacts to changes in the voltage waveform.



- Causes of power disturbances range from electrical switching circuits to lightning.
- Harmonic distortions are **repetitive** and **continuous** deformations of the voltage or current waveforms.
- All distortions result in deviations from the ideal sinusoidal waveform.



Definition of Harmonics

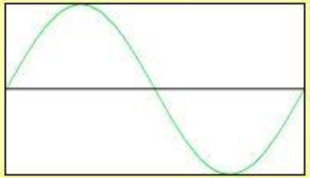
- In a periodic signal the primary, desired frequency is the "Fundamental Frequency".
- *A* "Harmonic" refers to a component of a periodic signal, that is itself:

  *"a periodic **sinusoidal** signal, with a frequency that is an integer multiple of the fundamental frequency".*

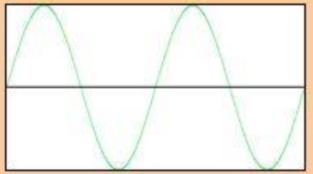
- Therefore in public power distribution networks:

  The frequency of an *n*th Harmonic is: fn = *n* X 50Hz or fn = *n* X 60Hz

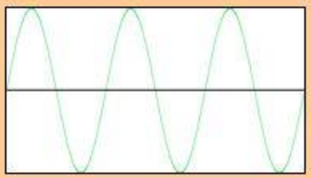
Fundamental Freq.
1st Harmonic
f1 = 50Hz
f1 = 60Hz



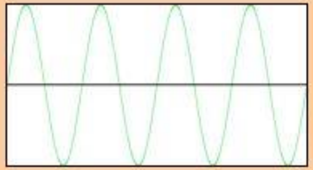
2nd Harmonic
f2 = 100Hz
f2 = 120Hz



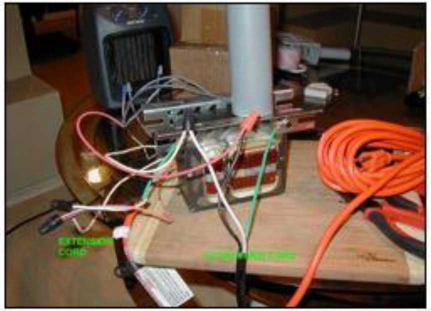
3rd Harmonic
f3 = 150Hz
f3 = 180Hz



4th Harmonic
f4 = 200 Hz
f4 = 240 Hz



Causes: repetitive non linear loads



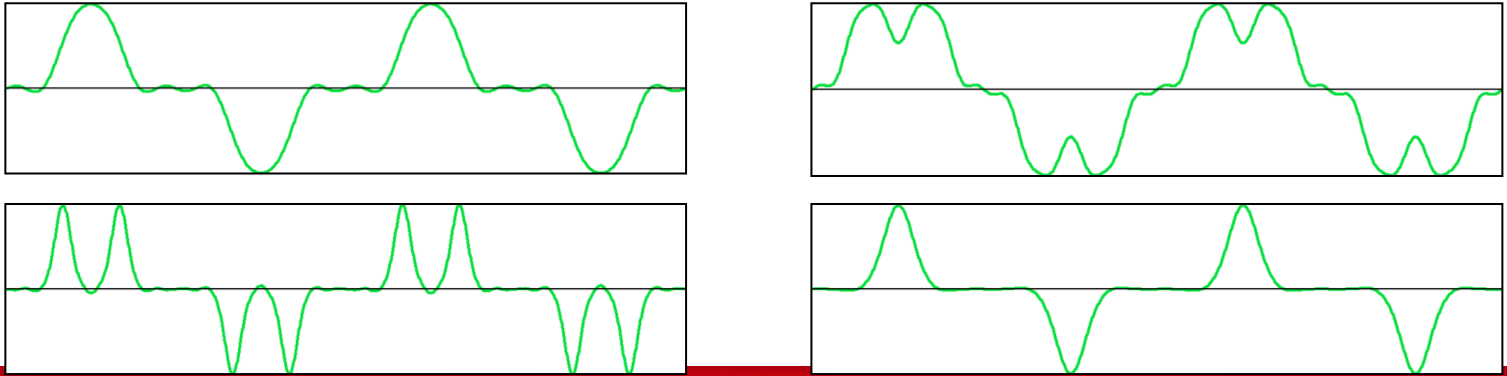
- Ballast Lighting
- DC switching power supplies such as computers
- AFDs,
- Arc Welders

Harmonic Producing Loads

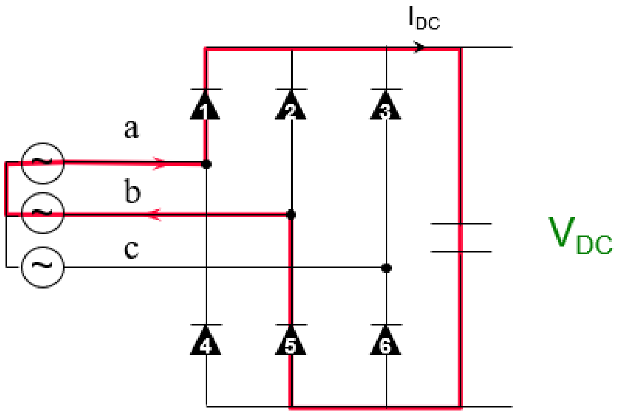
- Harmonics are primarily caused by loads that draw current repetitively but in a non-sinusoidal manner.

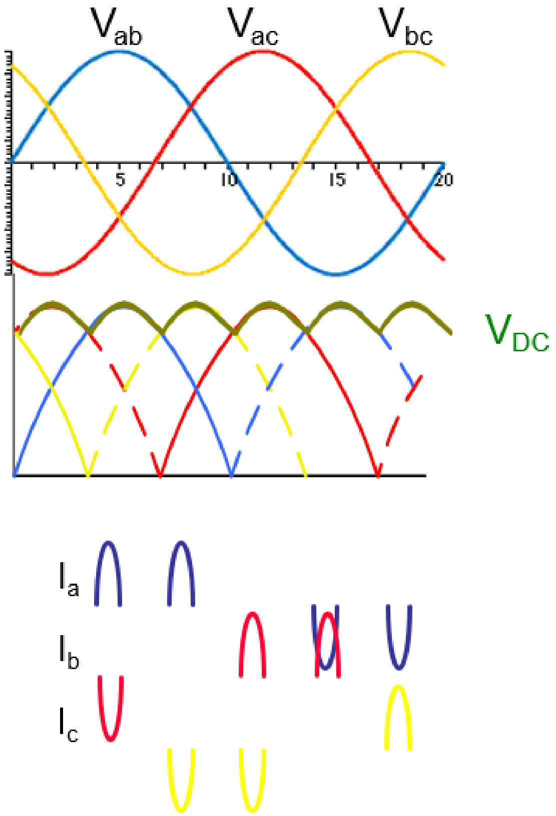
- Examples of Harmonic Loads include:
  - Ballast / Fluorescent Lighting & Computer power supplies
  - Uninterruptable Power Supplies (UPS’) & Variable Speed Drives
  - Charging circuits incorporating rectifiers
  - Arc Welders & 3 phase machines

- Examples of load current waveforms with harmonics.



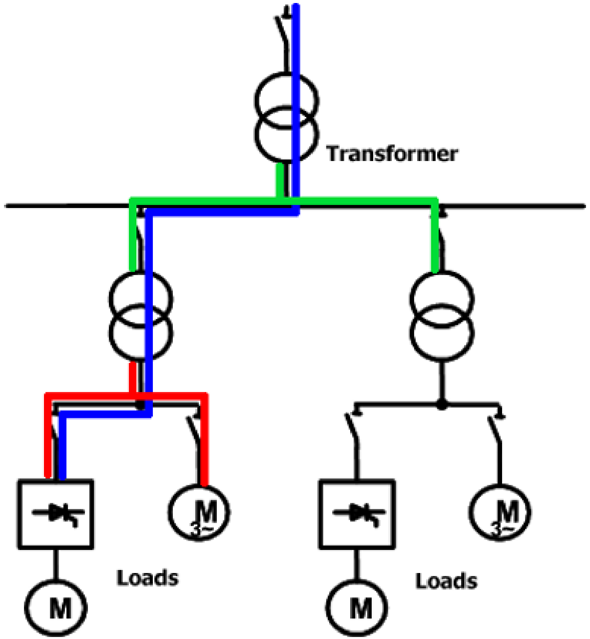
Causes of Harmonic Currents





- The basic 6-pulse rectifier draws a non sinusoidal current.
- A pulsating current is drawn from supply grid.
- Current pulse shape is dependent on capacitor size.
- Current pulse shape is also load dependent.

Current VS Voltage Distortion

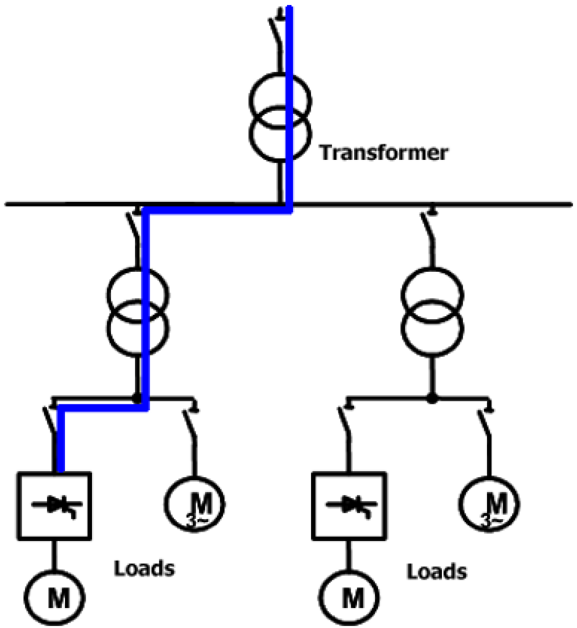


- Current distortion relates to **load level** performance
- I*Z=V
- Voltage distortion relates to **system level** performance.
- Harmonic currents of the non-linear load AND the system short-circuit impedance are required to calculate voltage distortion. It is NOT possible to predict the voltage distortion knowing only the load performance.
- Background voltage distortion is also related to system level performance. Same as secondary transformer side voltage distortion. Background distortion can be caused by energy consumers far away and is always present to some extent (0.5 - 3%).

Current VS Voltage Distortion

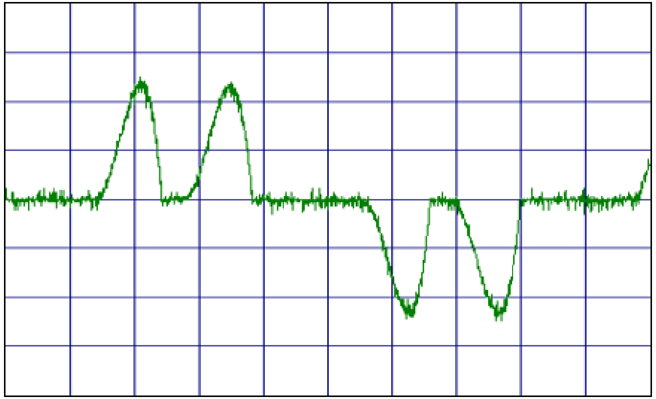
- **Effects of current distortion.** Since operation of nonlinear loads causes the distorted current, which is path dependent, the effect of current distortion on loads within a facility is minimal. Therefore, harmonic currents can't flow into equipment other than the nonlinear loads that caused them. However, the effect of current distortion on distribution systems can be serious, primarily because of the increased current flowing in the system.

Current Distortion



Problems caused by current distortion

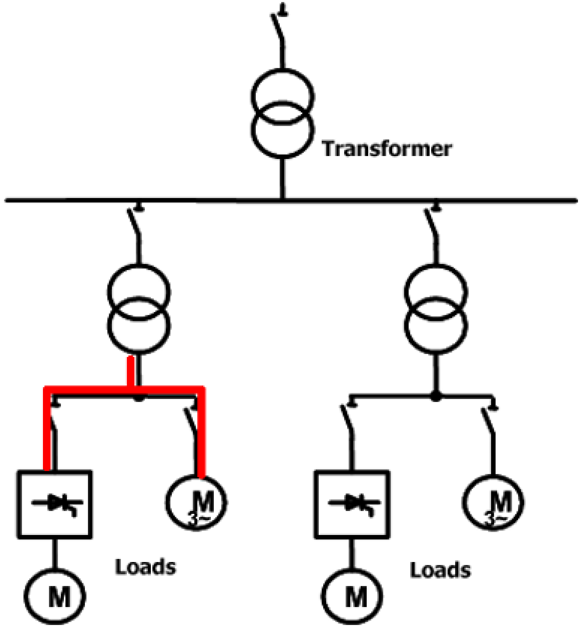
- Transformer overload and audible noise.
- Tripping of serial relays and circuit breakers.
- Stressing of Power Factor correction capacitors.
- Premature aging of serially installed equipment.
- Overheating of cables and insulation stress.
- Overheating of transformers and insulation stress.



Current VS Voltage Distortion

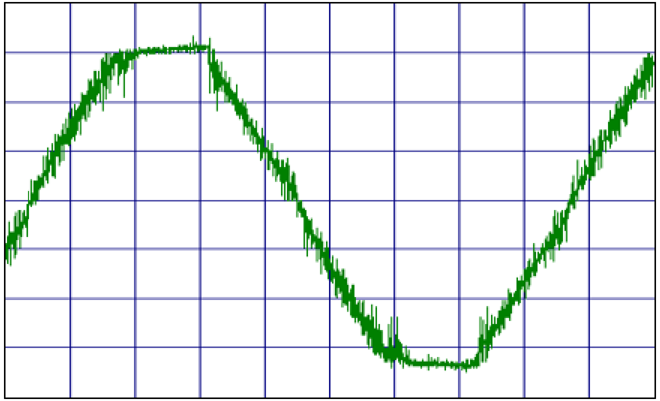
- **Effects of voltage distortion.** Besides overheating, the other major effect of current distortion on an electrical system is the creation of voltage distortion. This distortion will have minimal effect on a distribution system, but unlike current distortion, **it isn't path dependent. So harmonic voltages generated in one part of a facility will appear on common buses within that facility**. High-voltage distortion at the terminals of a nonlinear load doesn't mean high distortion will be present throughout the system. In fact, the voltage distortion becomes lower the closer a bus is located to the service transformer. However, if excessive voltage distortion does exist at the transformer, it can pass through the unit and appear in facilities distant from the origin.

Voltage Distortion

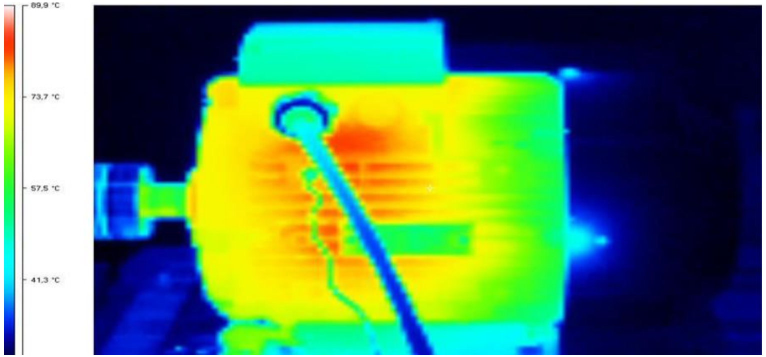


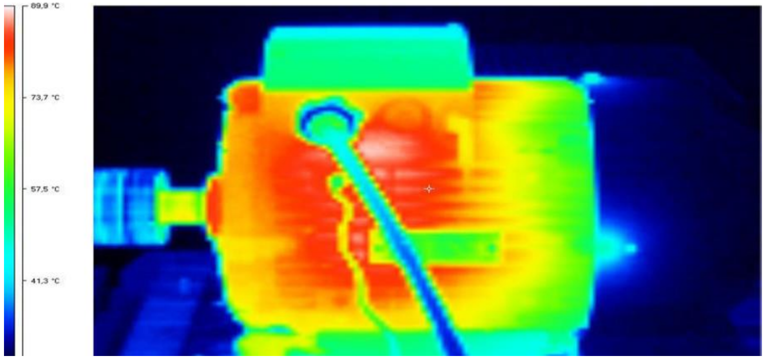
Problems caused by voltage distortion

- Malfunction of electronic equipment
- Breakdown of electronic equipment
- Increased Electromagnetic Interference (EMI)
- Increased losses at direct online motors
- Torque ripples from direct online motors
- Erratic operation



Harmonic effects on the power grid

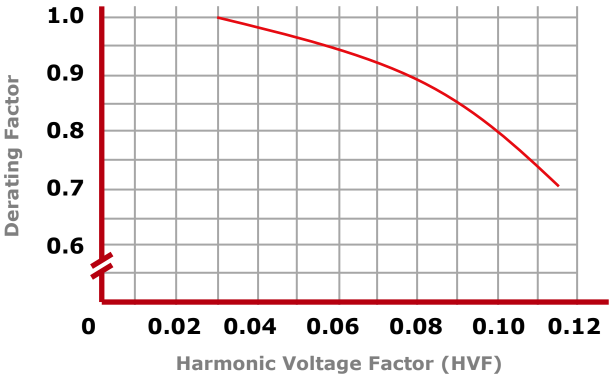




$$U_h = Z \times I_h$$

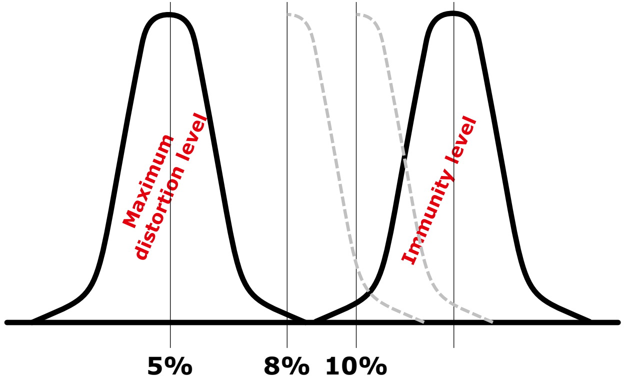
Harmonics lead to:

- Poor utilization of supply infrastructure
- Reduced equipment life
- Lower equipment efficiencies
- Increased likelihood of trips and production stops



DOL Motor with 8% THvD can only be loaded to 85%

What is a **safe level?**



Odd harmonics Non-multiple of 3		Odd harmonics Multiple of 3		Even harmonics	
Order 'h'	**Harmonic Voltage (%)**	**Order 'h'**	**Harmonic Voltage (%)**	**Order 'h'**	**Harmonic Voltage (%)**
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0.5
13	3	21	0.2	8	0.5
17	2	21<h≤45	0.2	10	0.5
17<h≤49	2.27(17/h)-0.27			10<h≤50	0.25(10/h)+0.25

Total Harmonic Distortion (THD) level is 8%

- You can be sure **your supply is already polluted** with harmonics.
- Current distortion is less important but **restrict voltage distortion.**
- Product immunity has to be higher than system distortion to prevent breakdown but **product life is a function of distortion level.**
- Good practice is aiming at system THDv of 5-8% to avoid damage to components.

Fast guidance

Reflect/calculate on harmonics if:

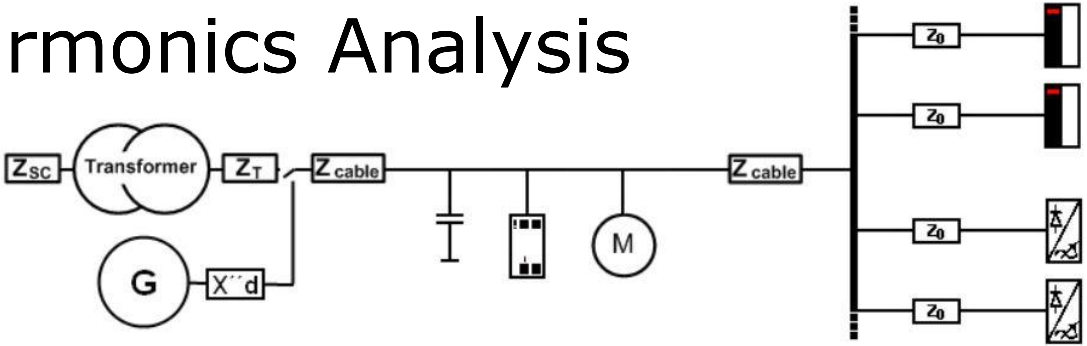
- Drive load on transformer is >30%
- The transformer is >90% loaded
- Generator fed supply

If problems occur consider:

- Use special drives
- Use filter(s)
- Change layout of transformer/generator
- Mix single and three phased non-linear loads

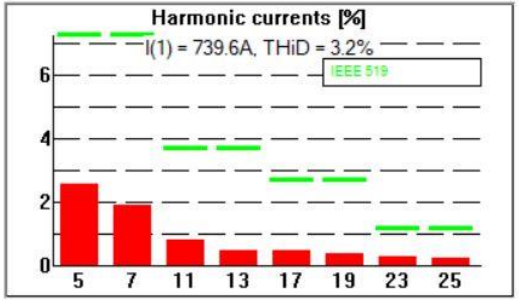
Do not use mitigation equipment if not needed.

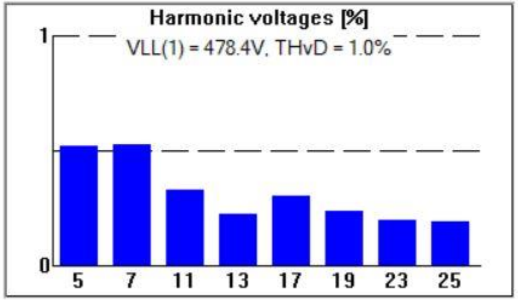
MCT – 31 Harmonics Analysis



Calculation results

RMS Current	739.937 A	Transformer load	81.7 %	Transformer Current Distortion THiD	3.188 %
Displacement power factor (cos Ø)	0.990	Transformer Primary THvD	0.001 %	Transformer Demand Distortion (TDiD)	3.186 %
True power factor	0.990	Transformer Secondary THvD	0.996 %	Short Circuit ratio	23.4
				Harmonic Current required for THiD ~0%	23.565 A





Norm compliances at transformer side

IEEE 519: YES

Mitigation Techniques

Non-VFD Mitigation Techniques

- Oversize hardware components, still abiding to regulations, and allow harmonics to flow.
  - Oversize distribution transformers.
  - Oversize switchgear and distribution cabling to reduce risk of insulation breakdown.
  - Use "K-factor" system transformers to increase heat tolerance.
- Hardware for over-sizing is expensive.
- Harmonic energy is dissipated in the form of heat which is also expensive.
- Harmonics can also be reduced by:
  - Balancing loads on phases.
  - Improving Displacement Power Factor

Mitigation Techniques

Non-VFD Harmonic Solutions Pros and Cons

Non-VFD Solution	Pro	Con
Balance Distortions	No added hardware	Expensive or impractical to move loads
Balance Distortions	Take advantage of system capability	May just be "moving" problem
Oversize	Simple	Low Efficiency
Oversize	Relatively low cost	Limited Solution
Transformer	Relatively low cost	Low Efficiency
Transformer	Adapts to Load Cause	Very limited Solution

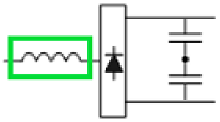
Mitigation Techniques

Drive Based Passive Harmonic Solution Features & Benefits

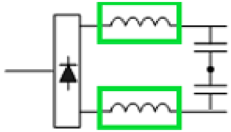
Passive Solution	Feature	Benefit
DC Inductor	1. Reduce THiD~40%	Smooth & Efficient
	2. Built-in top of VFD	Reliable, less heat
Trapping Filter	1. Reduce THiD to 5or 10% 2. Power match Danfoss VFD	Smooth & Efficient Easy to install
System Trapping Filter	1. Reduce THiD <5% 2. Small system solution	Smooth & Efficient Space saving
Multi-Pulse	1. 12P=9-15% THiD 2. Very robust	Smooth & Efficient Reliable, durable

Input Line Reactors or DC Links

AC & DC Inductors



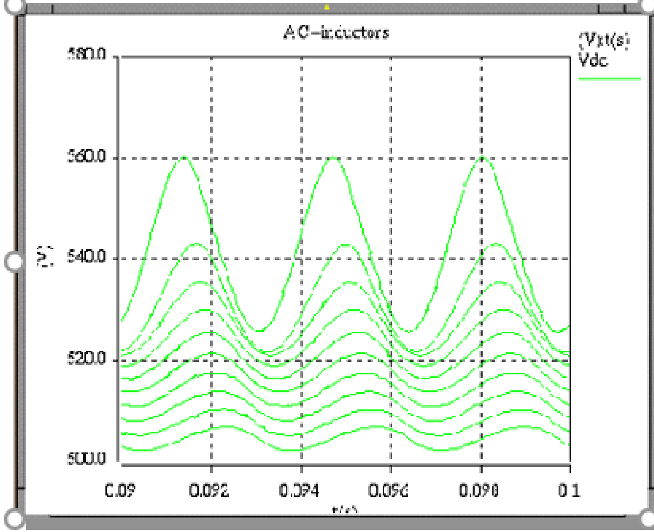
AC-Inductors

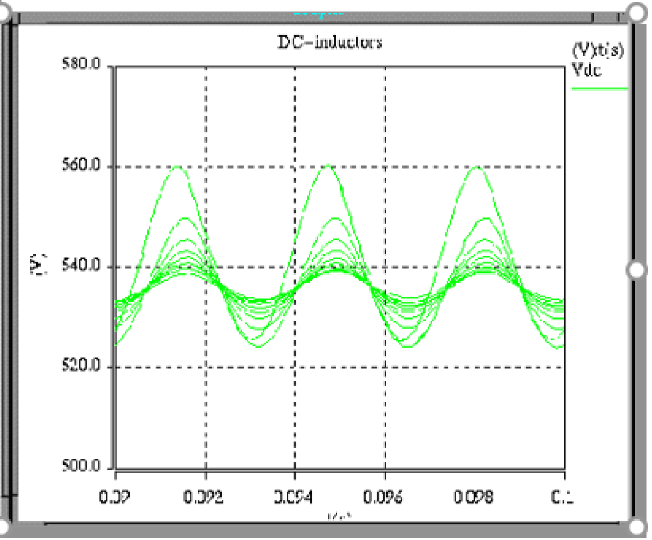


DC-Inductors

- DC-Inductors are typically built-in as standard.
- Overlapping of magnetic fields in the inductor reduces distortion.
- Offers moderate mitigation performance.
- Great RMS current reduction.
- Practical / Easy production.
- Cost efficient.

AC vs DC Impedance

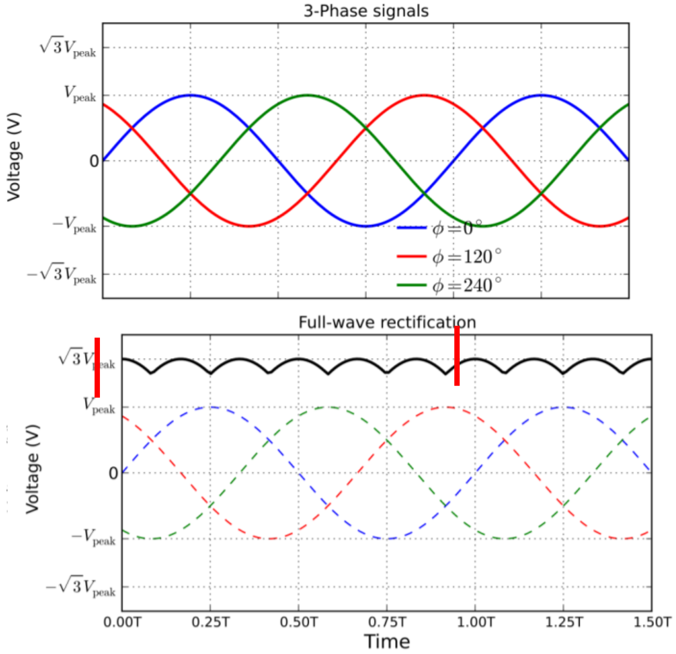




- As AC impedance increases on the AC side of the VFD, the DC bus voltage decreases
- As DC impedance increases on the DC bus, the voltage becomes more stable

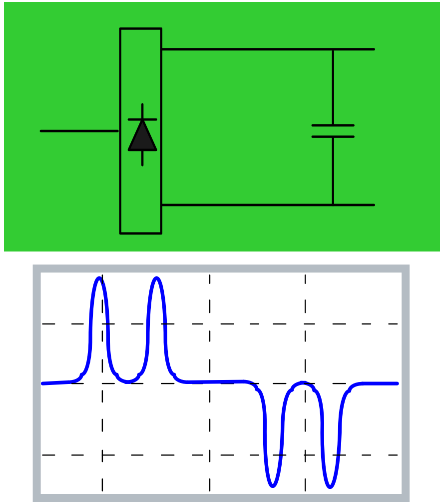
6-Pulse rectifier

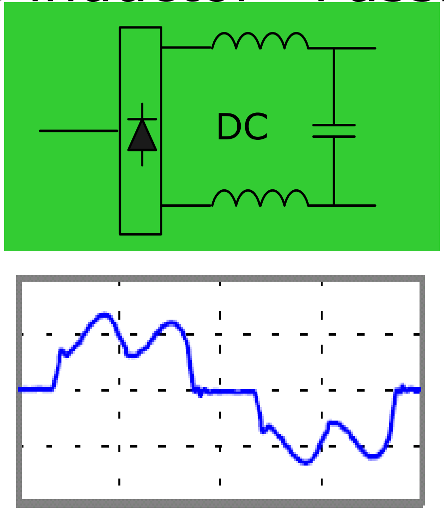
- When we convert 3 phase AC to DC, we get a DC waveform with AC content or AC ripple
- This gives us "6 Pulses" per cycle

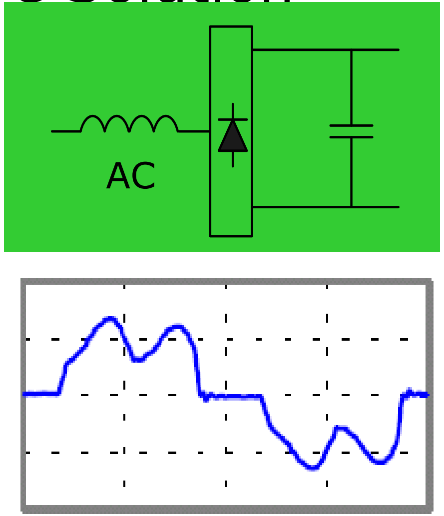


Six-pulse rectifier

-with AC or DC inductor—Passive Solution







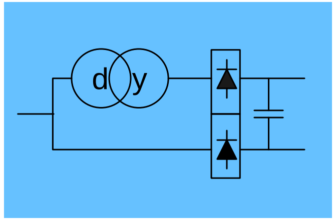
<u>HARMONIC CURRENT</u>
Fund. 38.57 A
THiD 104.52%
RMS current
55.79 A

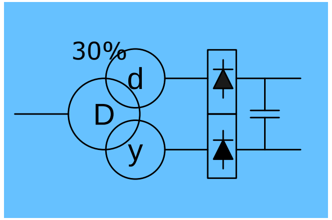
<u>HARMONIC CURRENT</u>
Fund. 36.22 A
THiD 42.51%
RMS current
39.47 A

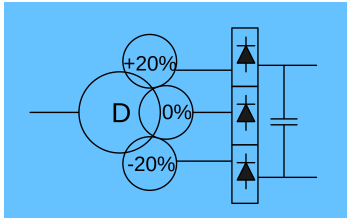
<u>HARMONIC CURRENT</u>
Fund. 36.84 A
THiD
43.84%
RMS current 40.22 A

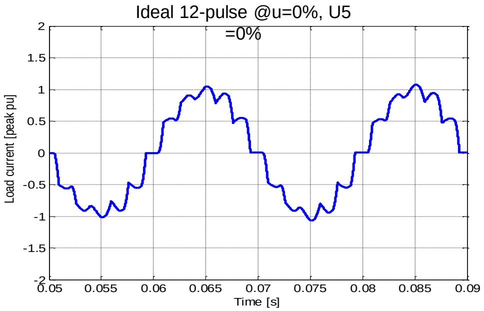
Multi-pulse rectifiers—Passive solution

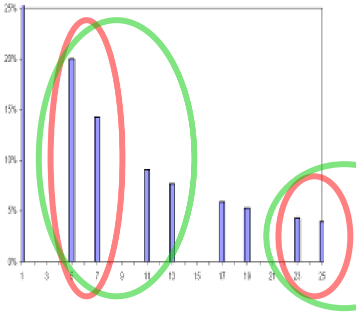
Many different types available. Autotransformers are the cheapest solution

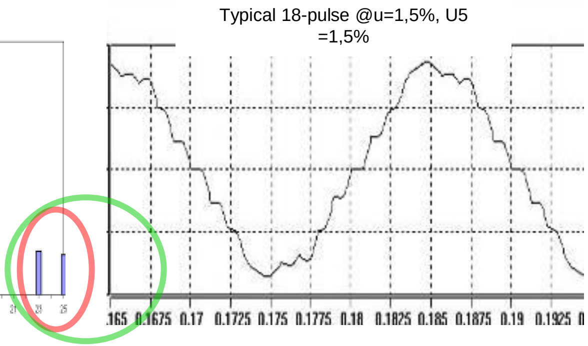












HARMONIC CURRENT ANALYSIS

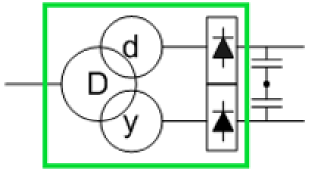
Fund. Current	36.11 A
THiD	10.68%
RMS current	36.32 A

HARMONIC CURRENT ANALYSIS

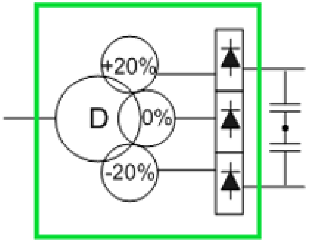
Fund. Current	36.05 A
THiD	8.9% (3-5% ideal)
RMS current	36.28 A

18 Pulse Solutions

12 & 18 Pulse Rectifiers



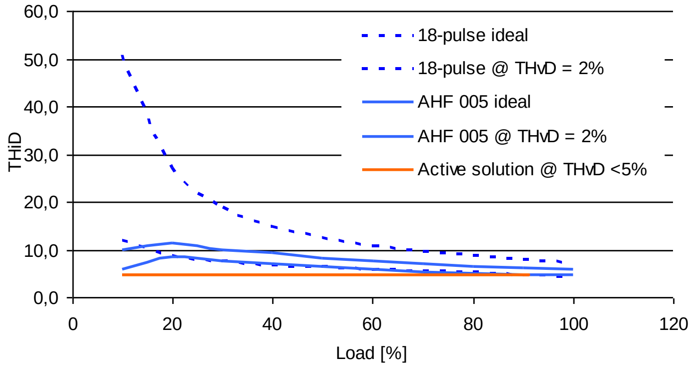
12-pulse rectifier

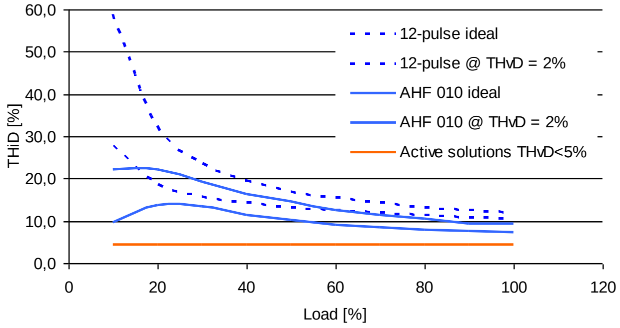


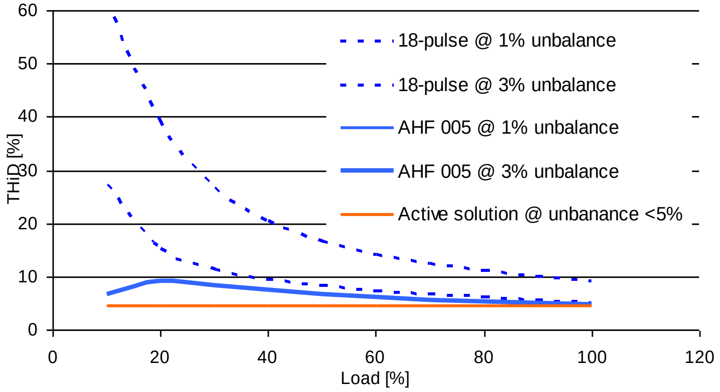
18-pulse rectifier

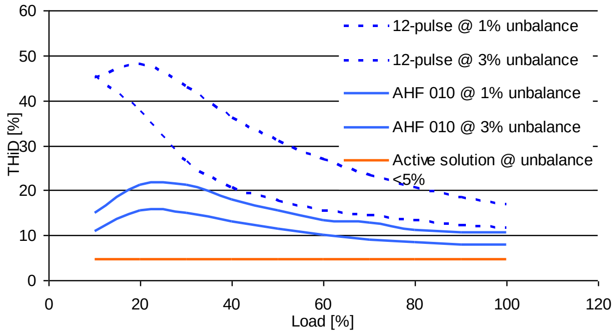
- Well-known technology.
- The power coming into the rectifier sections is phase shifted by a special transformer to cause cancellation of harmonics.
- Offers fair mitigation performance
- Dependent on high load and grid stability
- Optimal for step-down / step-up solutions
- Robust

Harmonic Performance

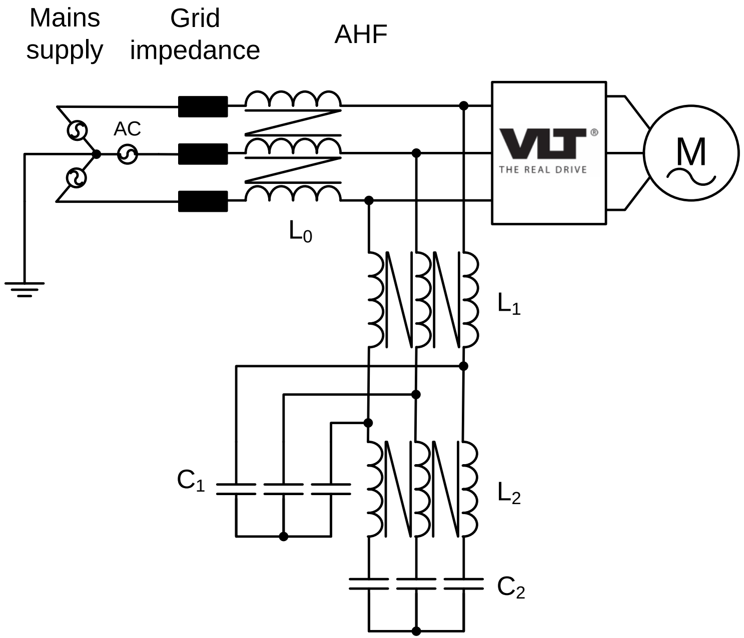








Passive Harmonic Filtering

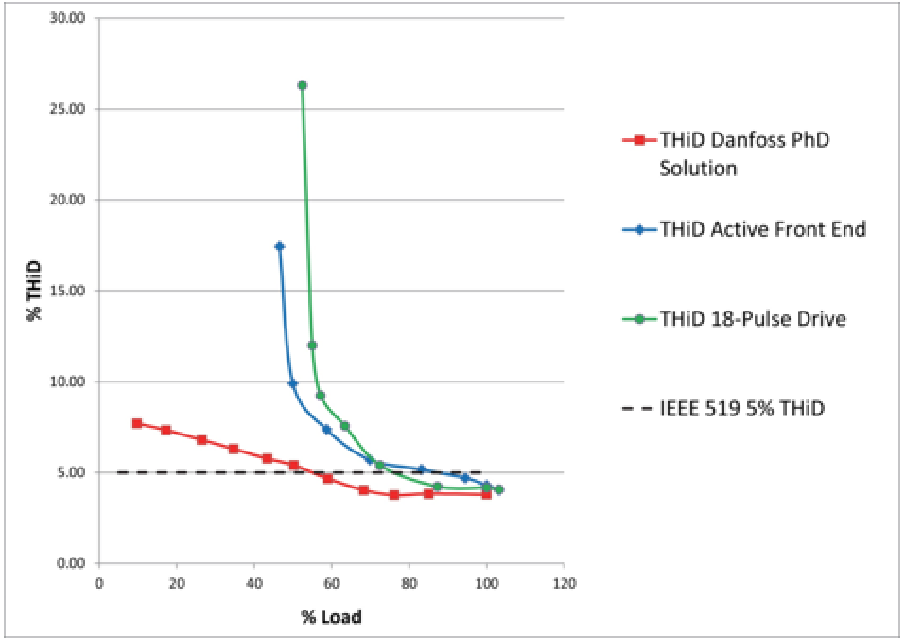


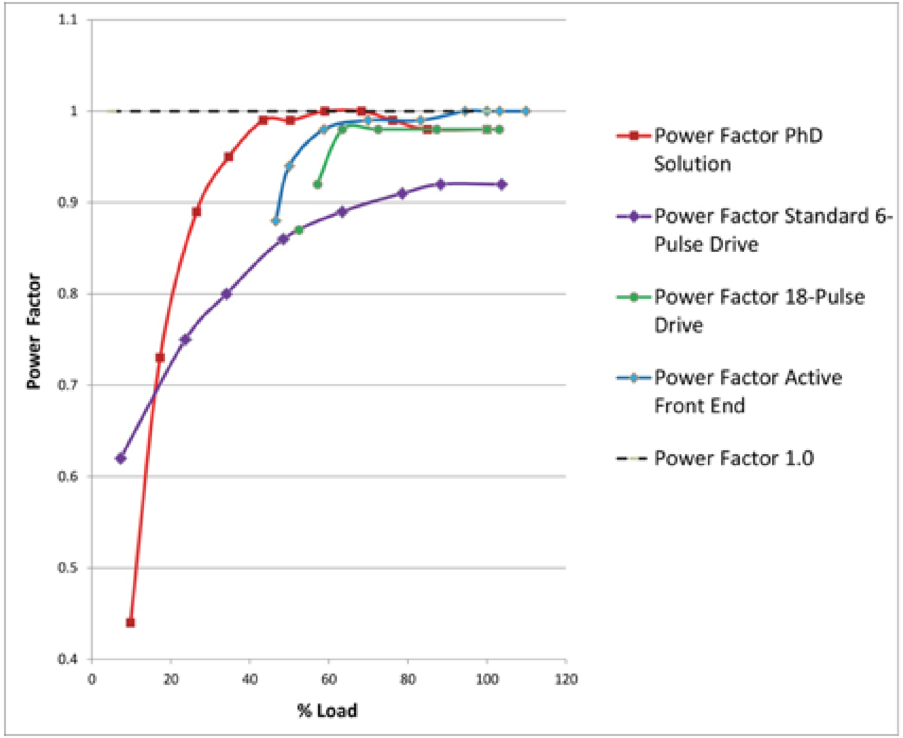
- Simple solution
  - 3 wires in & out
- Several manufacturers
- Off the shelf design
- Retrofitable
- Typically 2 options
  - 10% THiD
  - 5% THiD

PHD Passive Panel solution

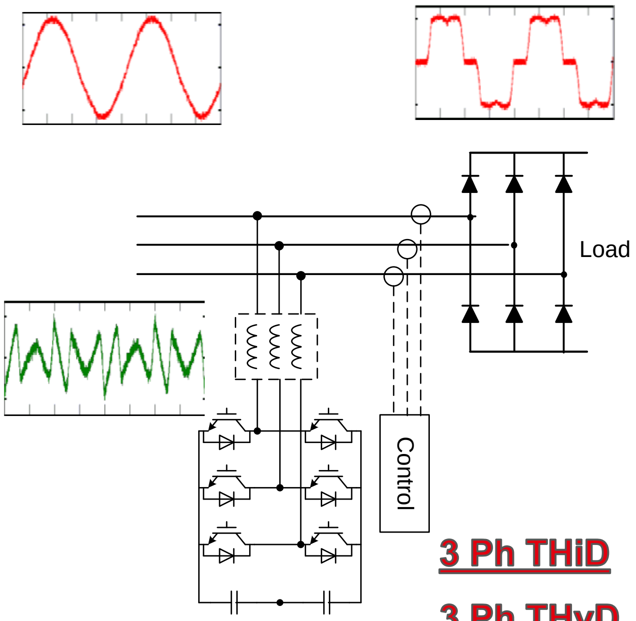
- Exceeds IEEE-519 5% requirements at full load
- Exceeds IEEE-519 5% requirements to almost 50% load
- Best overall performance achieving THD levels to almost 3%
- High overall system efficiency (typically 98%)
- Lower heat dissipation due to higher efficiencies
- Utilizes all standard components
- Robust
- Generally small size
- If the filter fails, the drive still operates
- Excels other harmonic mitigation techniques with imbalanced line applications.
- Now offered as a 3-wire in, 3-wire out standard panel solution

PHD Passive Panel Performance





Active Filters and Low Harmonic Drives



3 Ph THiD

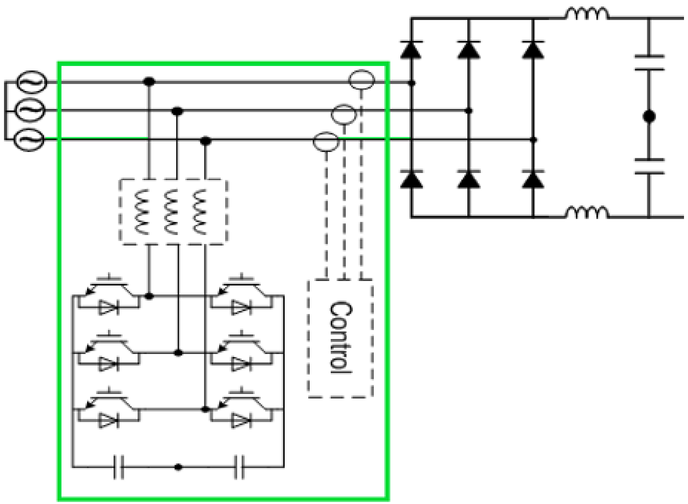
3 Ph THvD

Current waveform

- Induces “Anti-harmonics”
- Sized to allow some distortion, but is an engineered solution
- Preconfigured drive packages
- Can be a system solution
  - sized for total THiD
  - can increase PF
- If filter fails, drives still operate

Active Harmonic Filters

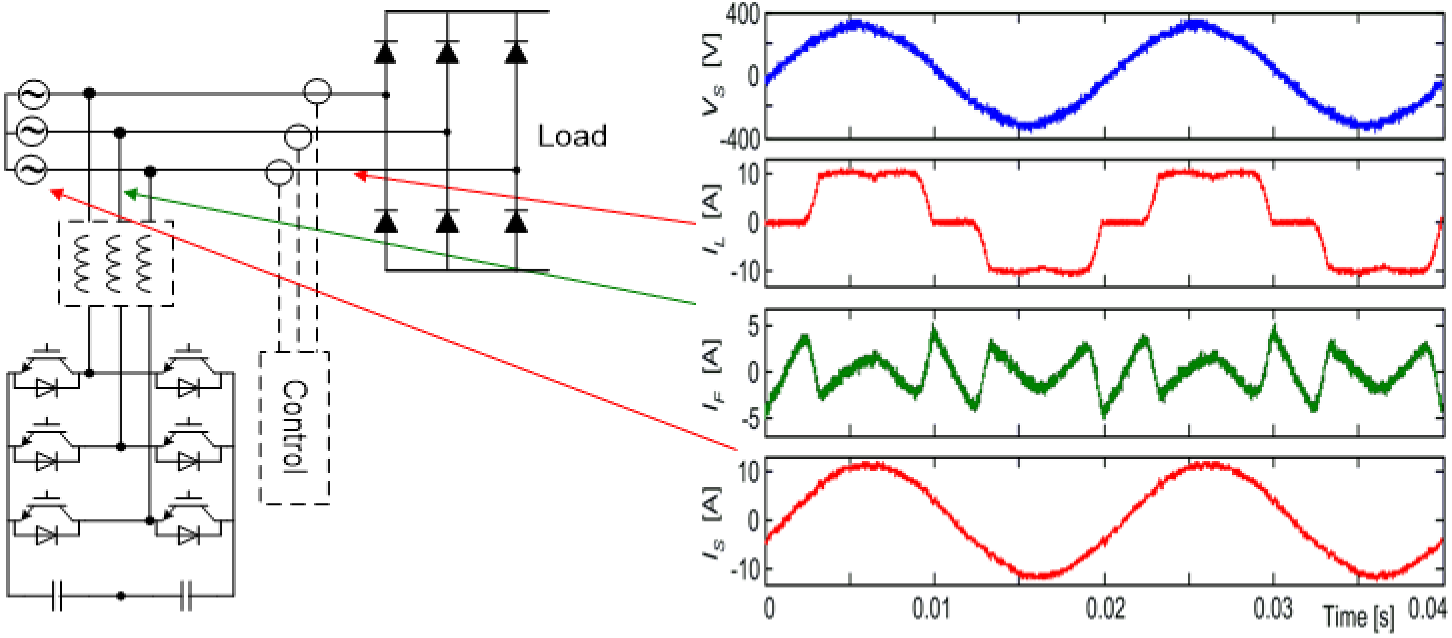
Active Filters



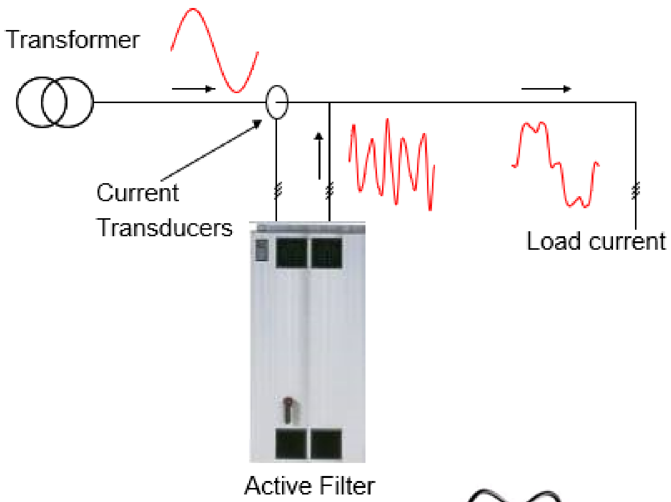
Active Filter

- Offers high performance mitigation
- The filter cancels the distortion by sensing it and inserting an equal signal with the opposite phase.
- Tolerant with load and grid imbalances
- More Expensive than passive solutions
- Customer / System level PCC installation possible. Group compensation, power factor correction and load balance correction)
- Danfoss Active Filter Products:
  - Active Filter – AAF
  - Low Harmonic Drive - LHD

Active Harmonic Filters



Active Filter Principles



Active filter principles

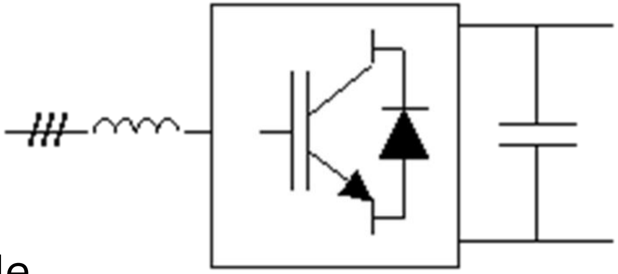
An Active Filter is

- a paralleled installed device,
- that measures the distortion,
- and compensates for the unwanted currents,
- by actively imposing signals in counter phase to the unwanted current signals.

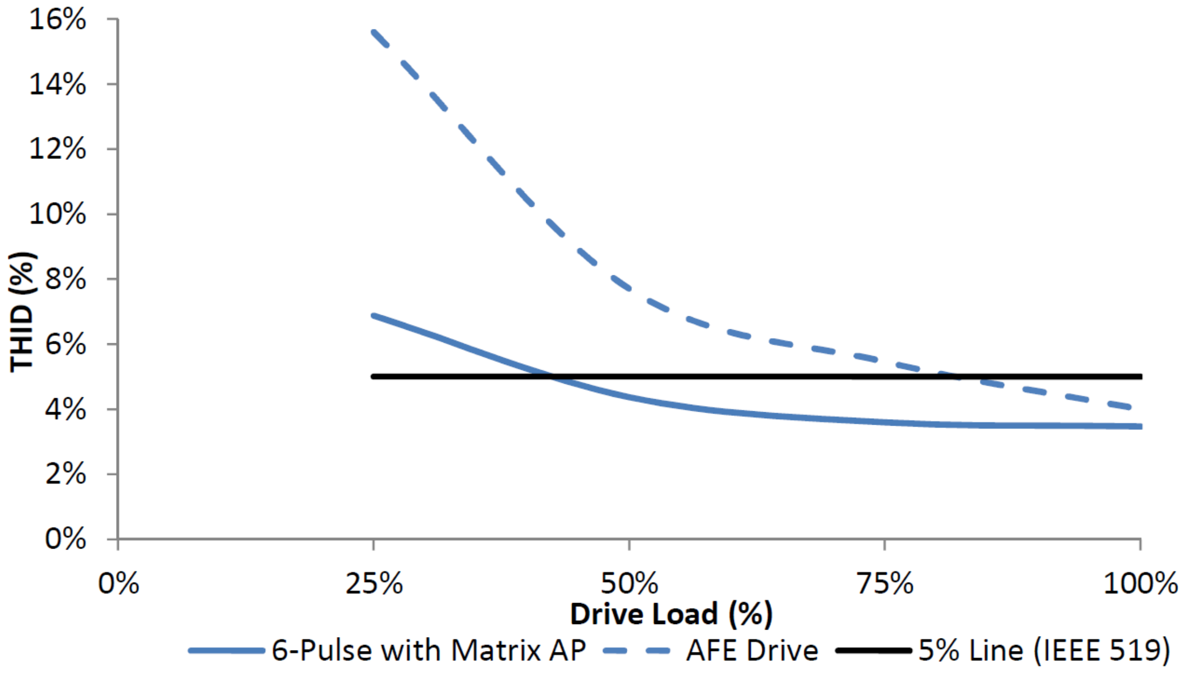
The working principle can be compared to a set of noise cancelling headphones.

Active Front End - REGENERATIVE

- Pulls voltage more uniformly to maintain the DC bus based on actual load by controlling the front end to eliminate generation of harmonics
  - final cleanup is in the input LCL
- Boosts DC voltage which can effect dv/dt to motors
- Typically used for regenerative applications
- If IGBT’s fail, drive is inoperable
- HI FREQ HARMONICS potentially an issue
- Higher losses (heat) due to twice the IGBT’s….more complex



6 Pulse MTE vs AFE Regen drive



- Full load performance good
- Passive filter shows better performance at reduced loads
- Ref: MTE Whitepaper December 2012

Matrix Filter Functionality

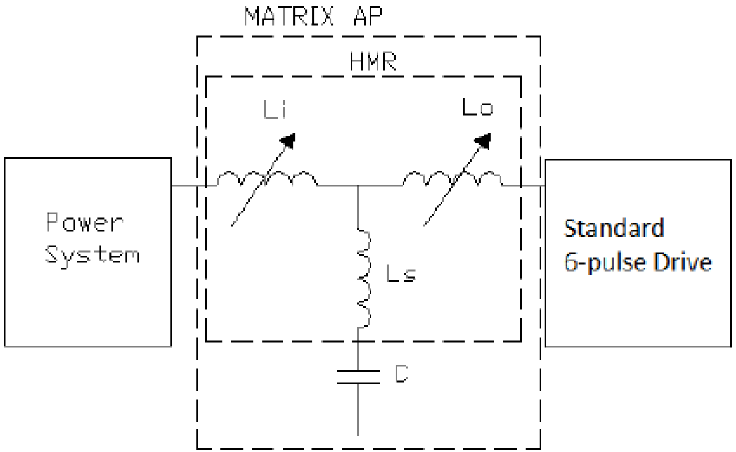


Fig.6. Matrix AP filter diagram

Fig. 7. MTE MAPP0044D adaptive passive filter

Ls and C are tuned to near the dominant 5th harmonic generated by 6-pulse drives. Li prevents the filter from importing the 5th harmonic from other sources and overloading the filter. The series combination of Li, Ls and C set the tuning frequency to the power system well below the 5th harmonic. Lo reduces the voltage boost due to the capacitors. Both Li and Lo also reduce the THID by adding wideband line filtering impedance.

REF: MTE White paper December 2012
Todd Shudarek, Principal Engineer

Matrix Filter Losses

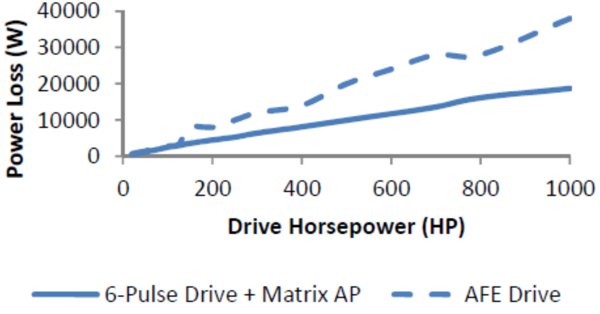
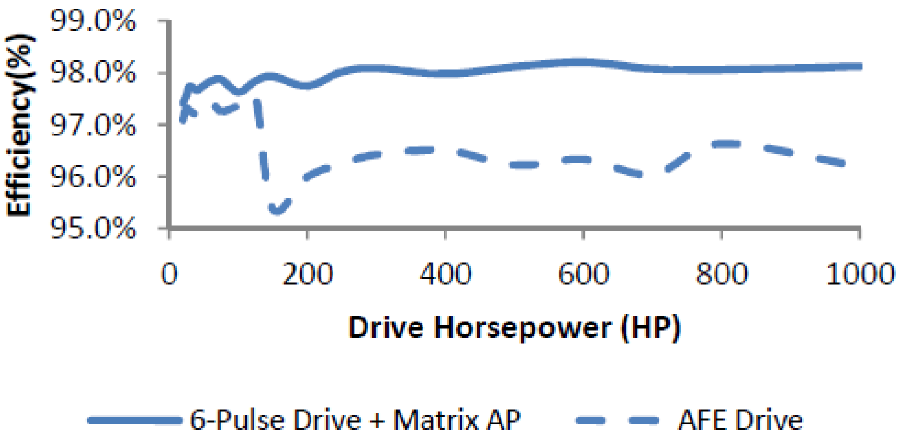


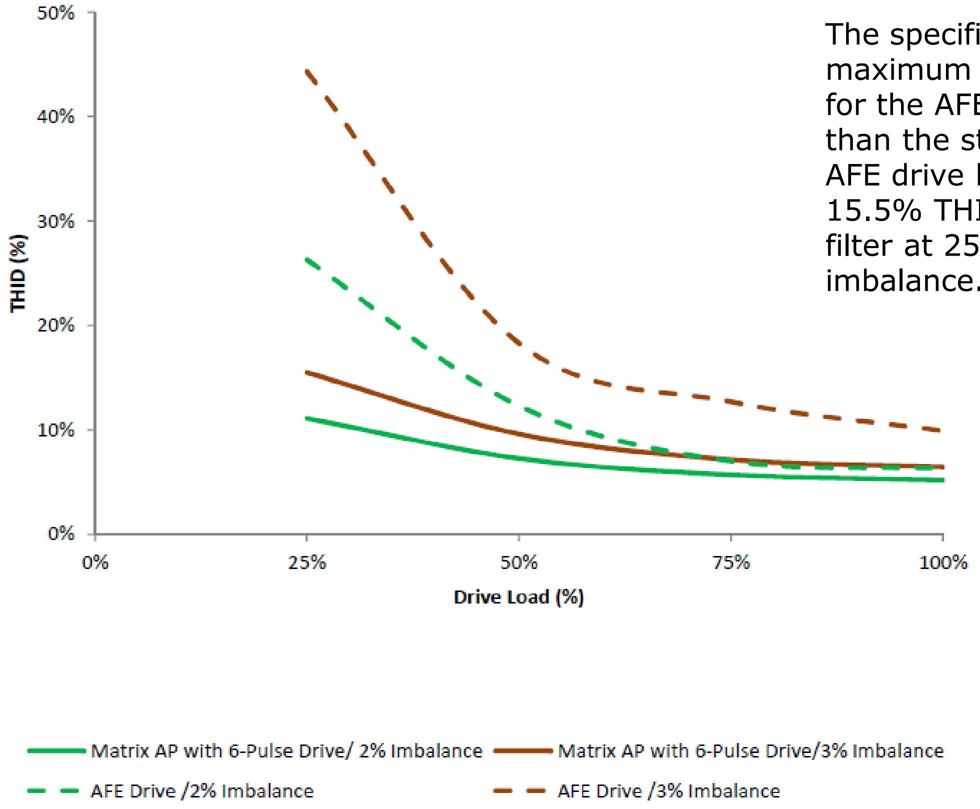
Fig. 8. Power loss comparison

- Losses of low HP AFE Regen drives vs. 6 Pulse with Matrix filter ~ 15%
- Losses nearly double as HP increases

- Efficiency of typical AFE Regen drive VS 6 Pulse with Matrix AP
- Most AFE Regen drives are at least 1.5% LESS efficient that 6 Pulse with Matrix Filter



Total Harmonics Performance



The specification for the AFE drive allowed for a maximum 3% voltage imbalance. At reduced load, the THID for the AFE drive was considerably worse than the standard 6-pulse drive with a Matrix AP filter. The AFE drive had 44.3% THID compared to 15.5% THID for the standard 6-pulse drive with a Matrix AP filter at 25% drive load and 3% voltage imbalance.

REF: MTE whitepaper by Todd Shudarek, Principal Engineer