Active Harmonic Mitigation – What the Manufacturers Don't Tell You!

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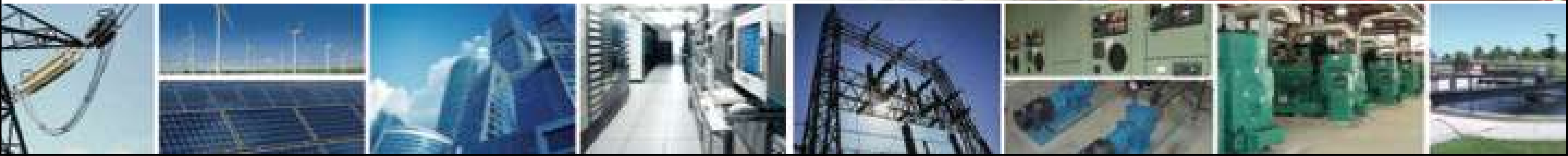
Mirus Is Harmonic Mitigation

MIRUS International Inc. designs and develops world-class power quality improvement products for mission critical operations

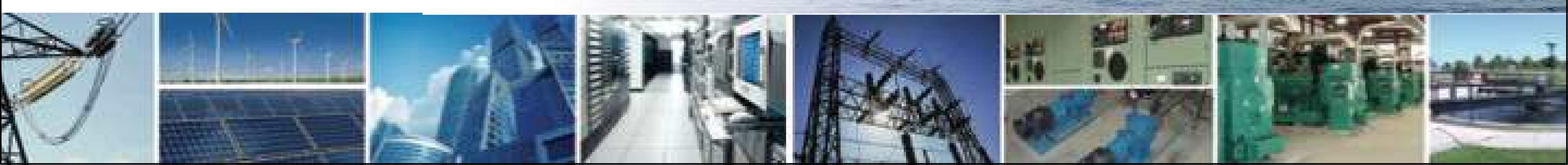
Our solutions:

- Minimize disruption to the power supply
- Improve reliability
- Adhere to the strictest regulatory requirements
- Save energy and reduce operating costs



Harmonics are a Massive Pain for Oil & Gas, Marine, HVAC, Water/Wastewater, Data Centers, Industrial and Commercial Facilities

- Harmonic disturbances damage expensive equipment, cause failure, and add expense via maintenance, replacement, energy consumption, etc.
- They need a solution to mitigate disruptions, high costs and associated risks.
- A proactive approach helps solve harmonic issues and prevent future problems.



Example of an Active Harmonic Mitigation Solution gone Wrong

Detroit Brazil Built Oil Rig Supply Vessels

- 8 Oil Rig Supply Vessels originally equipped with Active Front-end (AFE) Drives for propulsion
- AFE Drives created high frequency distortion that caused their own operational issues
- Ultimately replaced by a competitor's propulsion package equipped with passive Wide Spectrum Harmonic Filters (WSHF)
  - 3500 HP WSHF with water cooled reactors

Replaced with a 6-P Drive with Passive Harmonic Filter Propulsion System

Solution:

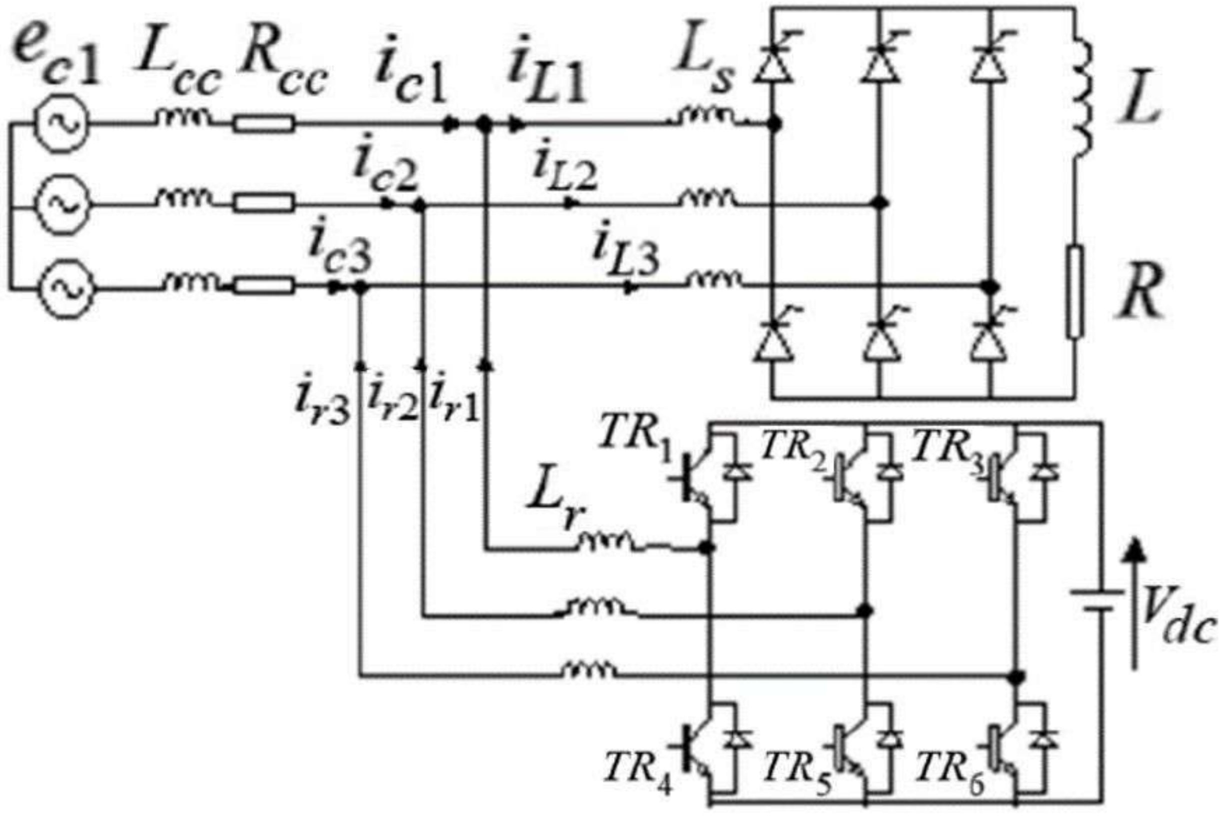
Petrobras removed all the AFE (Active Front End) Drives and replaced with 3500HP Liquid-Cooled WSHF and 6-pulse VSDs.

Outcome:

Power quality met ABS marine standards and IEEE519 recommended practices. The combination of a simple liquid cooled 6-Pulse variable frequency drive and a liquid cooled passive harmonic filter now provides the vessel owner with the most compact and most efficient harmonic free diesel electric propulsion drive available today.

Another Active Harmonic Mitigation Solution gone Wrong

Parallel Active Harmonic Filter (AHF) was used to cancel harmonic currents generated by the rectifiers on a Solar Inverter Test line



Challenge:

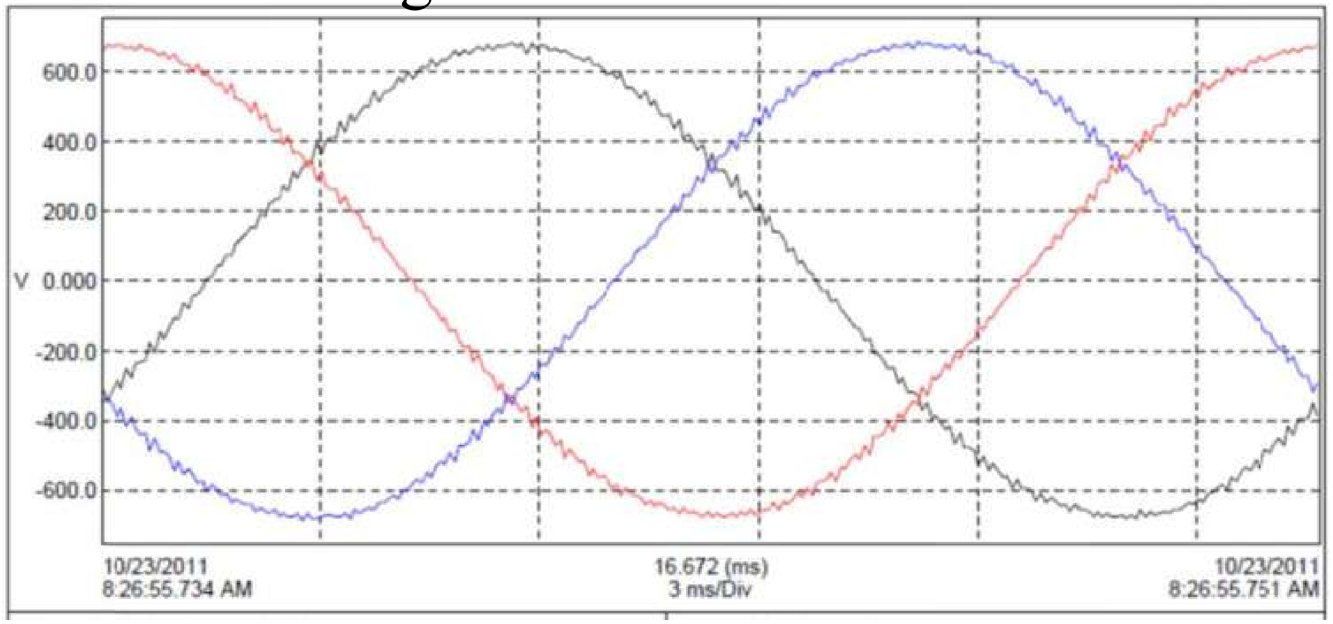
- Solar Equipment Mfr was having 48 Vdc power supply failures in a Photovoltaic Panel Tester
- These failures began to occur after a 450A AHF was installed but they were unaware of this

Active Harmonic Filter at Solar Inverter Manufacturer

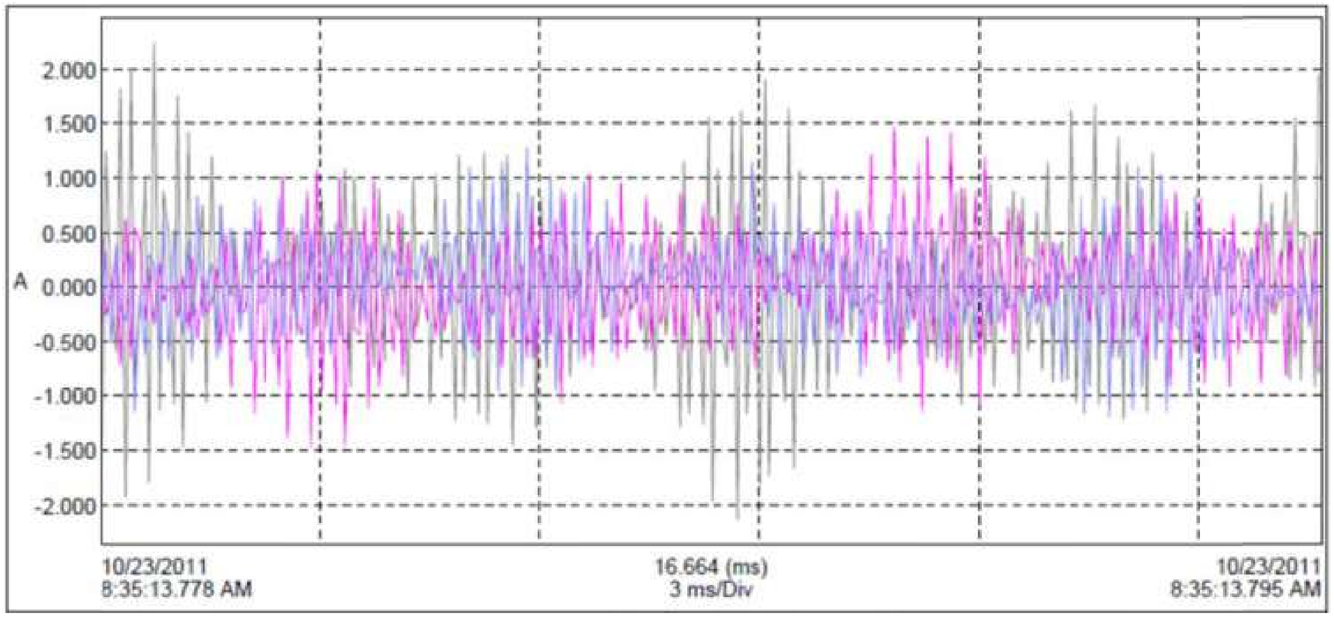
Challenge:

- AHF IGBT harmonics were creating a high frequency ripple on the supply voltage
- 48 Vdc power supply resonated near the 41st harmonic causing it to overheat and fail upon startup

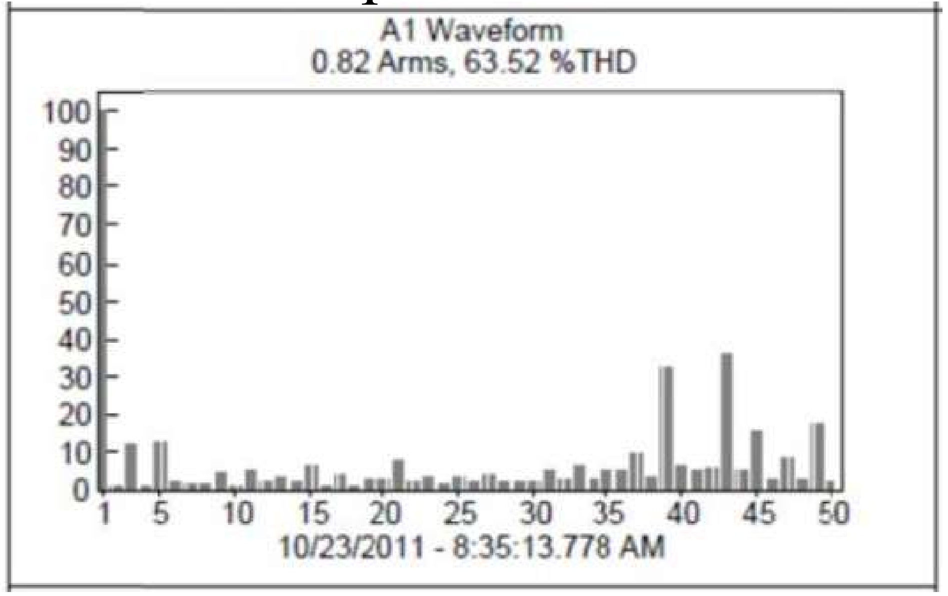
Voltage waveform – VTHD <1%



PS Current waveform at no load



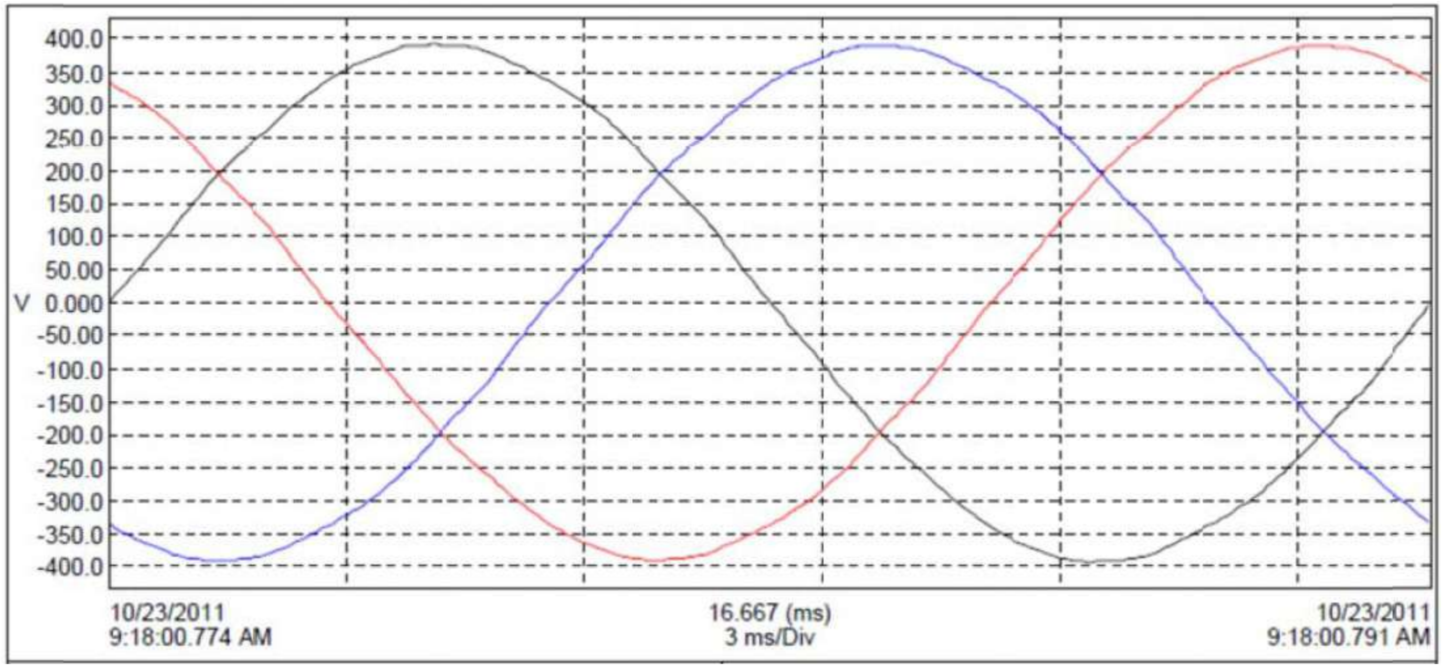
PS Current spectrum at no load

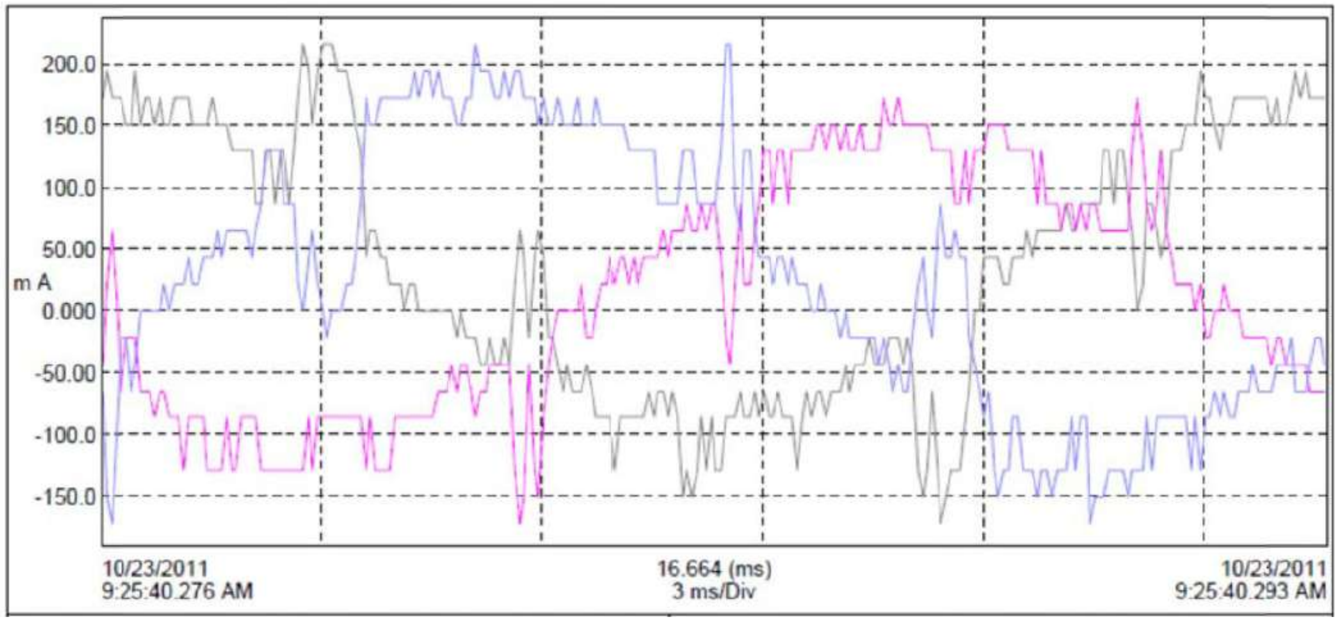


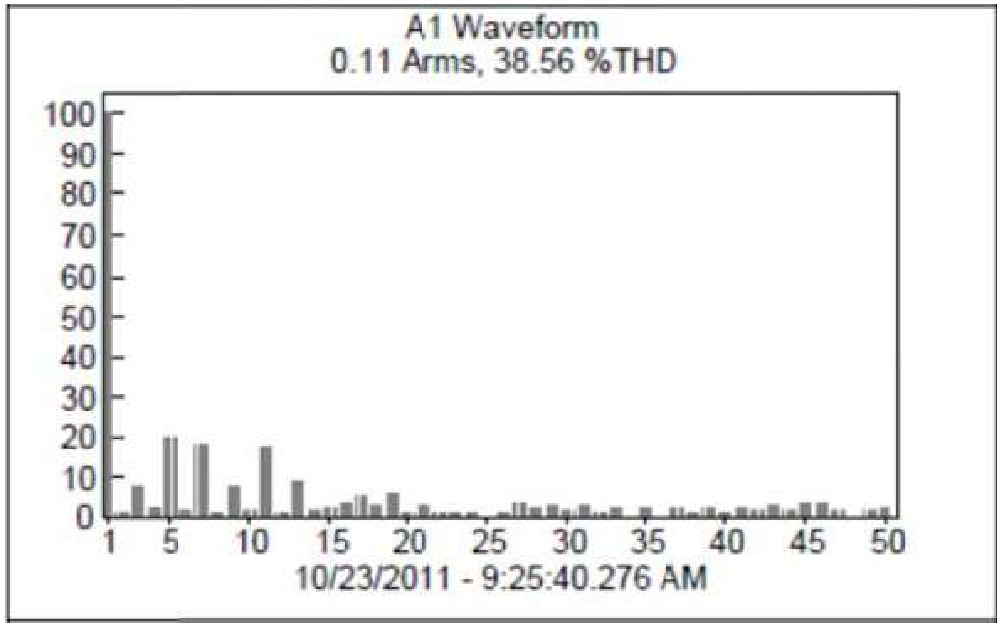
Active Harmonic Filter at Solar Inverter Manufacturer

Solution:

- Permanently turn off AHF







Active Harmonic Filter at iFly Lyon, France Free-fall Simulator

Initial design included two parallel Active Harmonic Filters (AHFs) to cancel harmonic currents generated by the large variable speed drive fan systems

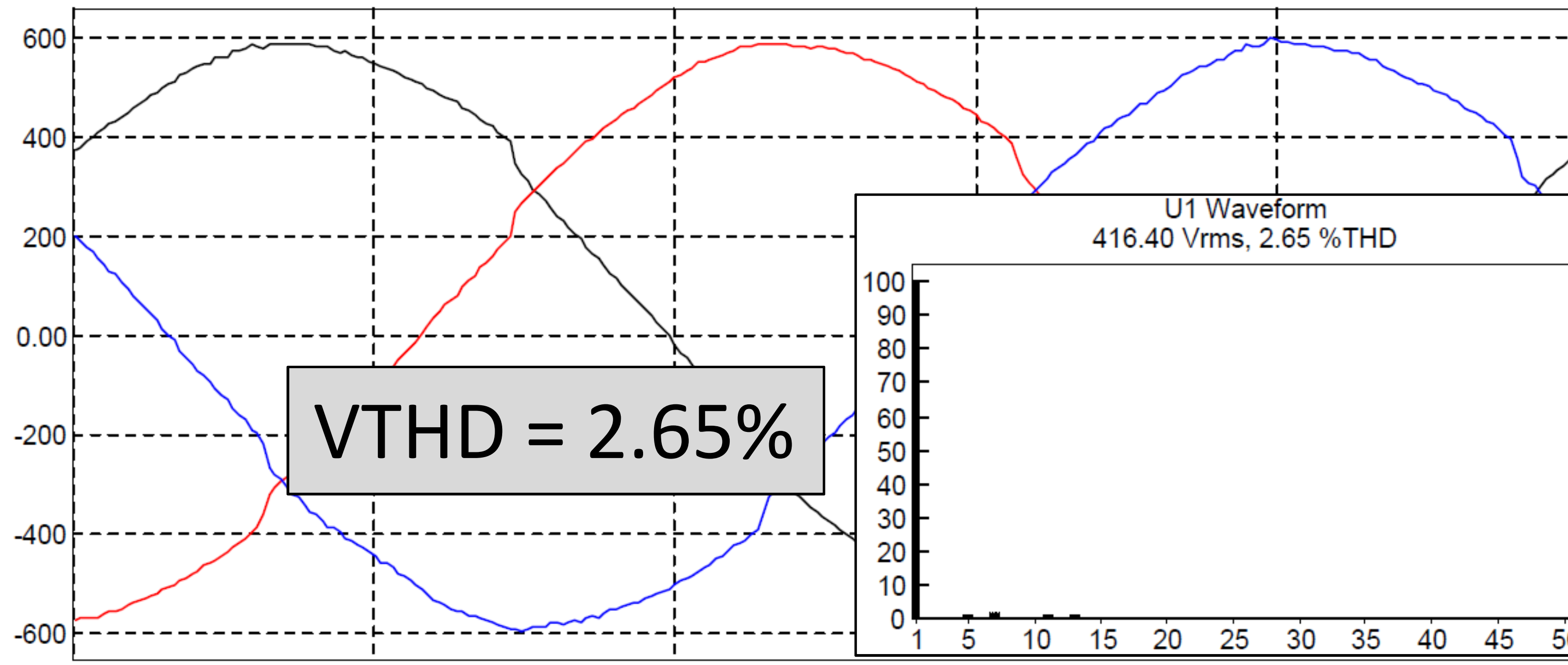
Challenge:

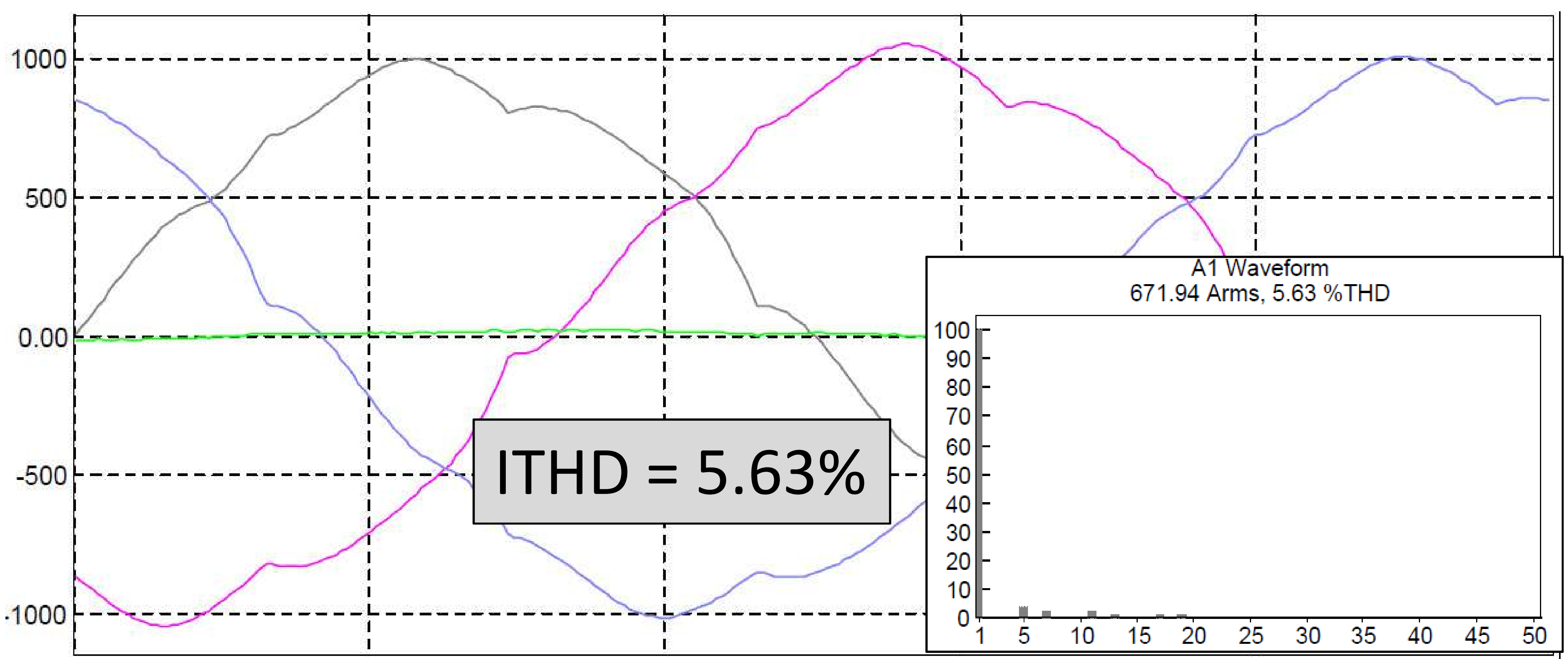
- AHFs had been disconnected because the fan systems would not operate properly with them in the circuit
- Therefore, the required harmonic limits were not being met

Active Harmonic Filter at iFly Lyon, France Free-fall Simulator

Solution:

- AHFs replaced by two 700HP Wide Spectrum Harmonic Filters
- Harmonic limits were easily met





6-Pulse VSD and Harmonics

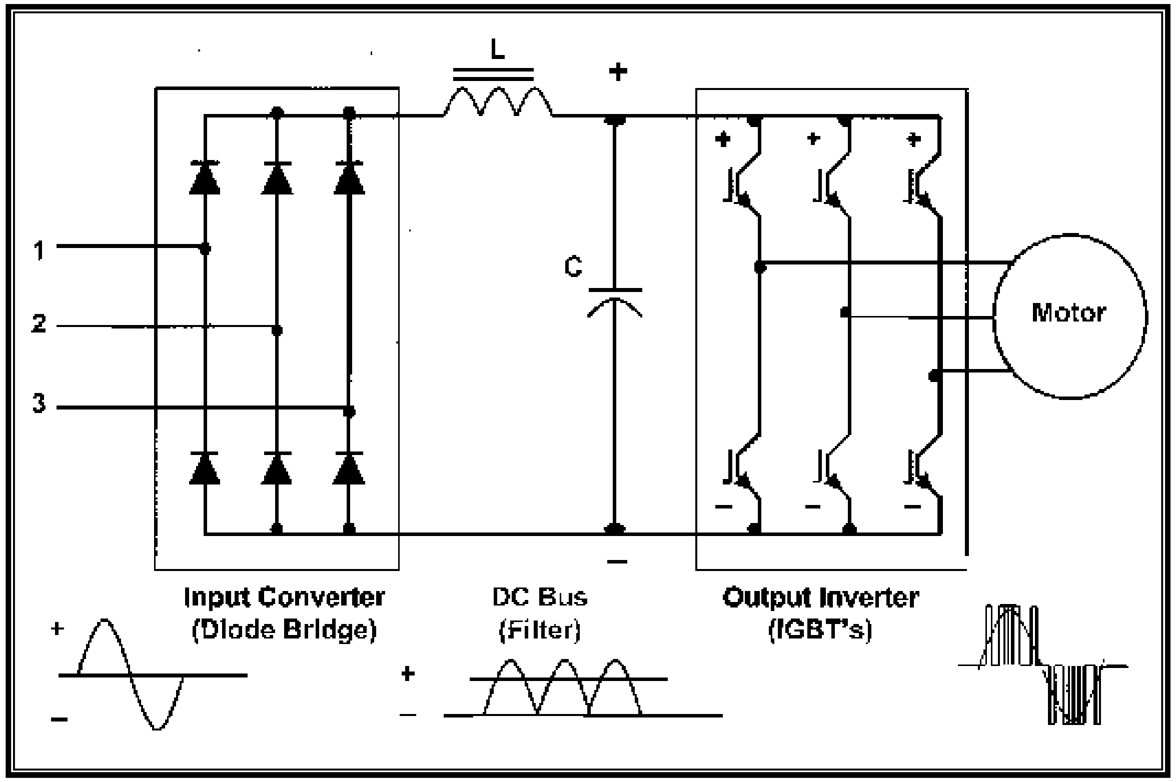
For simple diode bridge rectifiers:

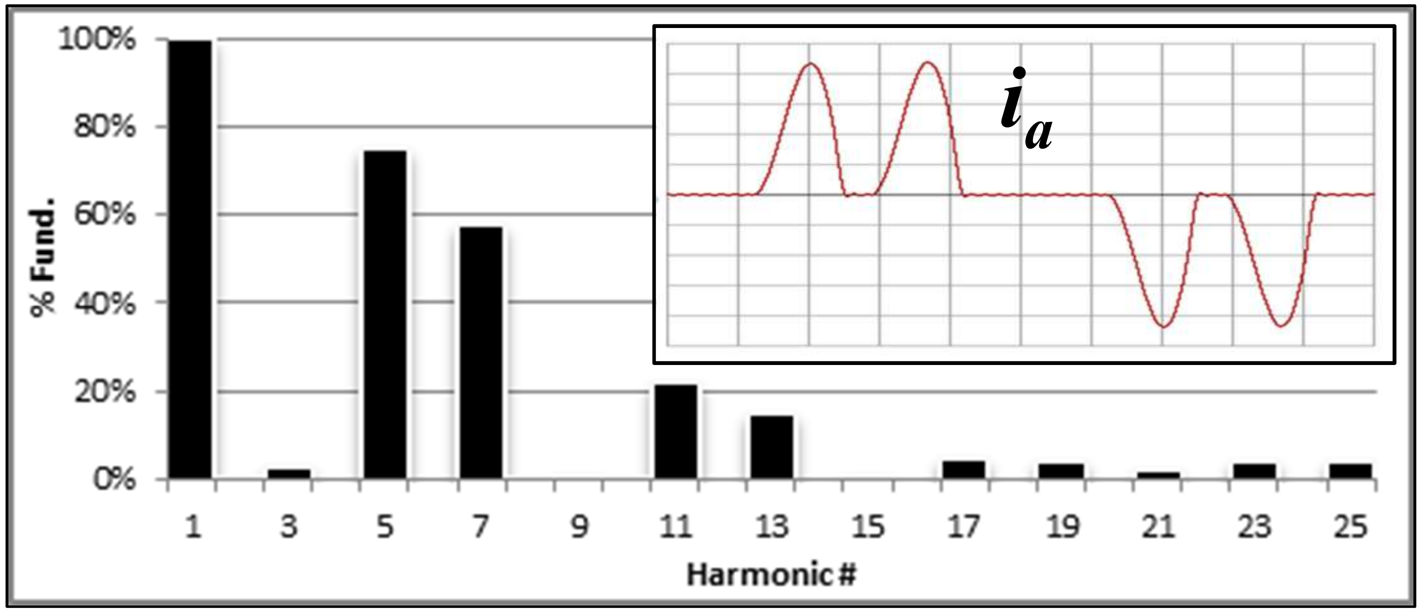
$$h = np \pm 1$$

$$I_h = \frac{I}{h}$$

h = harmonic number
p = # of pulses in rectification scheme
n = any integer (1, 2, 3, etc.)
I_h = magnitude of harmonic current
(addition of DC bus cap increases I_h)

When,
p = 6
h = -- 5,7,--,11,13,--,17,19...





Current Waveform and Spectrum

Active Front-end (AFE) Drives

Operation:

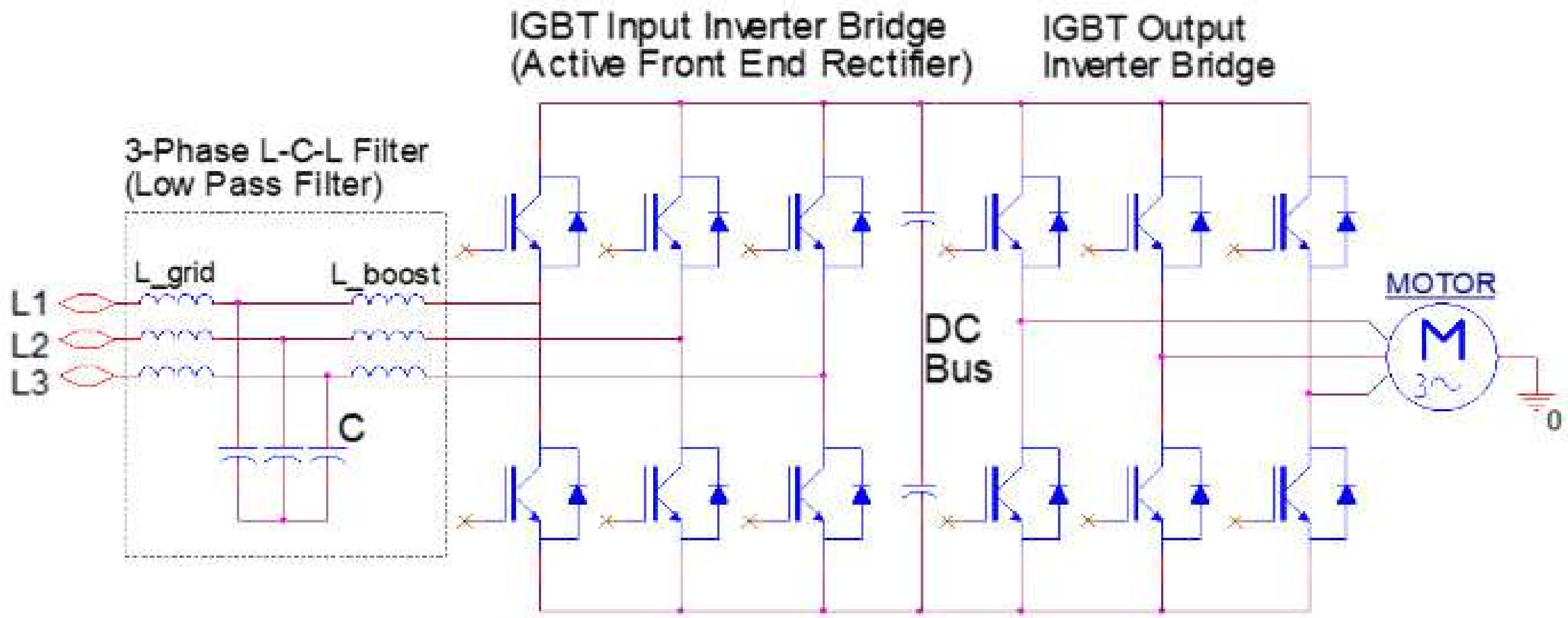
- 6-pulse diode bridge rectifier is replaced by a fully controlled IGBT bridge

Pros:

- Can achieve lowest ITHD but only when measured at harmonics lower than 50th
- Can provide bi-directional power flow

Cons:

- Expensive
- Introduces higher order harmonics and common-mode noise
- Higher EMI radiation
- Much higher losses
- Very complex requiring start-up and service by manufacturer

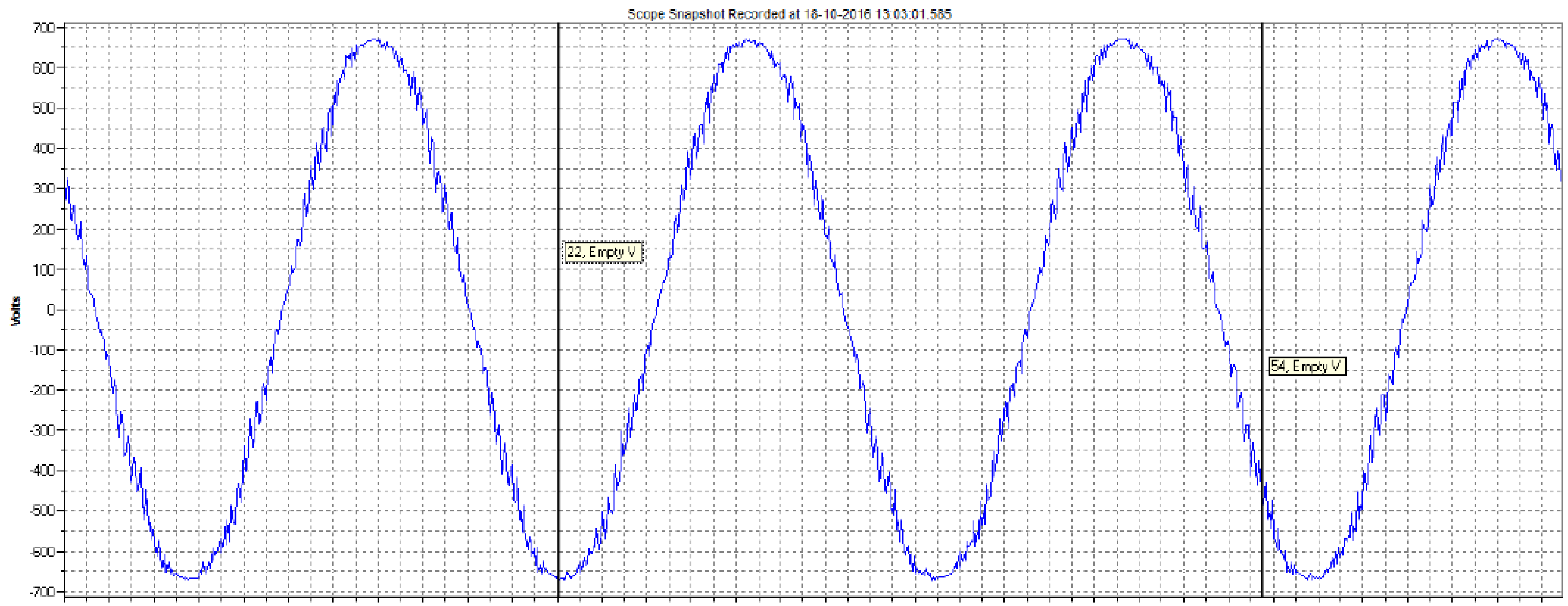


Active Front-end (AFE) Drives on Electrical Submersible Pump

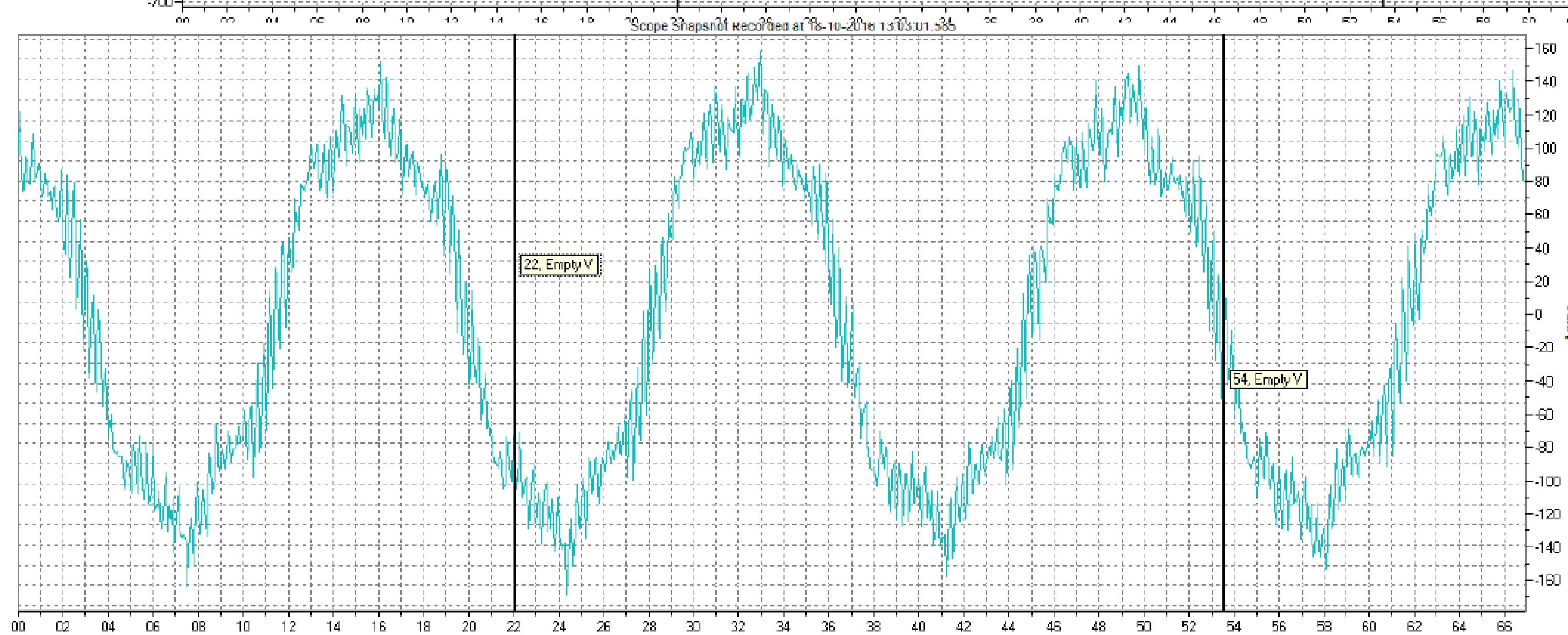
AFE Drive measurements on input to ESP

Switching frequency = 3.6 kHz (60^{th} harmonic)

Voltage Waveform



Current Waveform



Active Front-end (AFE) Drives on Electrical Submersible Pumps

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AFE Drive measurements on input to ESP

Voltage	AN	BN	CN	NG
V RMS	273.8	270.6	275.6	7.5
V PK	419.0	425.0	422.5	24.9
V CF				3.3
% THD				488.7
Freq				
Current				N
A RMS	96.6	86.0	91.6	0.0
A PK	188.9	165.6	165.0	0.0
A CF	2.0	1.9	1.8	1.4

%VTHD	**3.7**	**3.6**	**3.3**
% ITHD	13.8	14.7	14.1

VTHD and ITHD do not include 60th harmonic switching frequency since meter only measured to the 50th

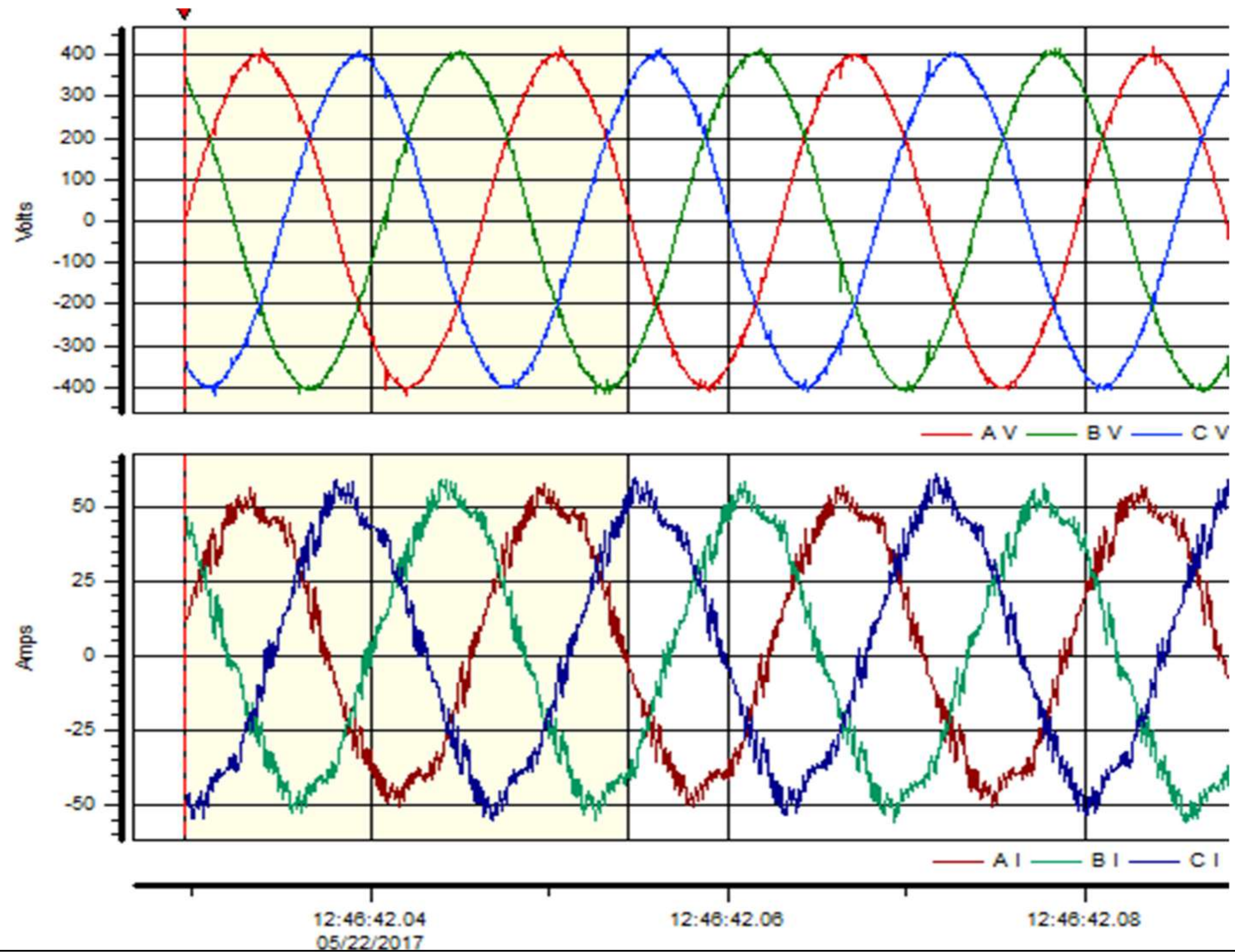
Power	A	B	C	Total
kW	25.484	22.081	24.534	72.100
kVA	26.456	23.269	25.249	75.029
kvar	7.104	7.339	5.967	20.759
PF	0.963	0.949	0.972	0.961
DPF	0.991	0.975	0.996	0.989
	Lag	Lag	Lag	

New AFE Topology with no DC Bus

Voltage and Current Waveforms in ESP Application

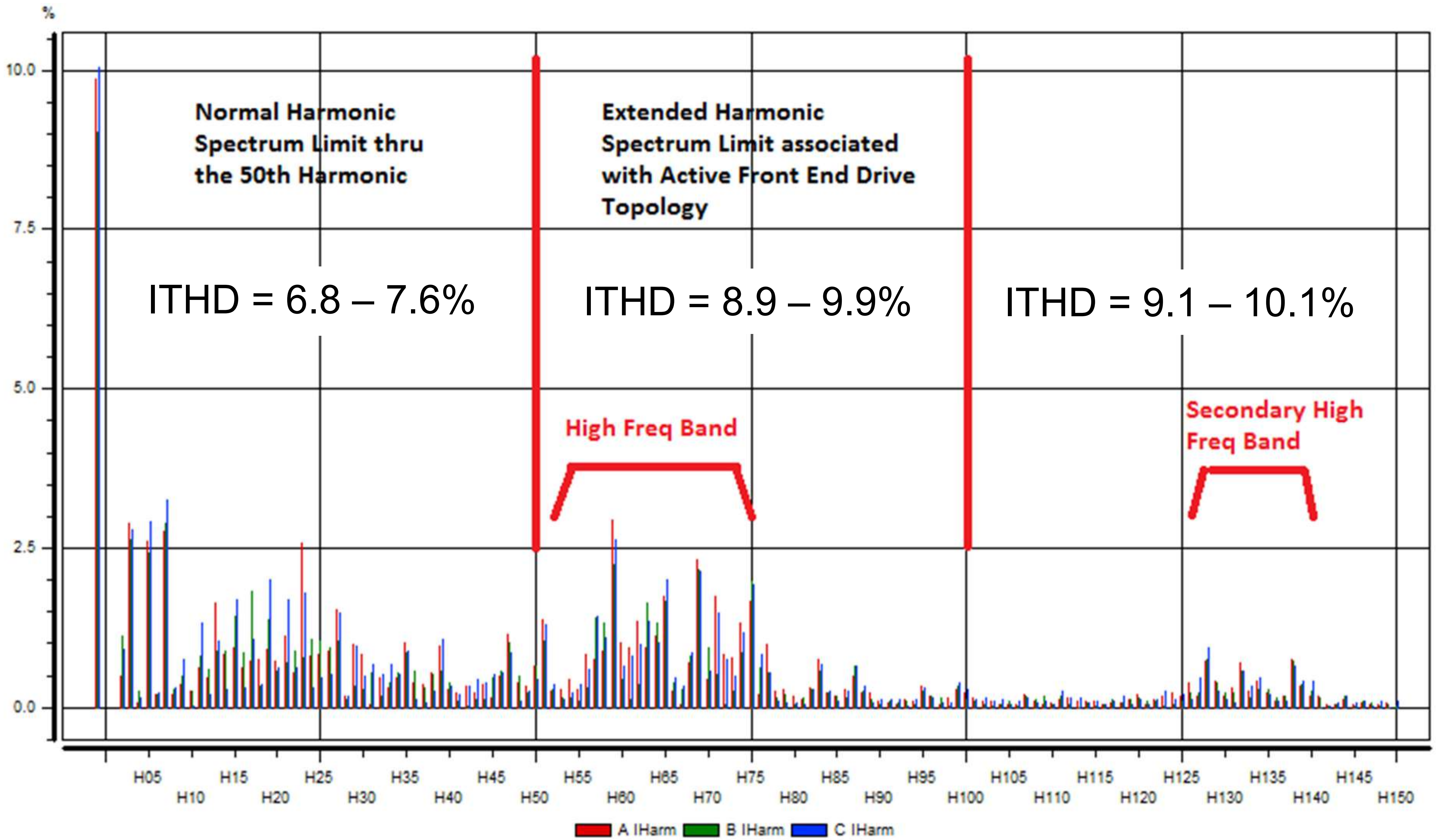
Voltage Waveform

Current Waveform



New AFE Topology with no DC Bus

Input Current Harmonics with IGBT Switching Frequency Contribution



Parallel Active Harmonic Filter

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Operation:

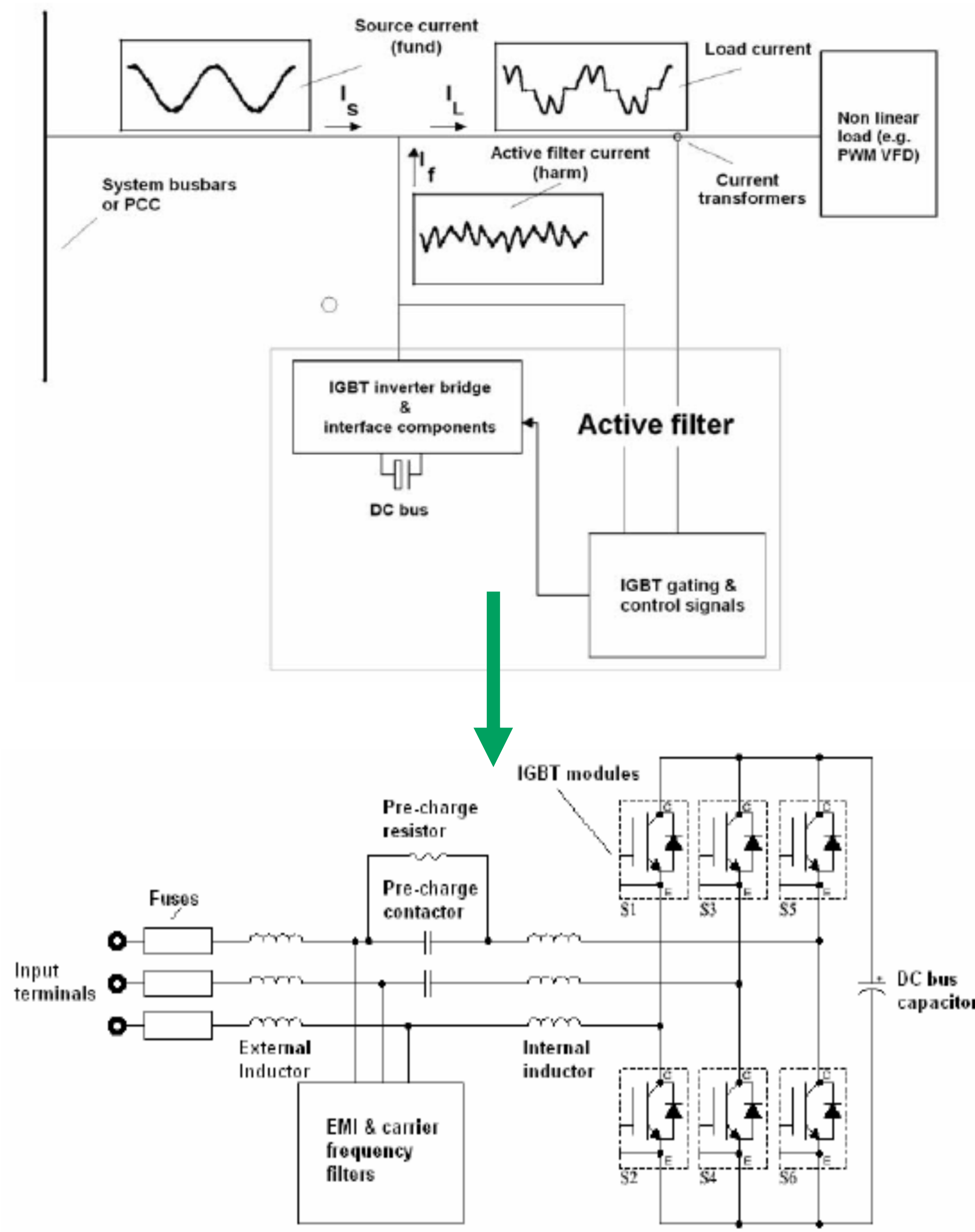
- Distorted current is sampled
- Fast acting IGBT's are used to generate harmonic currents and inject them 180 deg out-of-phase

Pros:

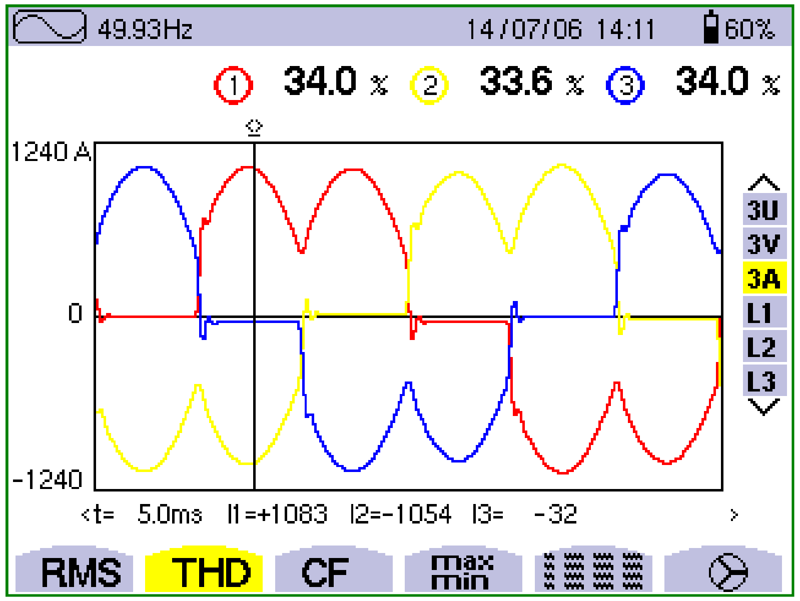
- Sized to harmonic content only
- Relatively easy parallel connection
- Maintains good performance at light loads

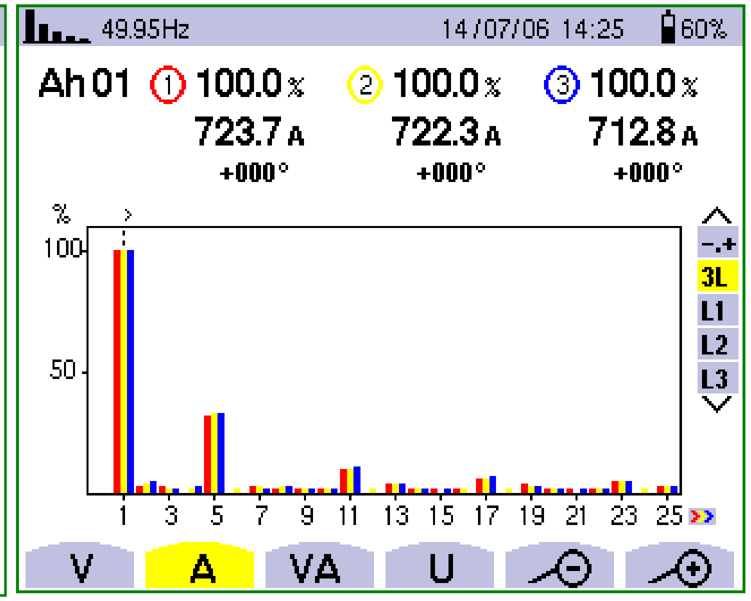
Cons:

- Expensive
- Requires AC or DC reactors on all VSDs
- Introduces higher frequency harmonics
- Susceptible to background voltage THD
- Complexity requires start-up and regular service by manufacturer



Parallel Active Harmonic Filter Application
3 x 800HP DC SCR Drives

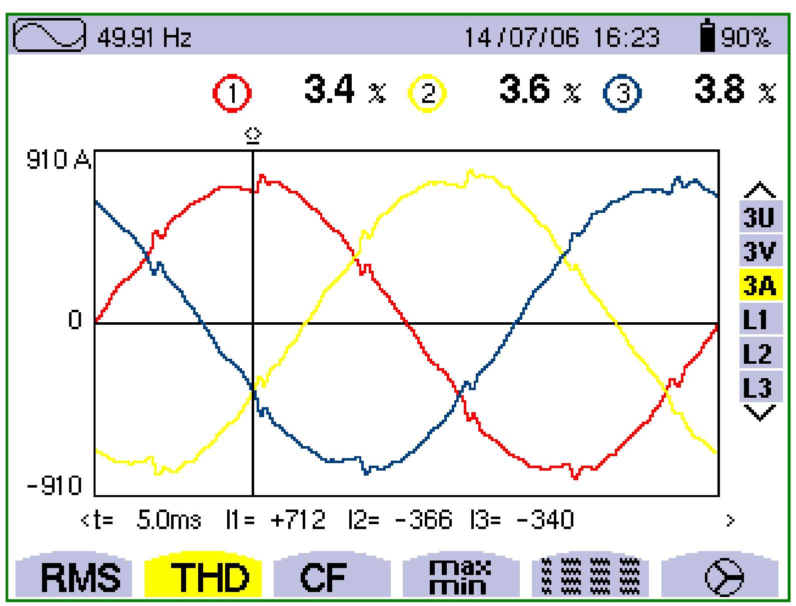


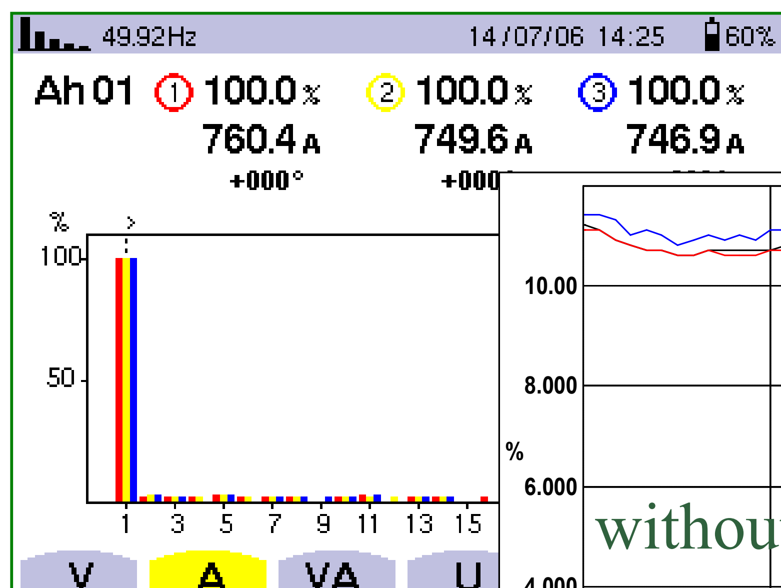


2 x 300A Parallel Active Harmonic Filters applied

Current waveform and spectrum without active filter, THDi = 34%

Voltage Distortion (THDv) dropped from 11.2% to 3.7%





Current waveform and spectrum with active fi

THDi = 3.6%

Problems with Active Harmonic Mitigation

- Current harmonic distortion much higher when measured above the 50th harmonic
- High levels of voltage distortion when measured above the 50th
- Connected equipment malfunction, including the AFE drives themselves and standard diode bridge front end drives
- Failure of transformers and other power distribution equipment due to excessive losses at the IGBT switching freq.
  - At one installation, a 2000 kVA transformer failed as a result of switching frequency harmonics above 10 kHz introduced by active power filters
- Stability and system resonance issues, especially with capacitors in the LCL and EMI filters or installed downstream for power factor correction
- Higher losses and lower efficiencies than similarly rated 6 Pulse ASDs with passive harmonic filters

IEEE Std 519 – 2014 Harmonic Standard

Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

- Defines voltage and current distortion limits at PCC
- Intended to be used as a system standard
- Recognizes responsibility of both User and Utility
- Considers both linear and non-linear loading
- Definitions for Total Demand Distortion (current) and Total Harmonic Distortion (voltage) apply to harmonics up to 50th but allow for inclusion of > 50 when necessary

total demand distortion (TDD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

IEEE Std 519-2014: Recommended Practices and Requirements for Harmonic Control In Electrical Power Systems

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2 Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5

Table 1: Voltage Distortion Limits

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
$< 20^c$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 2: Current Distortion Limits for Systems Rated 120V through 9 kV

Some Important Differences between Revision 2014 and 1992 of IEEE Std 519

- THD and TDD definitions now allow the inclusion of harmonics above the 50^{th} when necessary
- Voltage distortion limits for < 1kV systems have been relaxed to 8% from 5%
- Lower voltage distortion limits for Special Applications and higher limits for Dedicated Systems have been removed
- Current distortion limits for > 161kV systems have been changed. Current limits for other voltage systems remain the same.
- Very Short Time and Short Time limits have been introduced
- An allowance for increased harmonic limits at higher frequencies can be applied when steps are taken to reduce lower frequency harmonics

IEC Harmonic Standards – Low Frequency

- IEC 61000-3-2, Limits for harmonic current emissions (equipment input current < 16A/ph single & 3 phase)
- IEC 61000-3-12, Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16A and < 75A
- IEC 61000-3-6, Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems
- Only applied to harmonics up to the 40th

THD
ratio of the r.m.s. value of the harmonics (in this context harmonic currents I_n of the order n) to the r.m.s. value of the fundamental, viz.

$$THD = \sqrt{\sum_{n=2}^{\boxed{40}} \left(\frac{I_n}{I_1} \right)^2}$$

High Frequency Standards

- IEC 61800-3, EMC Product Standard for Power Drive Systems
  - “The source of high frequency emission from frequency converters is the fast switching of power components such as IGBTs”
  - Covers frequency range from 150 kHz to 30 MHz conducted and 30 MHz to 1000 MHz radiated

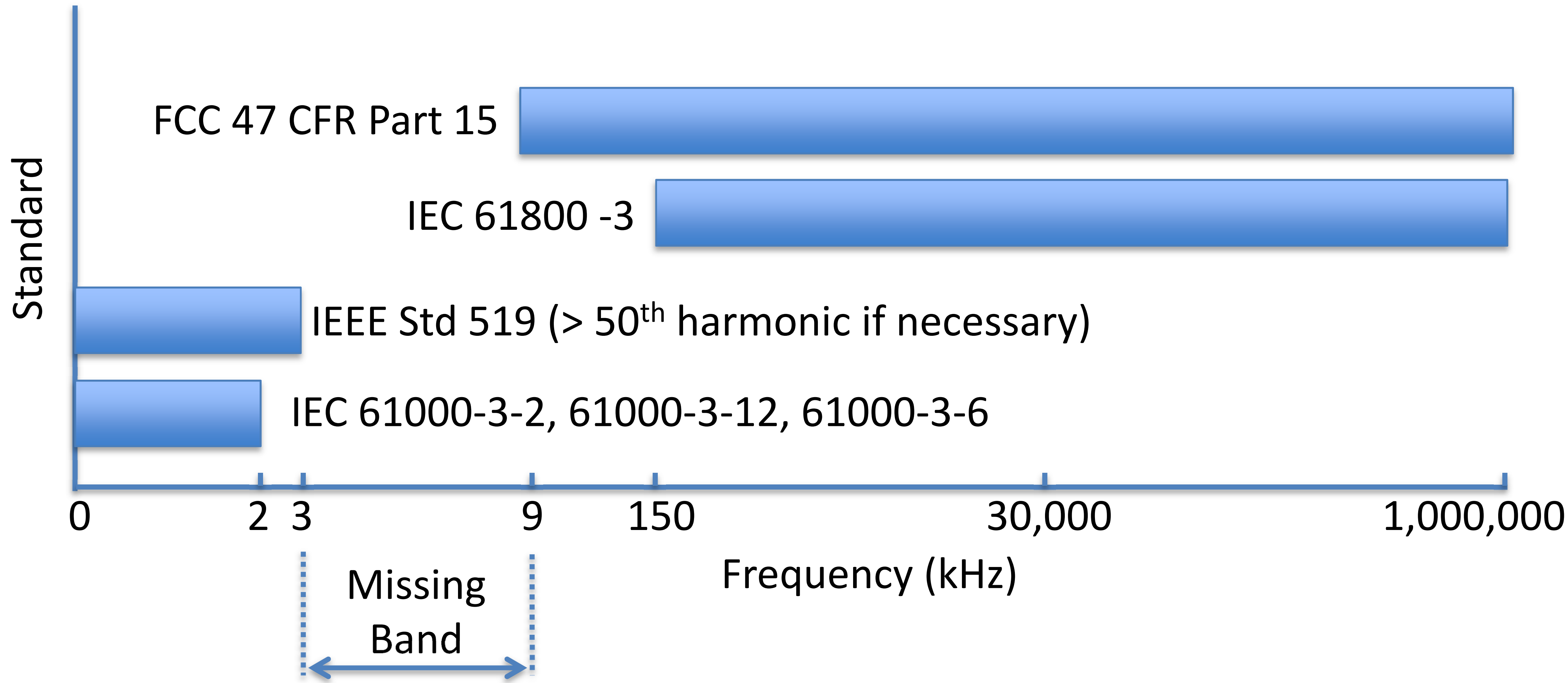
- FCC 47 CFR Part 15
  - Regulates emissions in the radio frequency spectrum from 9 kHz and higher

IEC Std 61800-3: Adjustable Speed Electrical Power Drive – EMC Product Standard

Values of Limits for Mains Terminal Disturbance Voltage in Frequency Band 150 kHz to 30 MHz

Size of PDS	Frequency band MHz	Unrestricted distribution		Restricted distribution	
		Quasi peak dB(μV)	Average dB(μV)	Quasi peak dB(μV)	Average dB(μV)
Low power drive system (I < 25 A)	$0{,}15 \leq f < 0{,}5$	66 Decreases with log of frequency down to 56	56 Decreases with log of frequency down to 46	79	66
	$0{,}5 \leq f \leq 5{,}0$	56	46	73	60
	$5{,}0 < f < 30{,}0$	60	50	73	60
Medium power drive system ($I \geq 25$ A)	$0{,}15 \leq f < 0{,}5$	79	66	79	66
	$0{,}5 \leq f \leq 5{,}0$	73	60	73	60
	$5{,}0 < f < 30{,}0$	73	60	73	60

Harmonic Standards and the Missing Frequency Band



- Low frequency regulations end at 40th or 50th harmonic unless IEEE 519 allowance of including harmonics above 50 is applied
- High frequency standards begin at 9 kHz

No standards exist from 50th harmonic to 9 kHz

Is this a concern?

Absolutely, since typical IGBT switching frequencies are between 2 kHz and 8 kHz which falls precisely within this band

Missing Frequency Band in Harmonic Standards

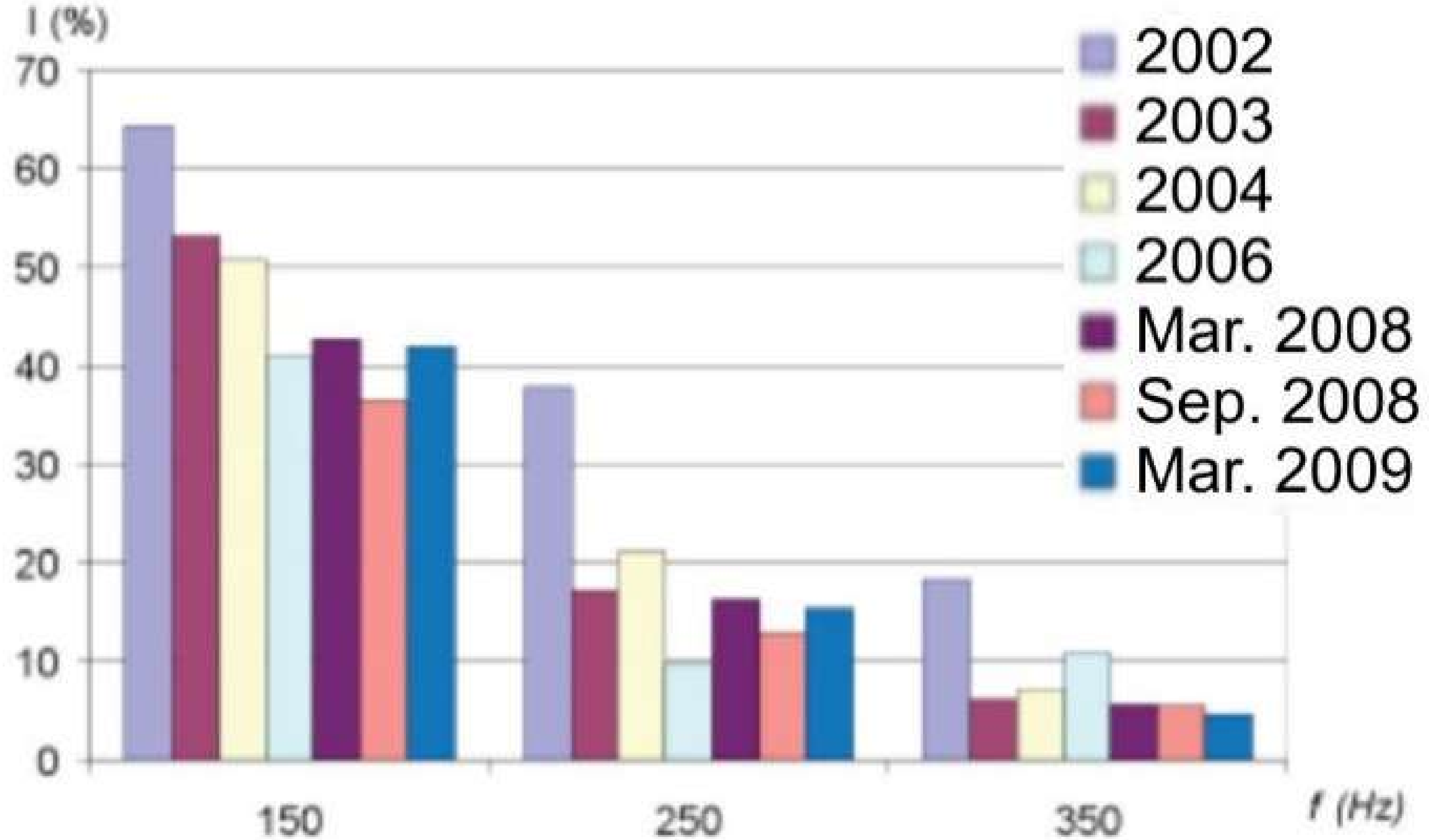
So we need to ask ourselves

Why are we applying harmonic mitigation?

Is it to truly resolve problems or simply comply with standards?

Effect of Harmonic Limits on Computer Equipment

Emissions from a large group of State-of-the-Art computers from 2002 to 2009

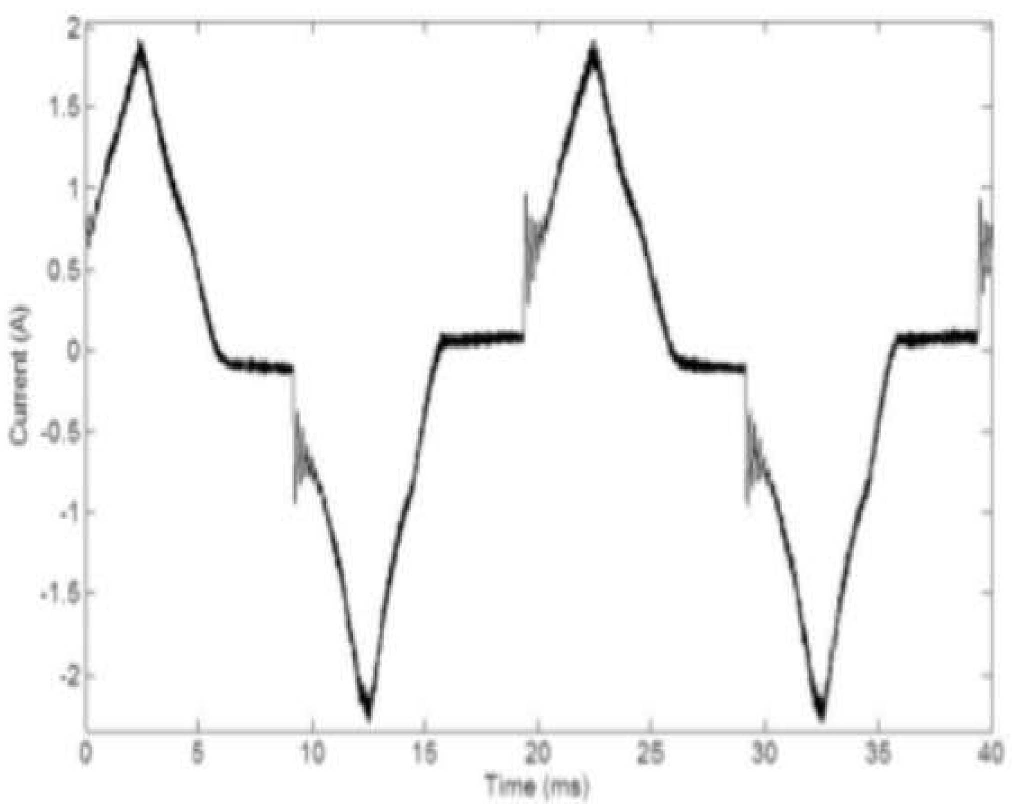


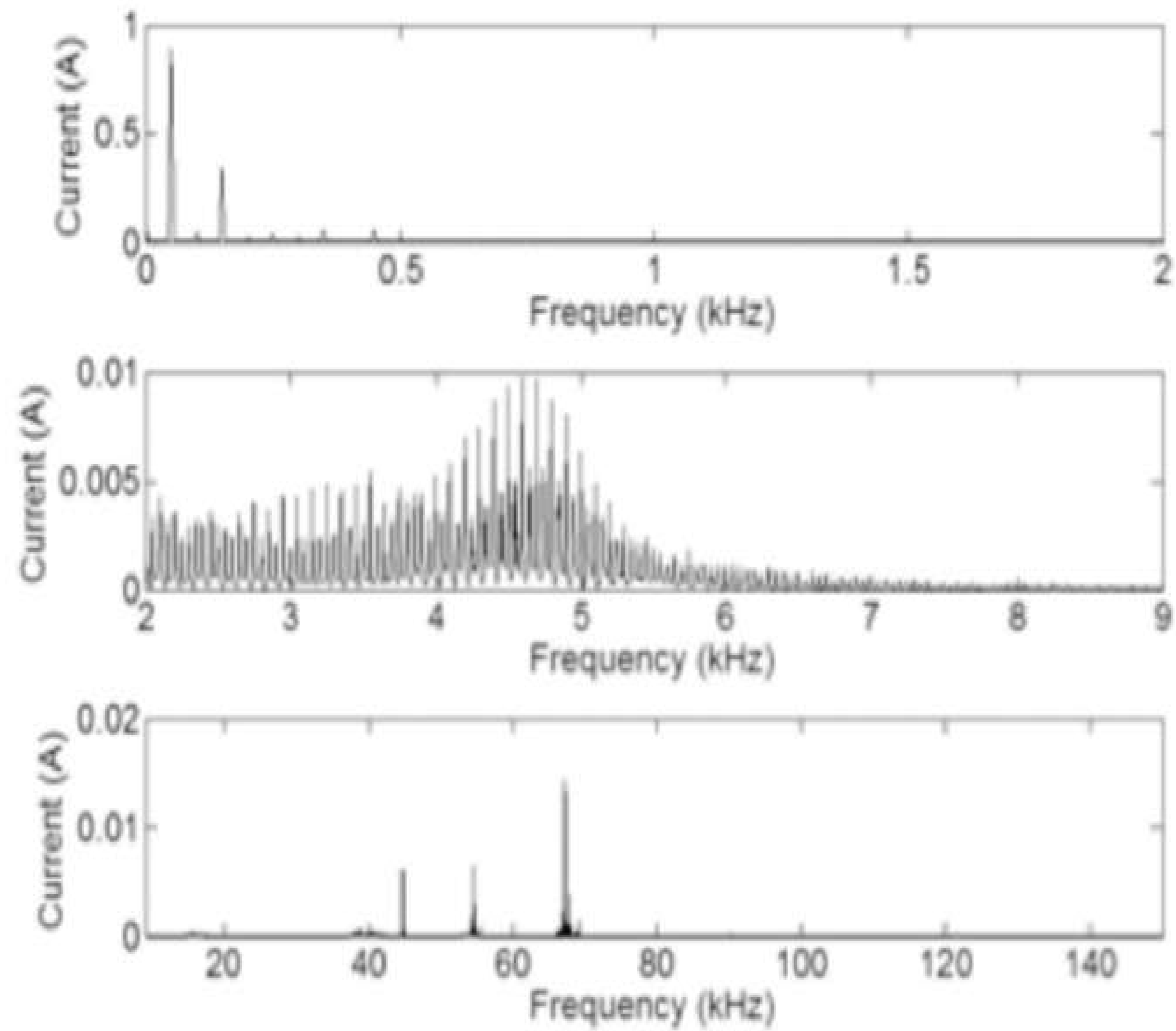
Reference:

1. F. Z. Peng, H. Akagi, A. Nabae, "*A New Approach to Harmonic Compensation in Power Systems - A Combined System of Shunt Passive and Series Active Filters*", IEEE Transactions on Industry Applications, Vol. 26, No. 6, Nov./Dec. 1990

Equipment Trend Towards Higher Frequency Harmonics

Current waveform and spectrums for a modern television





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Missing Frequency Band in Harmonic Standards

AFE and AHF solutions may comply with standards but they often introduce bigger problems than they resolve

Active Front-end (AFE) Drive and Parallel Active Harmonic Filters

AFE and AHF manufacturers will claim that their technology provides the best solution for treatment of VSD harmonics, but the reality is:

- AFE's and AHF's generate high frequency harmonics which can have more serious consequences than low frequency harmonics.
- AFE's and AHF's generate significant levels of ground leakage current which can cause inadvertent ground fault trips and failure of sensitive equipment.
- When 6-Pulse VSDs and AFE Drives are on the same switchboard, voltage ripple from the AFE Drive can raise the DC bus voltage in the 6-Pulse VSDs creating overvoltage conditions.

Active Front-end (AFE) Drives High Frequency Harmonics

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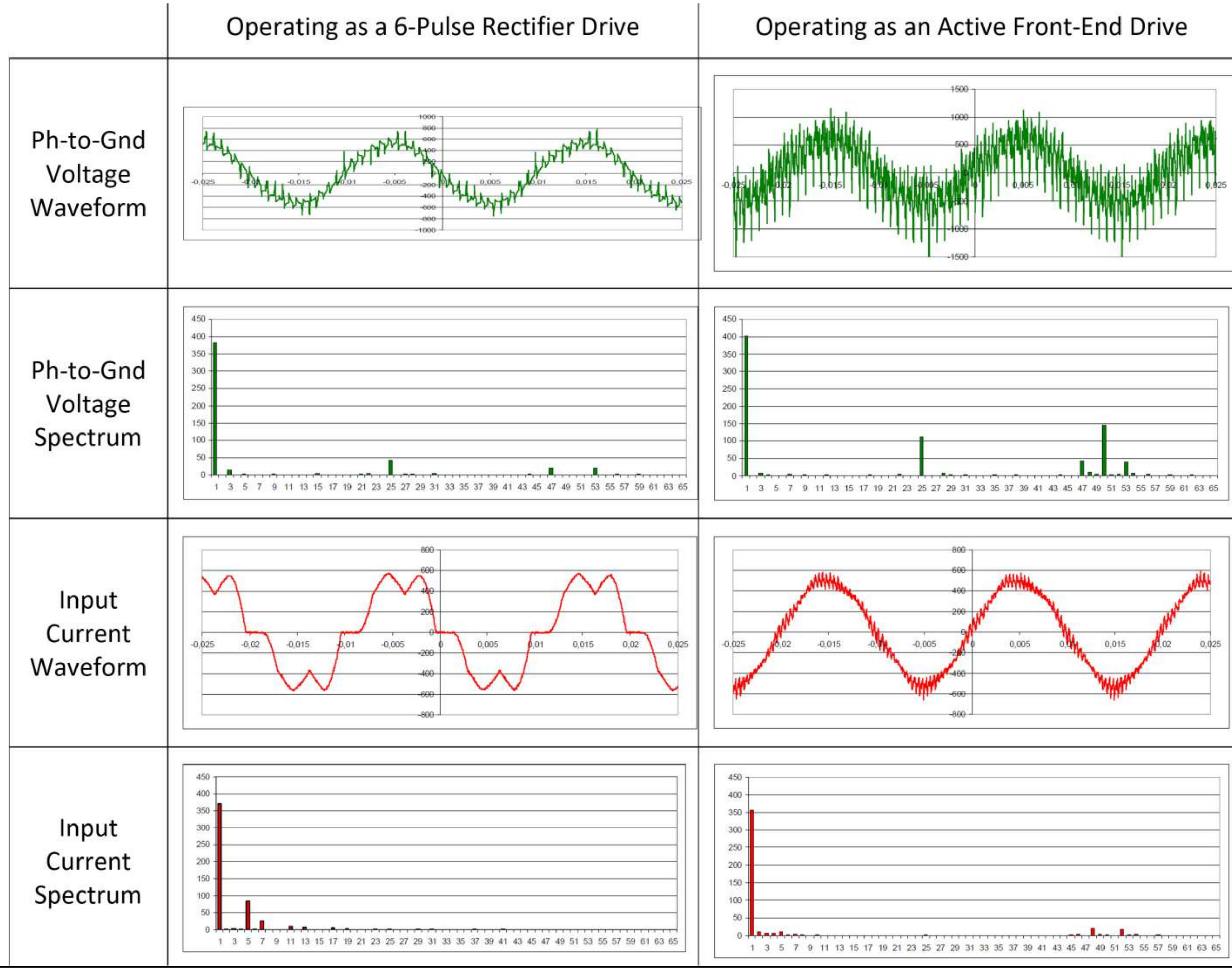
AFE's generate high frequency harmonics which can have more serious consequences than low frequency harmonics

Example of an AFE Drive operating in both 6-Pulse mode and AFE mode

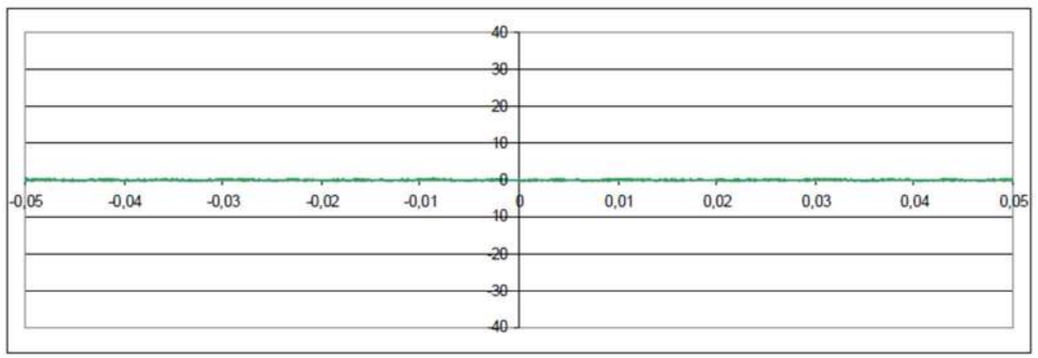
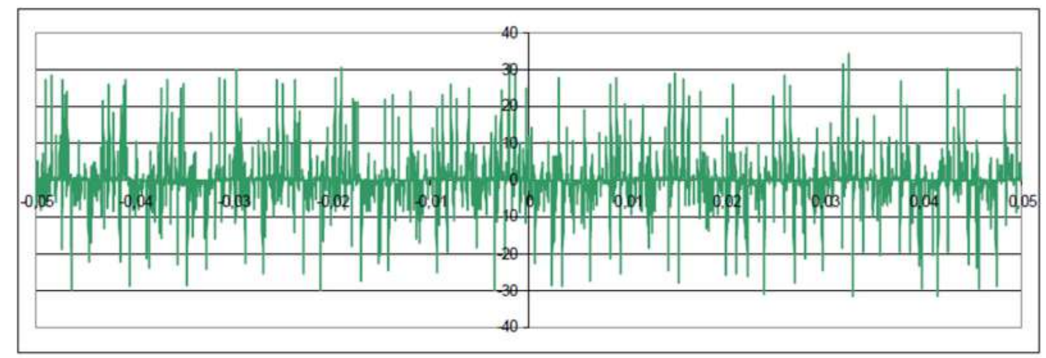
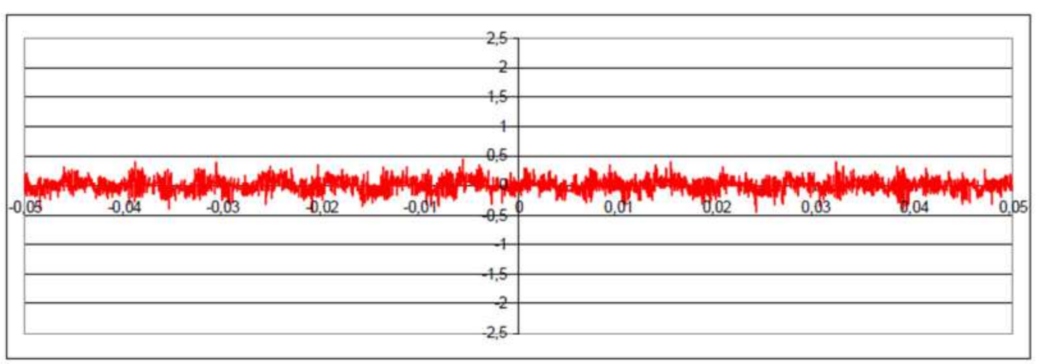
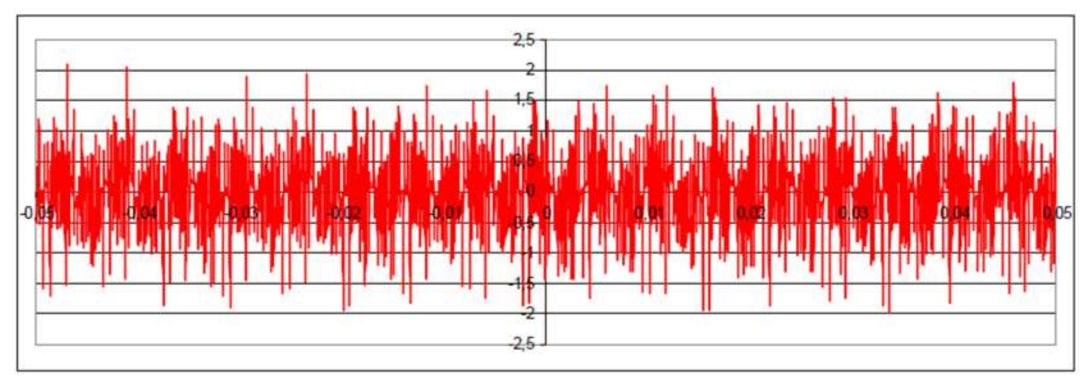


Reference:

1. Practical Problems Associated with the Operation of ASDs Based on Active Front End Converters in Power Distribution Systems, Luis Moran, Jose Espinoza, et al, IEEE Transactions on Industrial Applications, 2004

Active Front-end (AFE) Drives High Frequency Harmonics

AFE's generate significant levels of ground leakage current which can cause inadvertent ground fault trips and sensitive equipment failure

	Operating as a 6-Pulse Rectifier Drive	Operating as an Active Front-End Drive
N-to-Gnd Voltage		
N-to-Gnd Current		

Example of an AFE Drive operating in both 6-Pulse mode and AFE mode

- Much higher neutral-to-ground harmonics (common-mode) in AFE mode

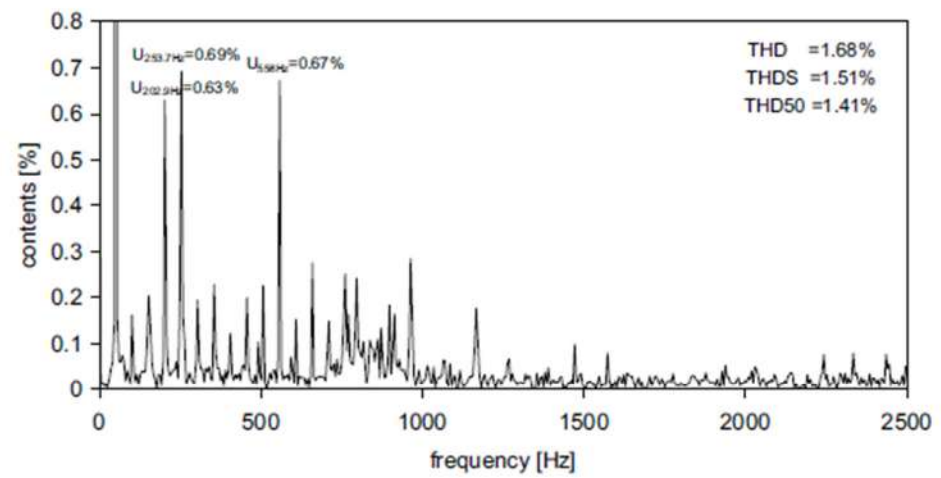
Reference:

1. Practical Problems Associated with the Operation of ASDs Based on Active Front End Converters in Power Distribution Systems, Luis Moran, Jose Espinoza, et al, IEEE Transactions on Industrial Applications, 2004

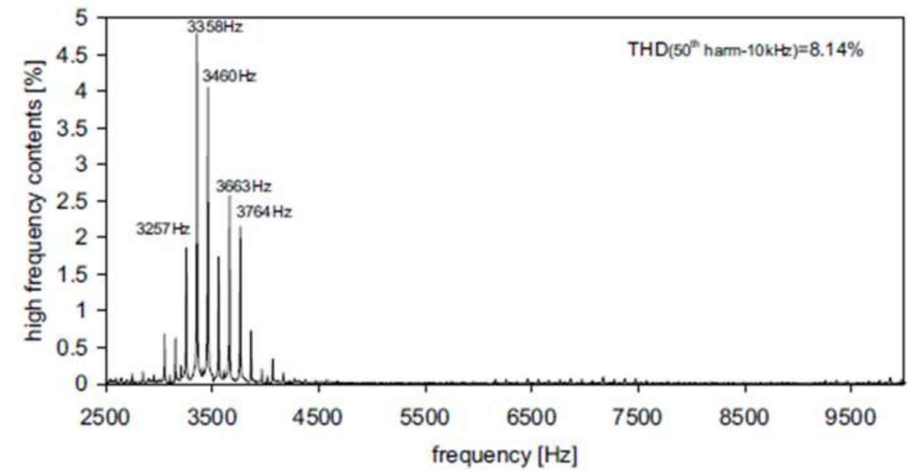
Active Front-end (AFE) Drives High Frequency Harmonics

An AFE Drive will generate higher levels of harmonics at its IGBT switching frequency

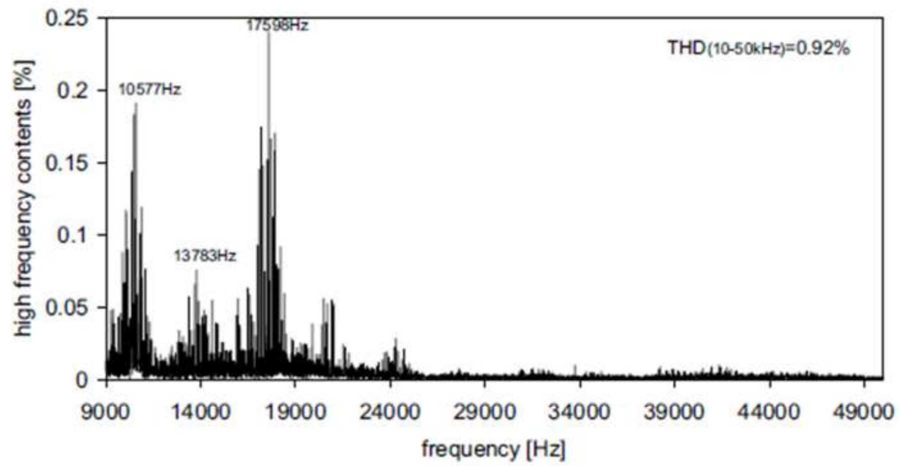
AFE voltage harmonic spectrums at various frequency ranges



a) Up to 50th harmonic (VTHD = 1.68%)



b) 50th harmonic to 10 kHz (VTHD = 8.14%)



c) 10 kHz to 50 kHz (VTHD = 0.92%)

Frequency bands	THD [%]
0-50kHz	8.38
0-50th harmonic	1.68
50th harmonic-10kHz	8.14
10-50kHz	0.92

d) Summary of VTHD at various frequency bands

VTHD = 8.38% when harmonics up to 100th are considered

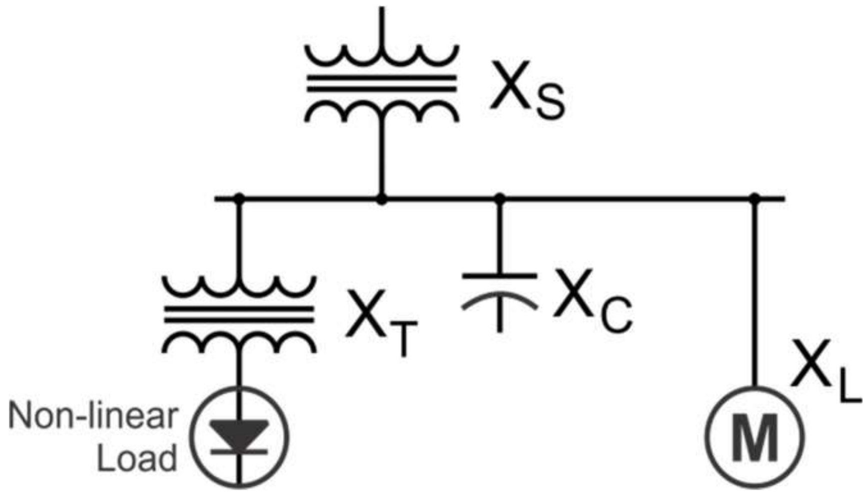
Reference:
1. An assessment of distortions of supply voltage waveform in All-Electric Ship Power Network, Marius Szweda, Tomasz Tarasiuk, Oct. 2007

Active Front-end (AFE) Drive and Parallel Active Harmonic Filter

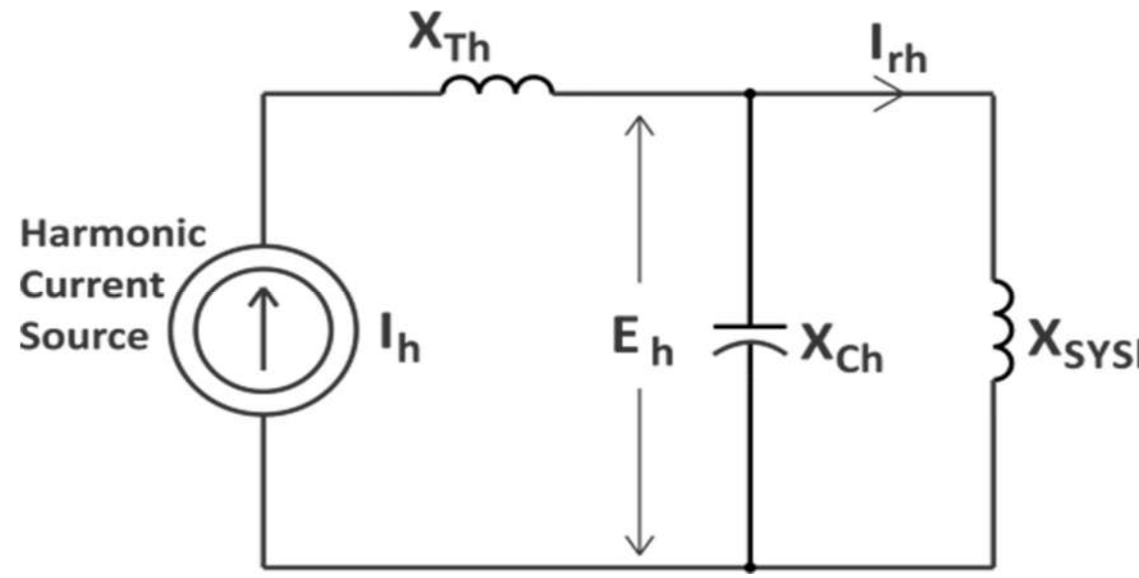
AFE and AHF manufacturers will claim that their technology provides the best solution for treatment of VSD harmonics, but the reality is:

- Although an active solution, AFE's and AHF's still require input passive filters (LCL and EMI/RFI filters) to control switching frequency harmonics and to attenuate ripple in the mains side voltage and current.
- LCL and EMI/RFI filters are more likely to resonate with the power system at the higher rectifier harmonic frequencies (ie. 11^{th}, 13^{th}, 17^{th}, 19^{th}, etc.) than are passive WSHF's tuned below the 5^{th}.

Power System Harmonic Resonance



Single Line Diagram



Equivalent Diagram

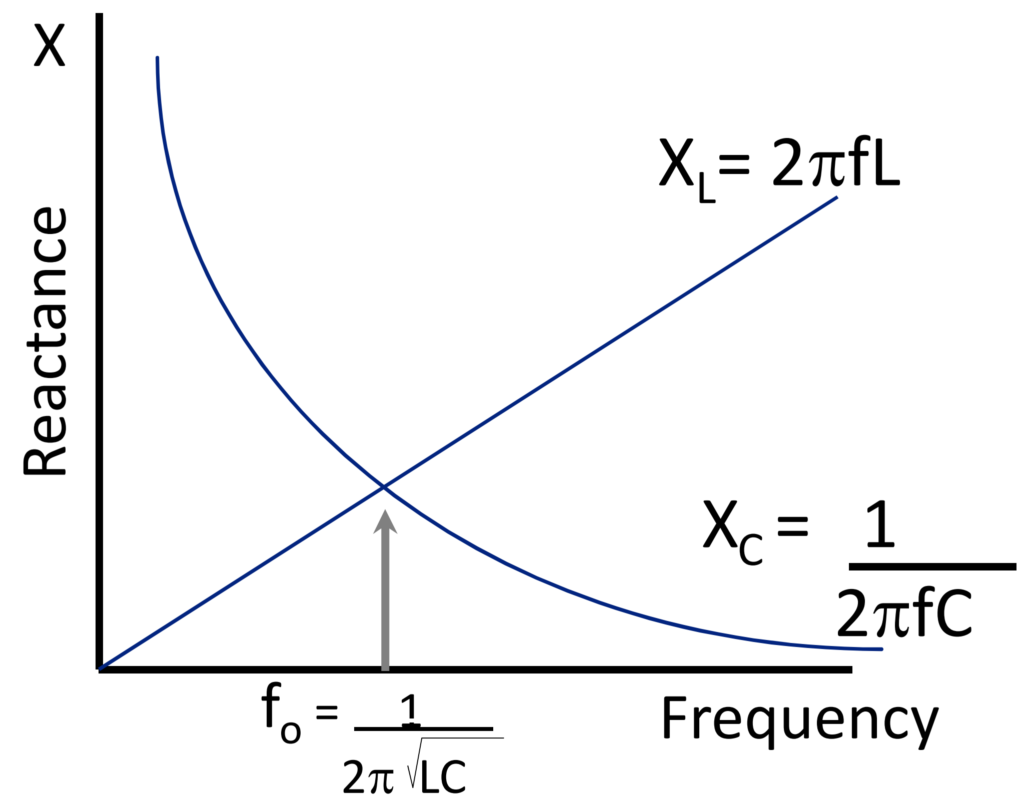
Resonance will occur when:

$$X_{Ch} = X_{SYSh} \qquad (X_{SYSh} = X_S \,||\, X_L)$$

At resonance, the circulating current is limited only by the resistance in the circuit.

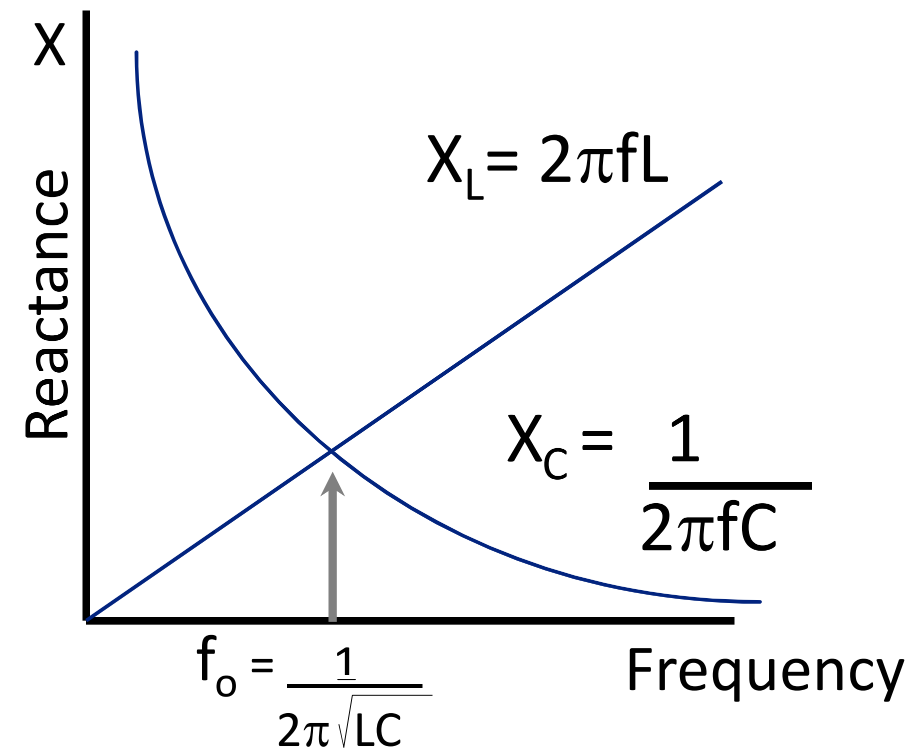
Problems that can result include:

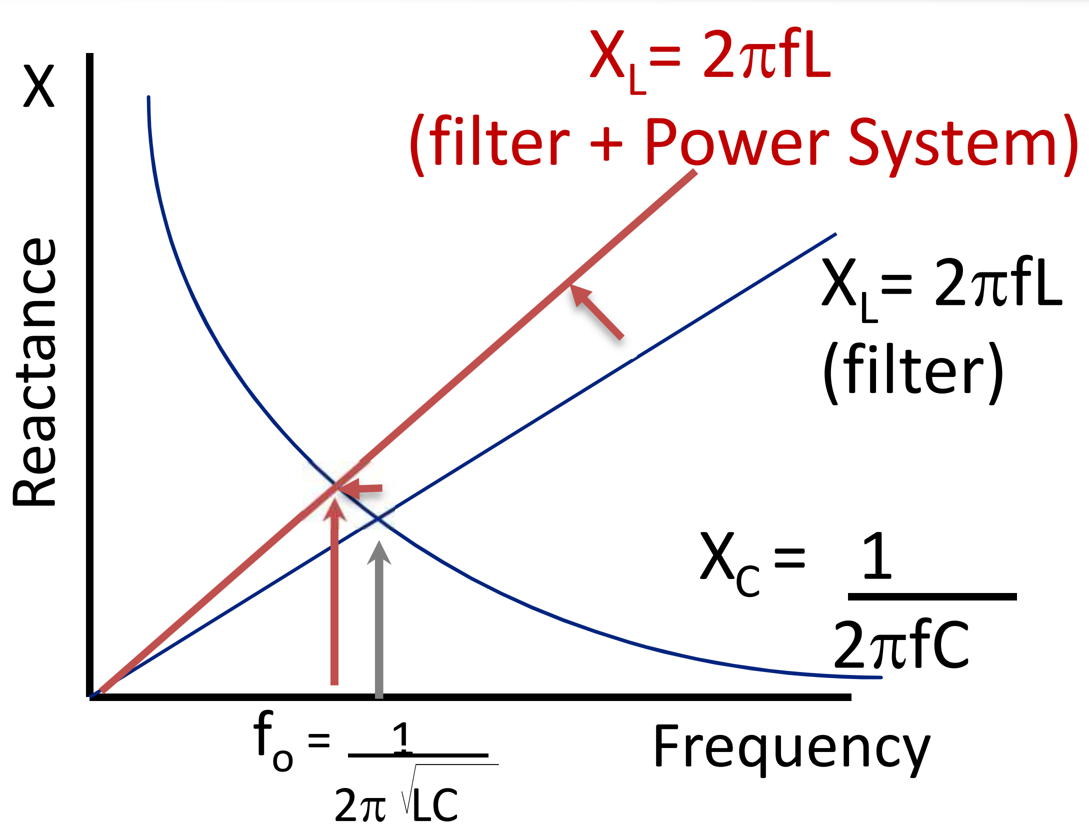
- High current and voltage distortion
- Destroyed capacitors and their fuses
- Damaged surge suppressors
- Failure of connected equipment
- System shutdowns



Effect of Passive Filter on Power System Resonance

- Power systems are inductive in nature
  - Only capacitive if overcompensated by PFC capacitors which must be avoided
- Power system will tend to move the resonant frequency of a passive filter lower as inductance increases moving curve upwards
- WSHF is tuned below the 5th harmonic, ensuring that power system resonance with predominant harmonics is avoided
- LCL filters used for active applications are tuned at higher frequencies so adding power system inductance can shift resonance to a predominant harmonic





Example of AFE LCL Failure – Australian Lithium Mine

AFE failure risks lithium mine expansion plans

The soaring demand for lithium for electric vehicle batteries has prompted an Australian mine to double its output. But its expansion plans risked being delayed when the filter in an AFE (active front-end) system, used in a drive for an on-site mill, failed.

Active Front-end (AFE) Drive and Parallel Active Harmonic Filter

AFE and AHF manufacturers will claim that their technology provides the best solution for treatment of VSD harmonics, but the reality is:

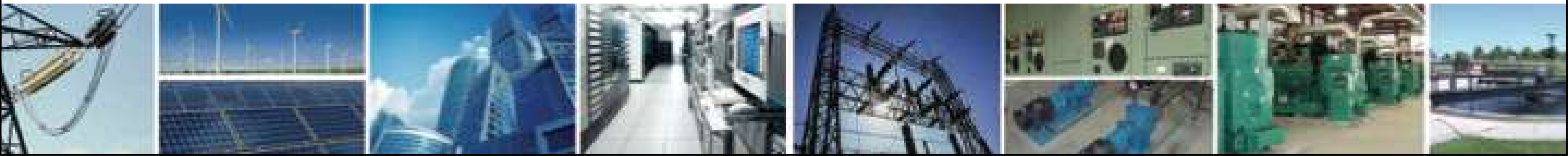
- AFE losses are significantly higher and efficiencies much lower than a 6-Pulse VSD with Lineator AUHF.

Efficiency Comparison: 6-Pulse with WSHF vs Active Front-end (AFE) Drives

AFE has much higher losses than 6-P with passive WSHF

Type	VSD Rating (kW)	VSD Losses (kW)	AUHF Losses (kW)	Total Losses (kW)	Efficiency	Difference
AFE Drive	75	4.1		4.1	94.8%	
6-P with Lineator		1.9	0.8	2.7	96.5%	1.7%
AFE Drive	400	20		20	95.2%	
6-P with Lineator		9.1	3.6	12.7	96.9%	1.7%

- AFE input bridge has higher losses than Lineator AUHF
- 1.7% higher overall efficiency with passive solution



Efficiency Comparison: 6-Pulse with WSHF vs Active Front-end (AFE) Drives

Energy Savings Analysis

Application: 400 kW VSD, Diesel-Electric Thruster on an Offshore Support Vessel (OSV)

Assumptions:

$L = 400\ kW$	VSD load (motor rating)
$t = 2935\ h/yr$	Operating time (average load of 33.5% based on Figure 3-1)[1]
$G = 0.017$	Efficiency %Gain (1.7% from previous slide)
$f = 0.4\ L/kWh$	Diesel generator consumption[2]
$c = 0.80\ \$/L$	Fuel Cost

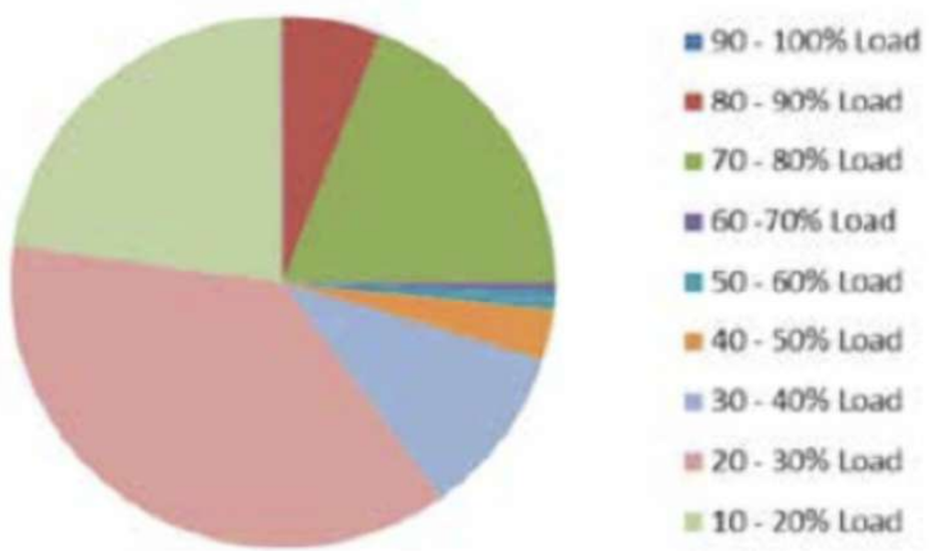


Figure 3-1 Example of Engine Operating Profile for typical OSV (14)

References:

1. Factors Influencing Machinery System Selection for Complex Operational Profiles, Mats Johan Heian, June 2014.
2. http://energyeducation.ca/encyclopedia/Diesel_generator

Efficiency Comparison: 6-Pulse with WSHF vs Active Front-end (AFE) Drives

Energy Savings Analysis

Application: 400 kW VSD, Diesel-Electric Thruster on an Offshore Support Vessel (OSV)

Calculations:

$$EnergySavings/year = L \times t \times G$$

$$= 400kW \times 2935\frac{h}{yr} \times 0.017$$

$$= 19955\ {}^{kWh}/_{yr}$$

$$FuelSavings/year = 19955\ {}^{kWh}/_{yr} \times 0.4\frac{L}{kWh} = 7982\frac{L}{yr}$$

$$\boldsymbol{CostSavings/year} = 7982\ {}^{L}/_{yr} \times 0.80\frac{\$USD}{L} = \mathbf{6386}\ {}^{\$USD}/_{yr}$$

Typical payback on harmonic mitigation equipment of 1-2 years based on Energy Savings alone.

Compared with AFE, initial capital costs are also lower.

Efficiency Comparison: 6-Pulse with WSHF vs Active Front-end (AFE) Drives

Energy Savings Analysis

Application: 400 kW VSD, Diesel-Electric Thruster on an Offshore Support Vessel (OSV)

$$FuelSavings/year = 7982\frac{L}{yr}$$

	Units	CO_2	CH_4	N_2O	CO_2e
Marine Diesel	kg/L	2.556	0.00015	0.0011	2.888
Emissions/yr	**kg/yr**	**20402**	**1.2**	**8.8**	**23052**

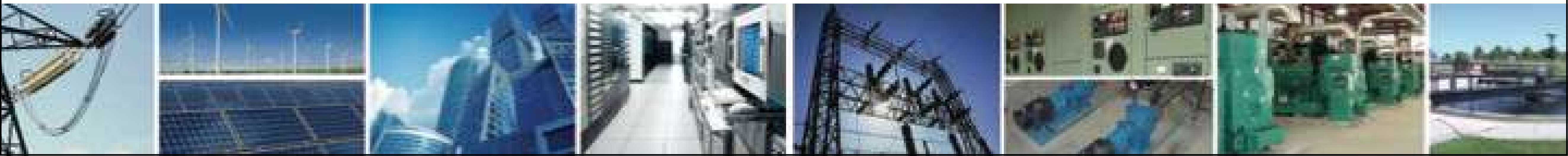
GHG Equivalent Savings for 10 yrs

References:

1. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

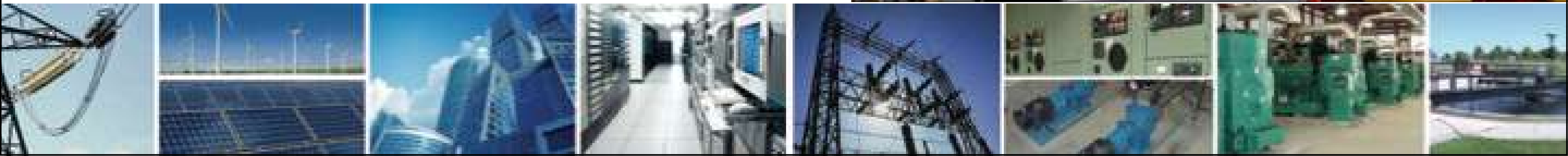
Summary

- Harmonics generated by non-linear loads require treatment by an effective means of harmonic mitigation
- Active methods of harmonic mitigation often introduce high frequency switching harmonics that can create more problems than the low frequency harmonics they are designed to reduce
- Present standards for harmonics miss a band of frequencies between 3 kHz and 150 kHz
  - As a result there is no incentive for manufacturers to reduce these switching frequencies
- There are passive solutions that effectively reduce lower frequency harmonics without introducing high frequencies



Discussion

Questions and feedback



Thank You

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