Understanding the Relationship Between Drives and Harmonics

IEEE-519 and Mitigation Methods

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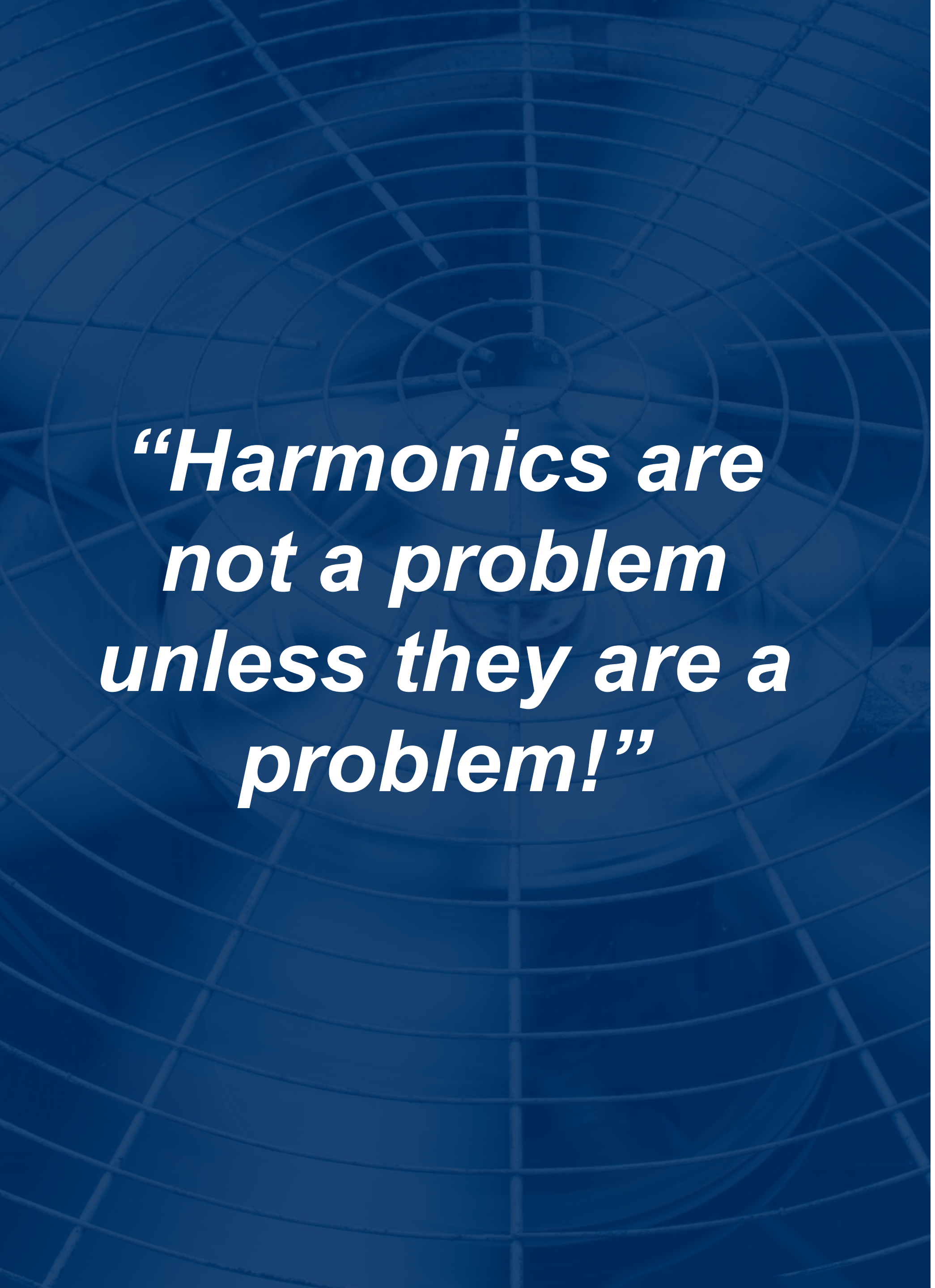

- Utility is responsible for providing "clean" voltage.
- Customer is responsible for not causing excessive current harmonics.
- Harmonics cause problems in power systems
- IEEE Std 519-2014 provides a basis for limiting harmonics.
- Multiple methods exist for mitigating harmonics and *one size does not fit all*.

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Topics

1. IEEE-519 Recommendations
2. AC Drives and Harmonics
3. Why Care?
4. How to Stomp out Harmonics

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IEEE 519-2014 Recommendations

The Institute of Electrical and Electronics Engineers (IEEE) has set guidelines for applying limits to the level of harmonic distortion that a utility customer may inject into the power system. The guidelines pertain to percent harmonic current and voltage distortion at the point of common coupling (PCC), which is defined as the point where the utility connects to multiple customers.

Voltage distortion limits @ PCC:

3% — **Special System**
Hospital

5% — **General System**
WWTP

10% — **Dedicated System**
AFD's Only

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Which Came First?

Voltage Distortion

Current Distortion

Which Came First?

Voltage Distortion

Current Distortion

In this case…the Egg!

Current distortion causes Voltage distortion

Voltage distortion is created by pulling distorted current through an impedance.

Amount of voltage distortion depends on:

- System impedance
- Amount of distorted current pulled through the impedance
- If either increases, V_{THD} will increase

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Point of Common Coupling

- PCC is where harmonic limits are assessed
- Very misunderstood and misapplied part of IEEE- 519
- Prevent one customer from harming another
- Not intended to be applied within a user’s system

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Point of Common Coupling

- True PCC will often be at MV transformer primary
  - Regardless of transformer ownership or meter location
- Not often practical to perform MV measurements
- Common to measure on LV secondary
  - Do what we can safely and easily
  - Use I_{SC}/I_L ratio from primary to determine current limits
  - LV measurements are sufficient most of the time
- If there is a dispute between utility and customer, it may be necessary to measure or calculate harmonics at the MV transformer primary

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Point of Common Coupling

Update for IEEE 519-1992

The 2014 version re-emphasizes and clarifies IEEE Std 519, as written, is to be applied at the PCC - the point of common coupling between the utility and the use.

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Total Demand Distortion

Harmonics meters measure THD

Individual harmonics in % of I1 (fundamental)

IEEE-519 current harmonic limits use TDD

Individual harmonics in % of IL (load)

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What Are Harmonics?

- Usually expressed as % of fundamental
- Voltage or current harmonics? Be clear!
- Often better to express as Volts or Amps

- When added together, harmonics result in a distorted waveform
- Diode converters convert AC to DC and require two diodes (pulses) per phase

- In AC drives, diode converter bridges produce harmonics according to the rule h = nk +/- 1
  - h is the harmonic produced
  - n is the number of diodes
  - k is an integer

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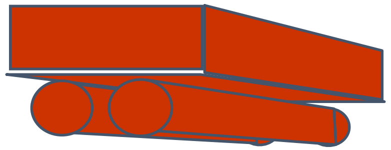
Harmonics Sources

Power Electronic Equipment (drives, rectifiers (UPS), computers, etc.)

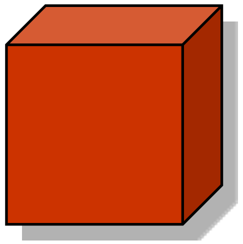
Arcing Devices (welders, arc furnaces, fluorescent lights, etc.)

Rotating Machines (generators)

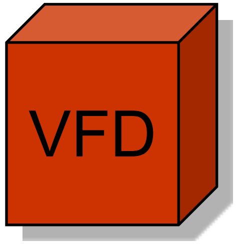
Common Sources



Lighting ballasts



UPS systems



AC and DC drives

Expected Harmonics

Source	Typical Harmonics*
6 Pulse Drive/Rectifier	5, 7, 11, 13, 17, 19…
12 Pulse Drive /Rectifier	11, 13, 23, 25…
18 Pulse Drive	17, 19, 35, 37…
Switch-Mode Power Supply	3, 5, 7, 9, 11, 13…
Fluorescent Lights	3, 5, 7, 9, 11, 13…
Arcing Devices	2, 3, 4, 5, 7…
Transformer Energization	2, 3, 4

* *Generally, magnitude decreases as harmonic order increases*

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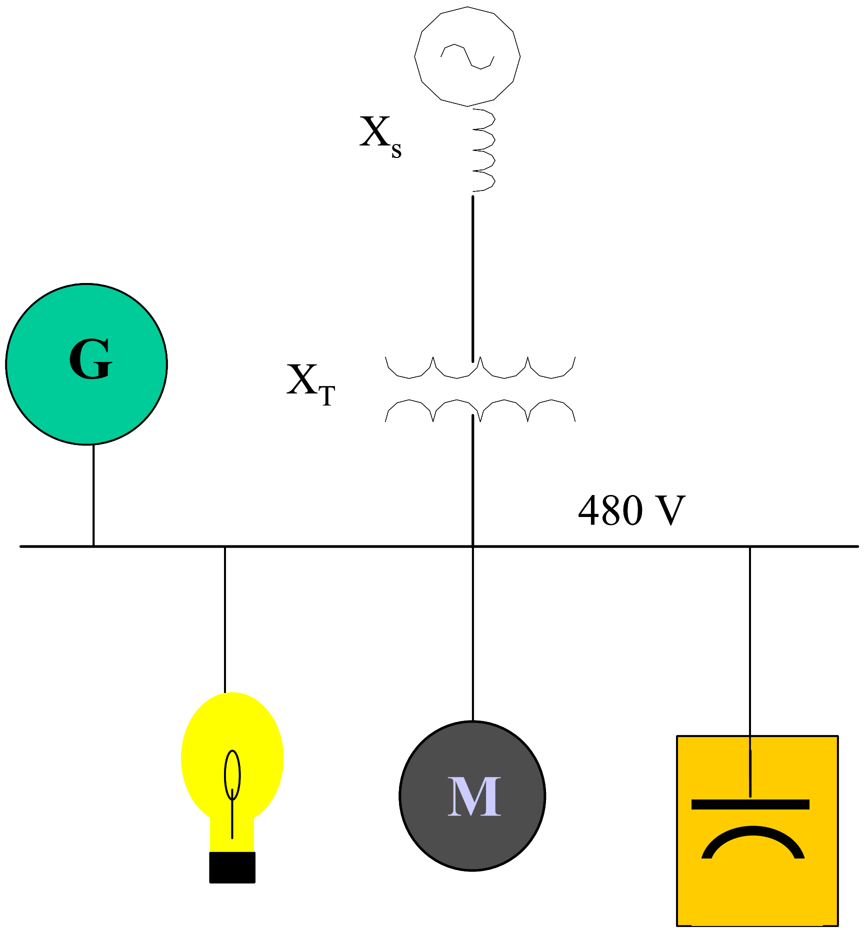
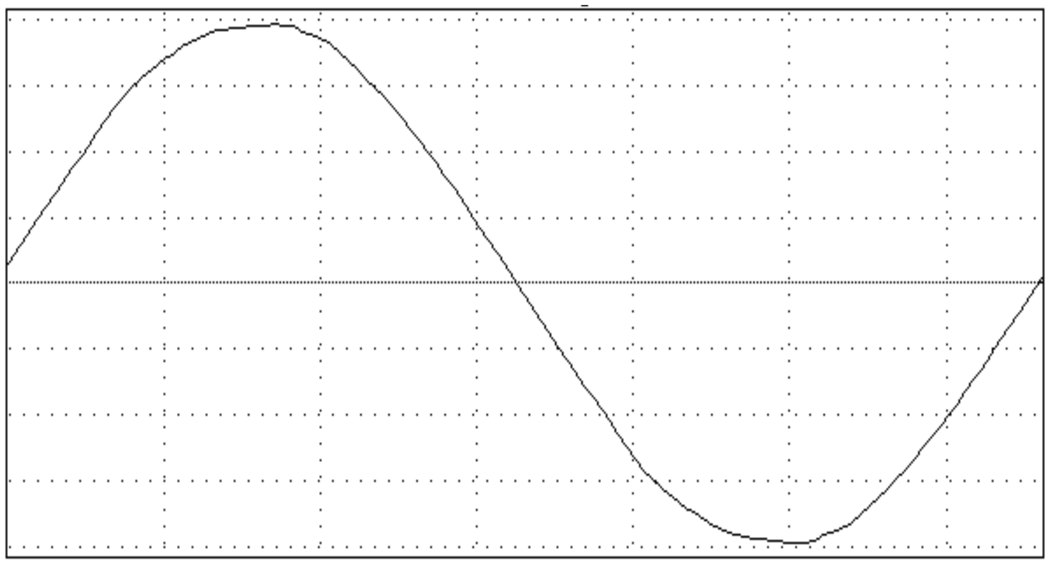
A Long, Long Time Ago....
Electrically Linear World





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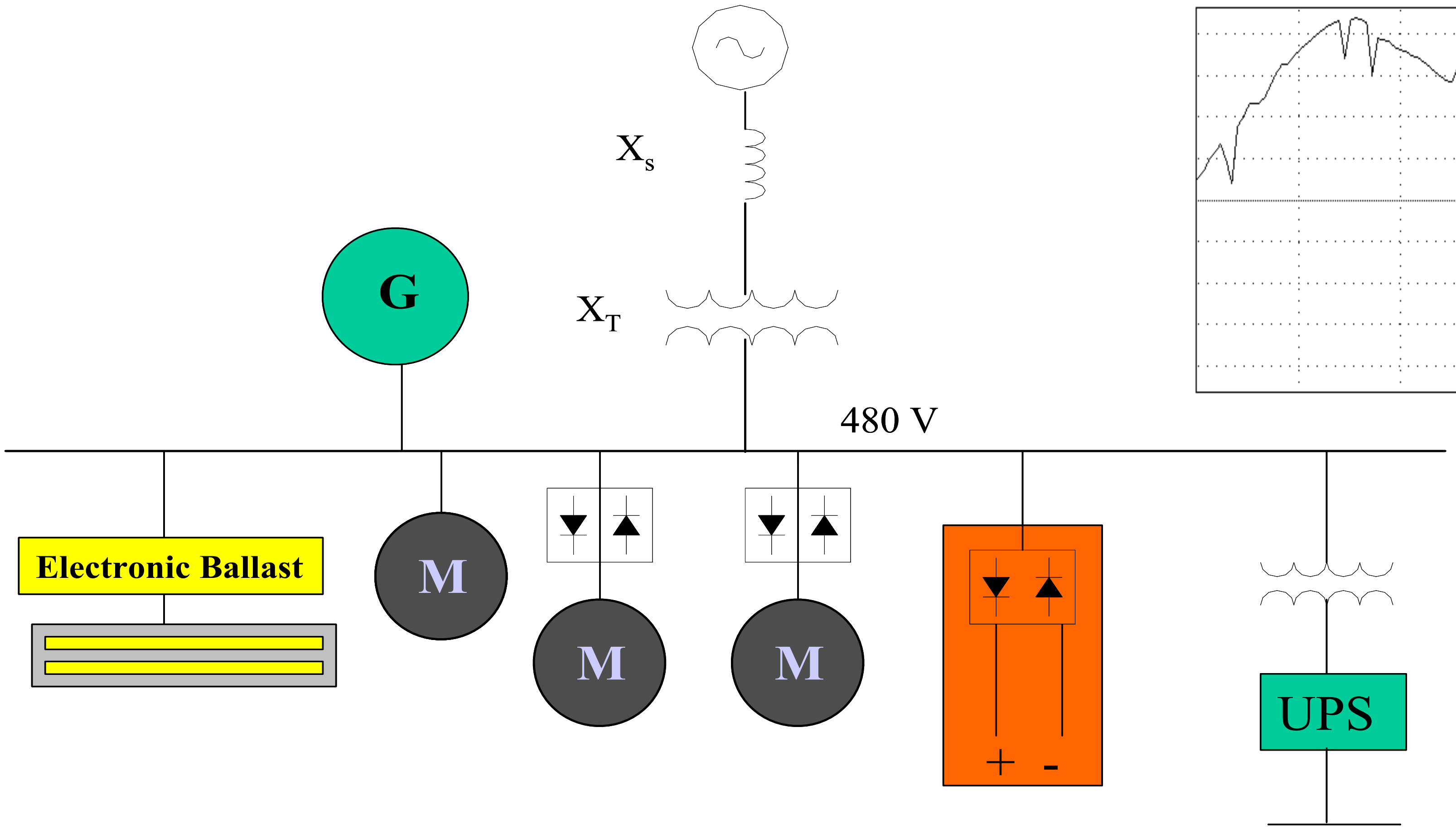
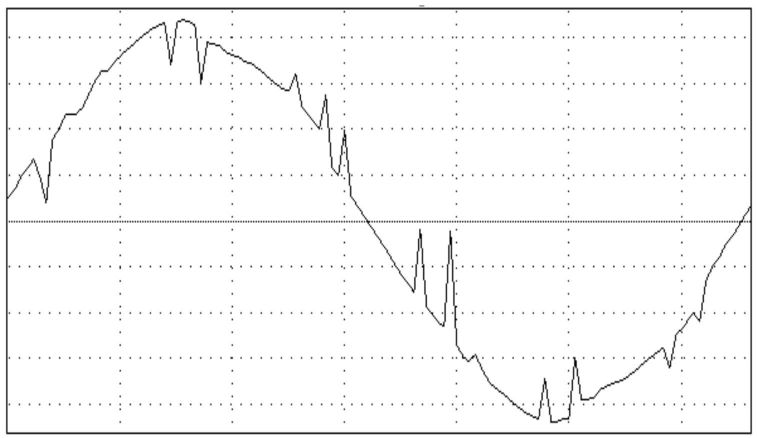
Today . . . Increasingly Non-linear





Who Cares About Harmonics?

Utilities

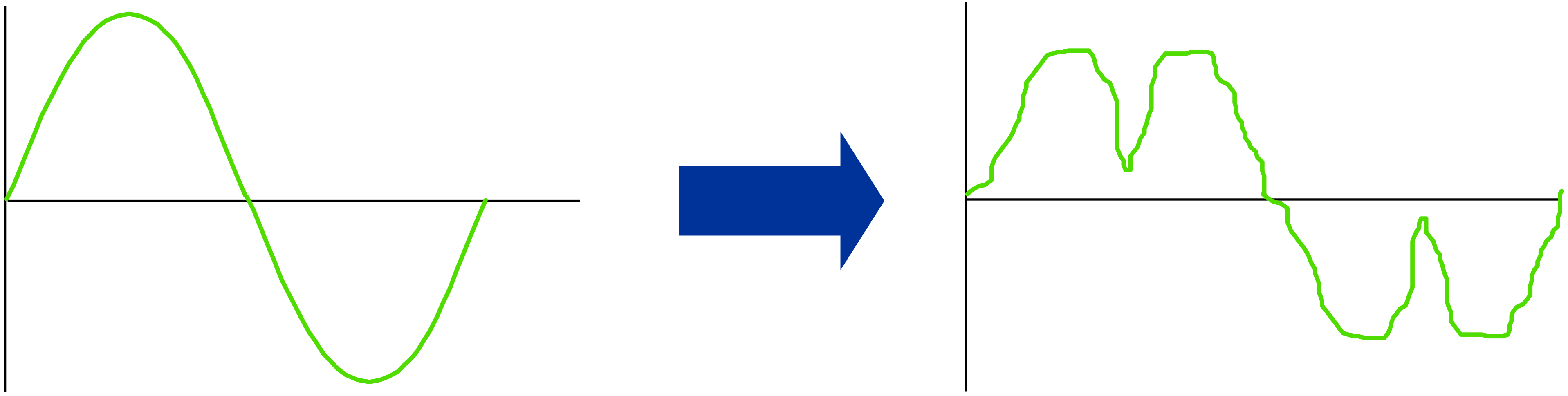
Users

Maintenance & Facility

Engineers

Utilities

The power company typically supplies a reasonably smooth sinusoidal waveform



…but nonlinear devices distort voltage and current waveforms resulting in poor power quality on the distribution grid with further implications

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Utilities

Harmonics can be thought of as power which does no useful work but requires extra generation and distribution capacity

With the increased number of motors controlled by inverters and other nonlinear power electronics, utilities are delivering a higher percentage of “harmonic power” without a comparable increase in revenue

Some utilities have introduced billable charges for harmonic distortion

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Users

- Control capital expenses
- Needs to be a good citizen in the electrical community via IEEE-519 compliance
- Seek increased uptime and profits
- Want to protect electrical assets
- Work to add value to facilities
- Desire reduced energy expenses

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Maintenance and Facility Engineers

- Need to protect sensitive electronic equipment
- Want to reduce downtime due to thermal and other problems
- Everything needs to look good on the oscilloscope
- Need to eliminate the problems of drive loads on emergency backup generators

Maintenance and Facility Engineers

System	Concern
Distribution Transformers	Overheating and efficiency loss, leads to over-sizing and more increased losses
Standby generator	Distortion dramatically reduces capacity, synch issues with zero crossings for relays
Communications Equipment	Downtime and loss of productivity
Computers & Computer Systems	Nuisance tripping and downtime
Diagnostic equipment	Nuisance tripping and erroneous results
Utility	Charges for harmonic pollution

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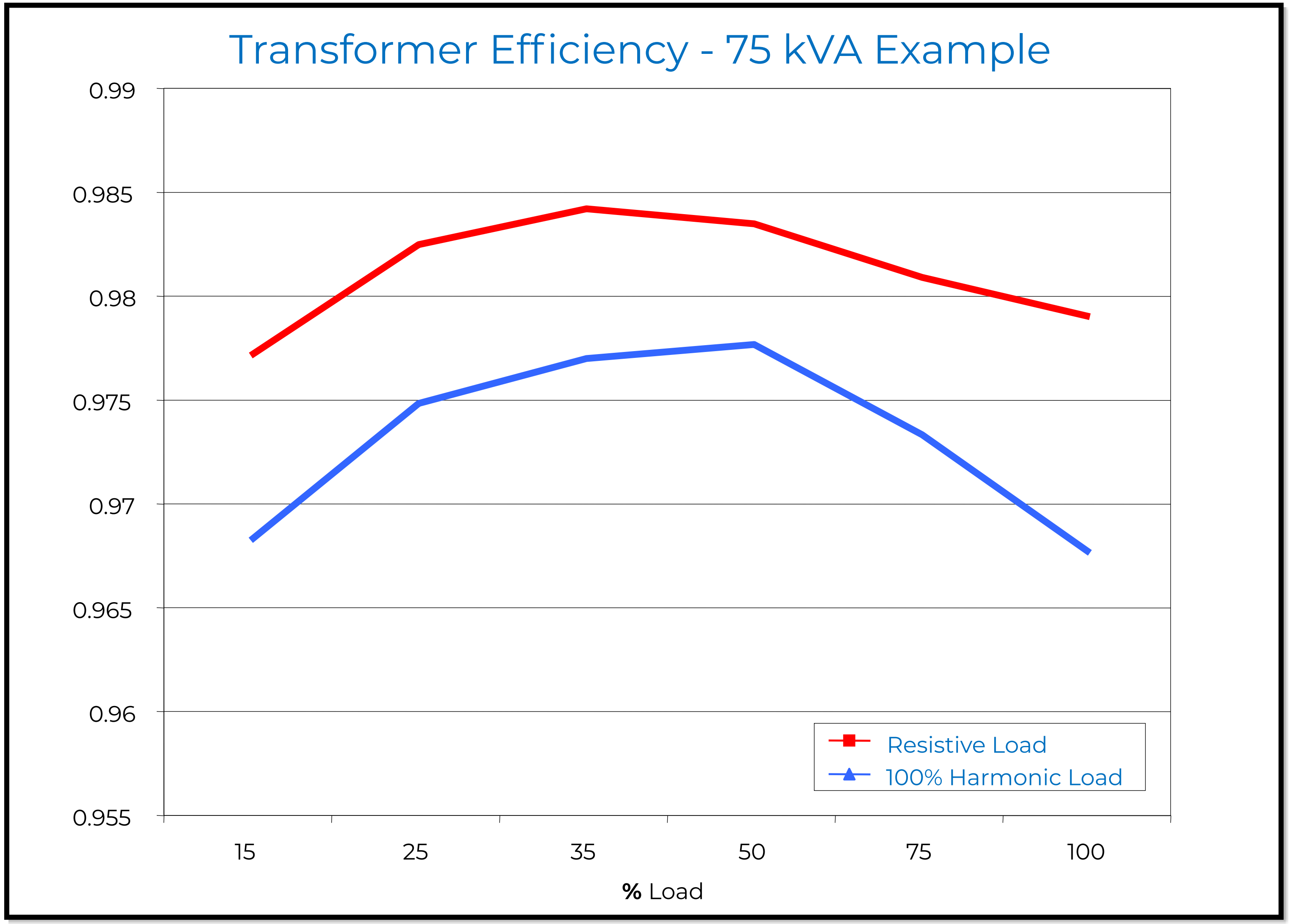
System Inefficiency with Harmonics



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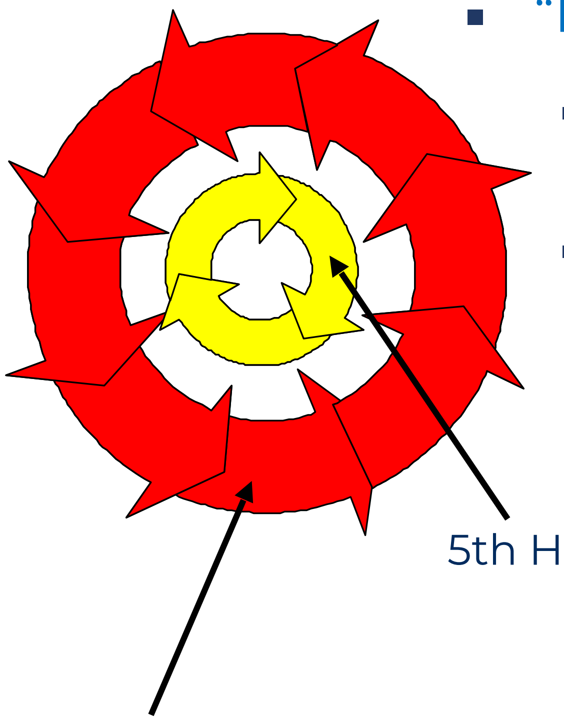
System Inefficiency with Harmonics

- Motor damage, losses (heating) from "negative sequence currents"
- High harmonics = low total power factor (utility penalties)

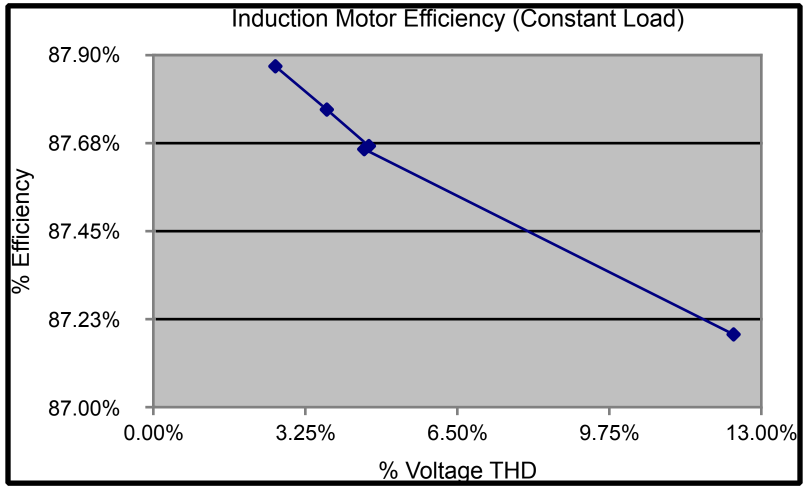


- "Negative Sequence Current"
  - Tries to rotate motor in opposite direction
  - Causes motor losses, heating and vibrations

System Inefficiency with Harmonics

Induction Motors

- Measured ~ 0.1% decrease in efficiency for each 1% increase in voltage THD
- Effects:
  - Slight capacity reduction
  - Slight increase in energy consumption
  - Higher temperatures and resultant life reduction
    - Arrhenius Equation
      “10°C increase decreases component life by 50%”



Why One Size Doesn't Fit All

IEEE-519 is a system recommendation not a product specification

The same drive in two different installations will have completely different harmonic profiles

Why spend more cleaning up harmonics than is needed to meet IEEE-519?

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Case Studies

2 case studies with 100 hp 6 pulse drive and 3% line reactor

	Case 1	**Case 2**
Utility XFMR	5 MVA	1 MVA
Local XFMR	3 MVA	500 KVA
Connected Linear Load	1200 HP	35 HP

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Case Study Results

		Case 1		Case 2	
	IEEE-519 Guideline	Distortion	IEEE-519	Distortion	IEEE-519
V_{THD} Local	3%	0.71%	**Pass**	3.55%	**Fail**
V_{THD} Main	3%	0.26%	**Pass**	1.12%	**Pass**
I_{THD} Main	8%	3.88%	**Pass**	29.33%	**Fail**

Even though both cases have identical drive loads, Case 1 meets the IEEE-519 recommendation, while Case 2 will require a 21% reduction in current distortion.

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Case Study Conclusions

		Case 1		Case 2	
	IEEE-519 Guideline	Distortion	IEEE-519	Distortion	IEEE-519
V_{THD} Local	3%	0.71%	**Pass**	3.55%	**Fail**
V_{THD} Main	3%	0.26%	**Pass**	1.12%	**Pass**
I_{THD} Main	8%	3.88%	**Pass**	29.33%	**Fail**

Even though both cases have identical drive loads, the drive harmonics in Case 1 are sufficiently diluted and no action is needed to meet IEEE-519. However, in Case 2, the drive harmonics dominate the source and some investment will be required to ensure compliance with IEEE-519.

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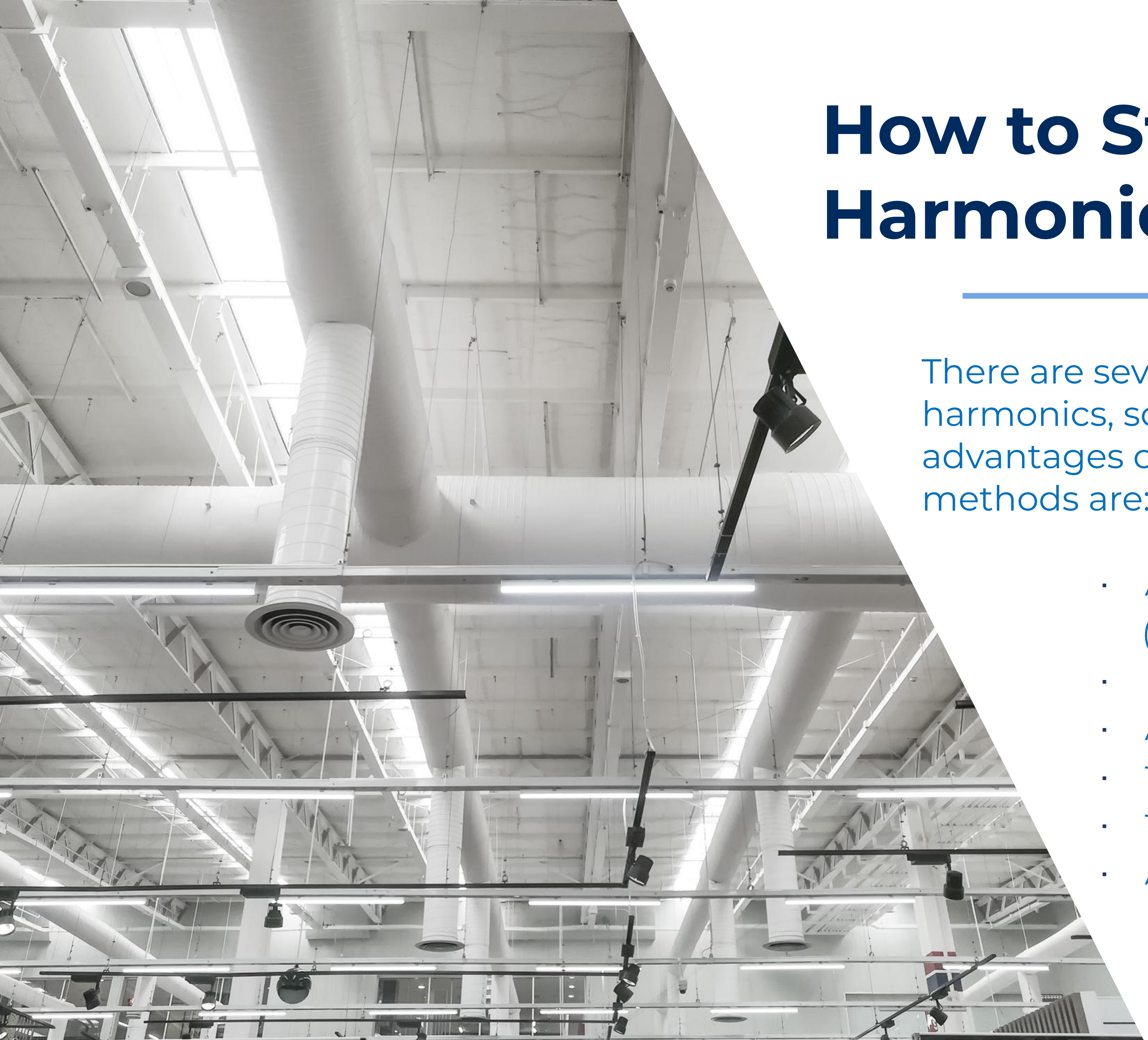

How to Stomp Out Harmonics

There are several alternatives for the attenuation of harmonics, some of which offer distinctive advantages over others. Among the most popular methods are:

- Additional inductive reactance (Reactors, ISO Transformer)
- Passive filters
- Active filters
- 12 pulse converters
- 18 Pulse converter
- Active Front End Drive- Z1000U

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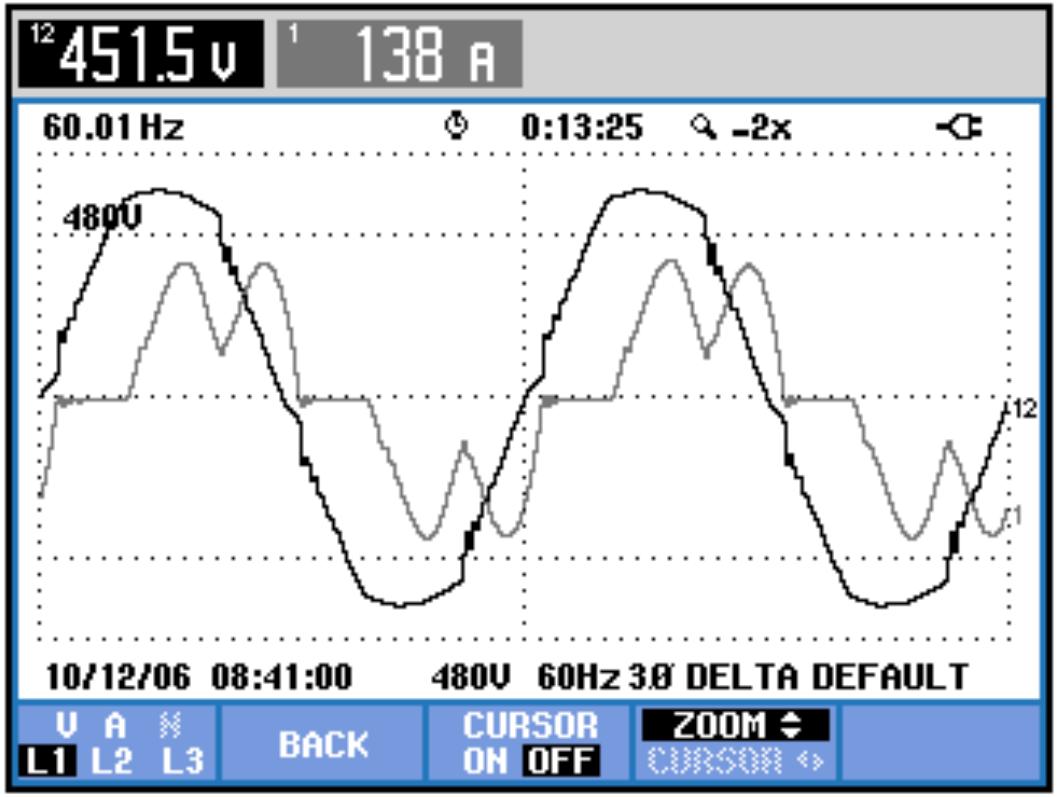
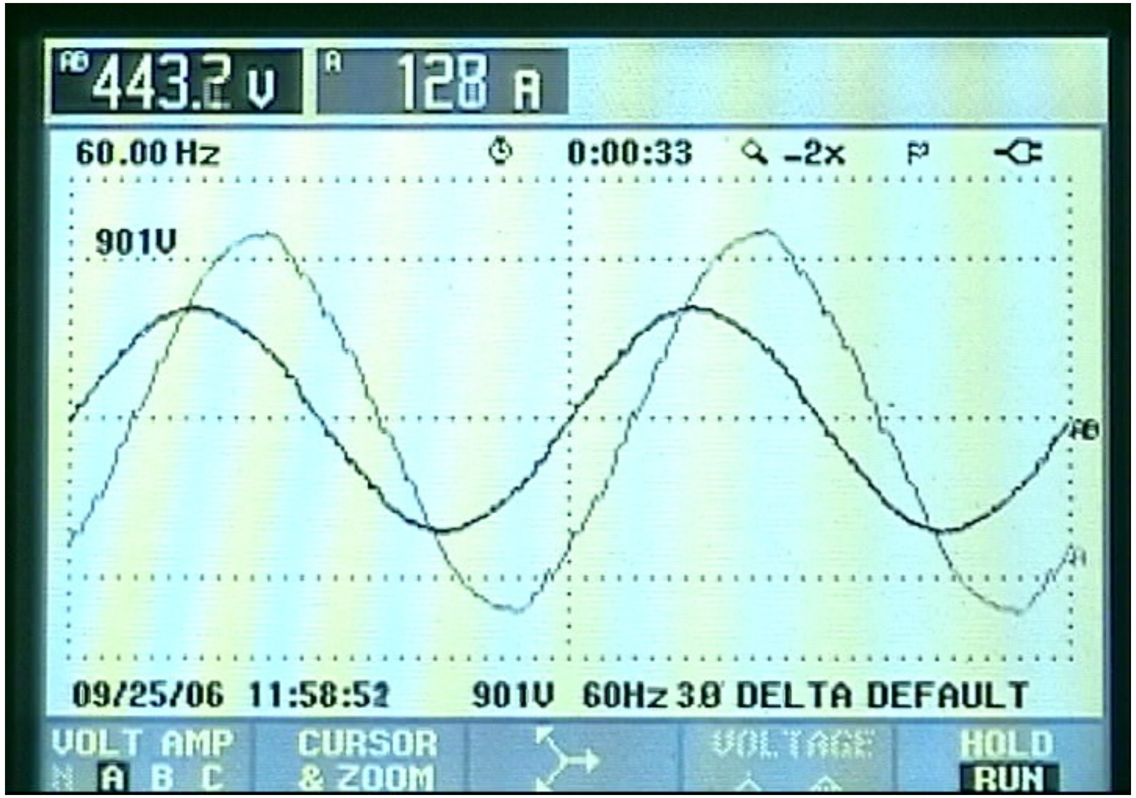
Harmonics & Cancellation

Without Cancellation



With Cancellation



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Inductive Reactance

Method

- Add a line reactor or isolation transformer to attenuate harmonics

Benefits

- Low cost
- Technically simple

Concerns

- Tends to offer reductions in only higher order harmonics
- Has little effect on the 5th and 7th harmonics
- Because of the associated voltage drop there are limits to the amount of reactance that may be added

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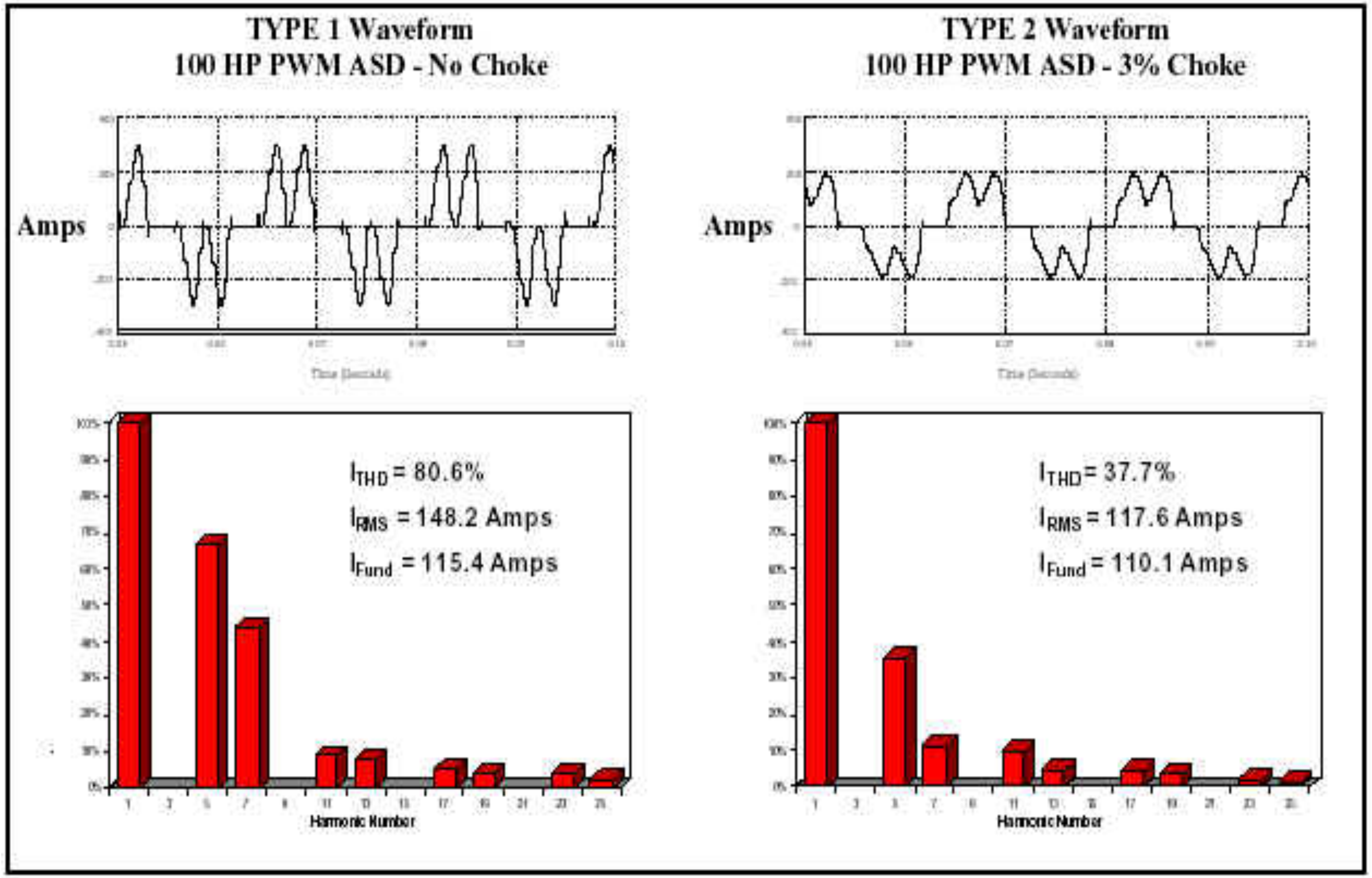
Inductive Reactance



Inductive Reactance

Harmonic Order	*Reactor Size*				
	0.5%	*1.0%*	*3.0%*	*5.0%*	*10.0%*
5th	80.0%	60.0%	40.0%	32.0%	23.0%
7th	60.0%	37.0%	16.0%	12.0%	7.5%
11th	18.0%	12.0%	7.3%	5.8%	4.0%
13th	10.0%	7.5%	4.9%	3.9%	2.8%
17th	7.3%	5.2%	3.0%	2.2%	0.4%
19th	6.0%	4.2%	2.2%	0.8%	0.2%
I_{THD} (%)	102.5%	72.2%	44.1%	35.0%	24.7%
I_T / I_1	143.0%	123.0%	109.0%	106.0%	103.0%

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Passive Filters

Method

- Provide a low-impedance path to ground for the harmonic frequencies
- Provides input reactance to mitigate higher order harmonics

Benefits

- Very cost-effective method of reducing harmonics at the source

Concerns

- Tuning the filters correctly may be challenging
- Filters are difficult to size because they can offer a path for harmonics from any source
- Failure of the filter provides no notification

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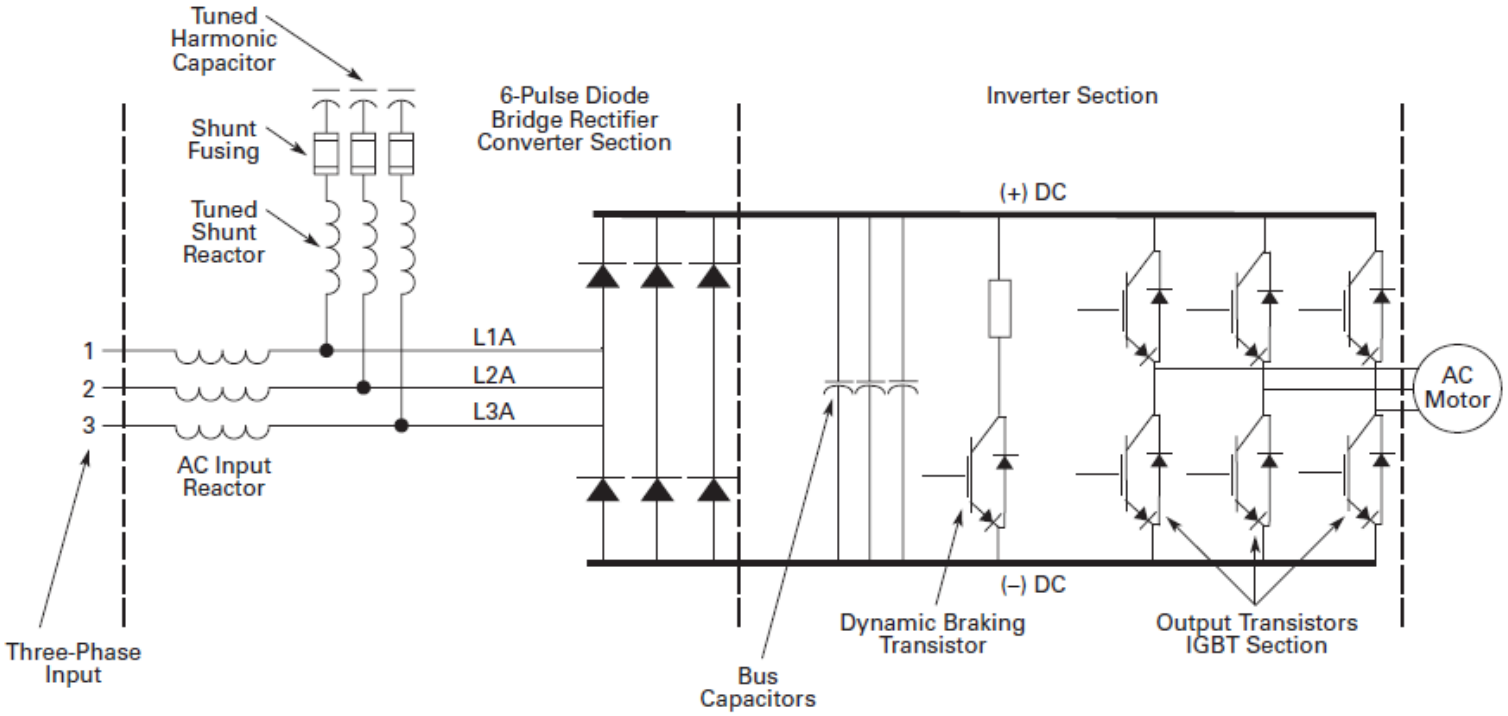
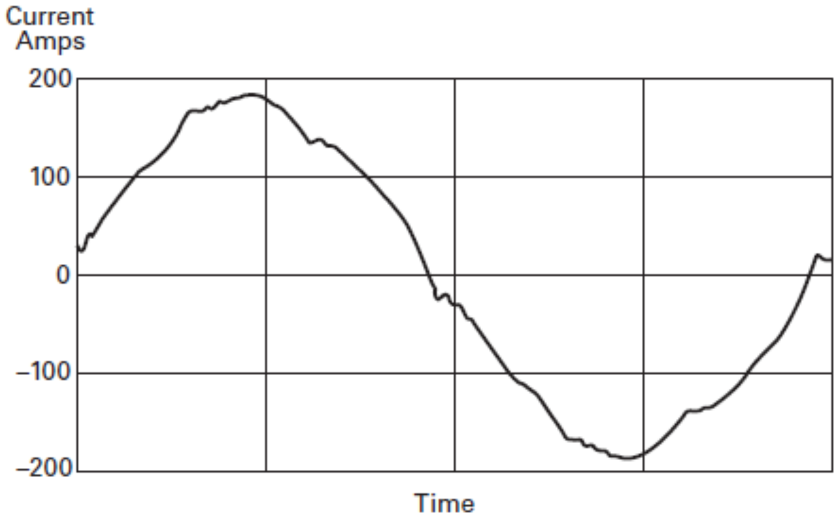
Passive Filters





Passive Filter

Current harmonics		
$I_1 = 100\%$	$I_{11} = 0.24\%$	$I_{19} = 0.50\%$
$I_5 = 3.76\%$	$I_{13} = 1.1\%$	$I_{23} = 0.55\%$
$I_7 = 1.65\%$	$I_{17} = 0.80\%$	$I_{25} = 0.80\%$
Power = 100 hp		
$H_C = 8.6$ Amps		

Active Filters

Method

- Inject equal and opposite harmonics onto the power system to cancel those generated by other equipment

Benefits

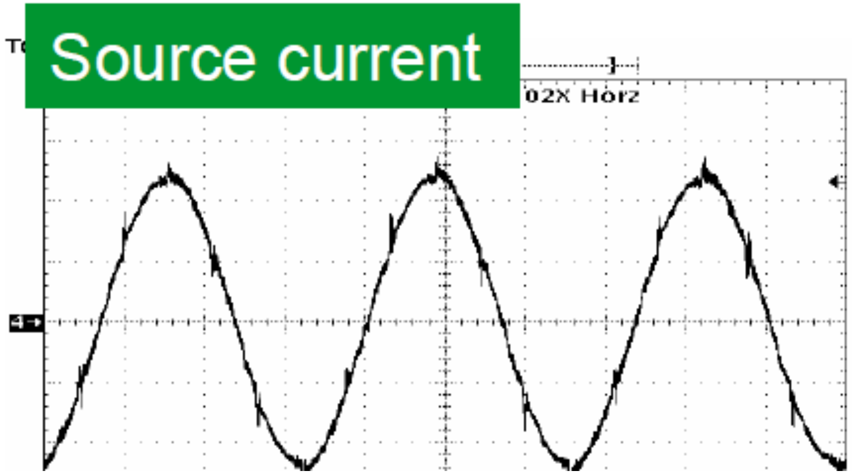
- Have proven very effective in reducing harmonics well below required levels
- New designs do not require power line to be opened

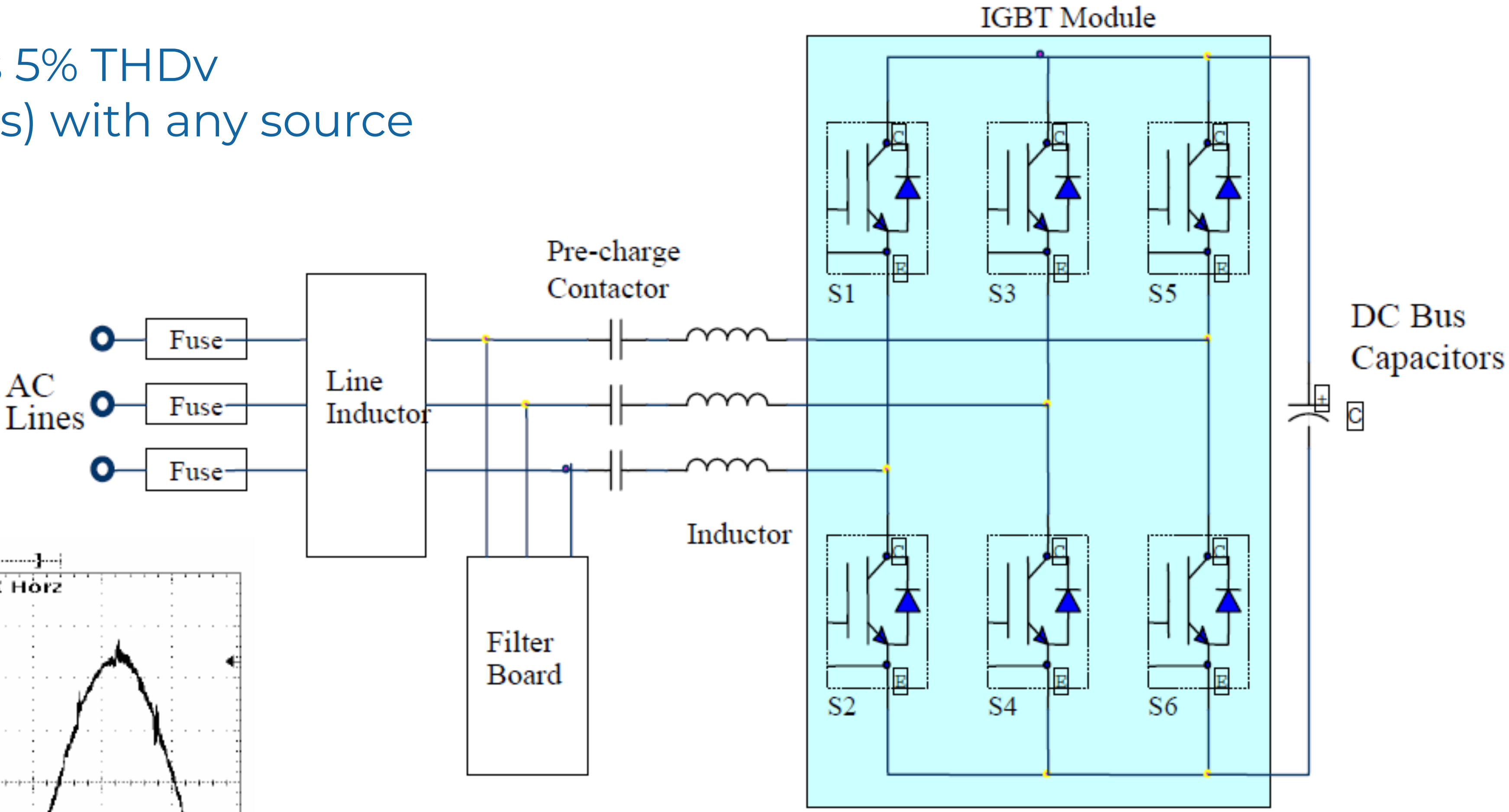
Concerns

- The high-performance inverter required for the harmonic injection is costly

Active Filters

5% TDD guarantees 5% THDv
(caused by the loads) with any source





12 Pulse Converter

Method

- Two separate converter bridges supply a single DC bus
- The two bridges are fed from phase-shifted supplies

Benefits

- Very effective in the elimination of 5th and 7th harmonics
- Stops harmonics at the source
- Insensitive to future system changes

Concerns

- May not meet the IEEE standards in every case
- Does little to attenuate the 11th and 13th harmonics

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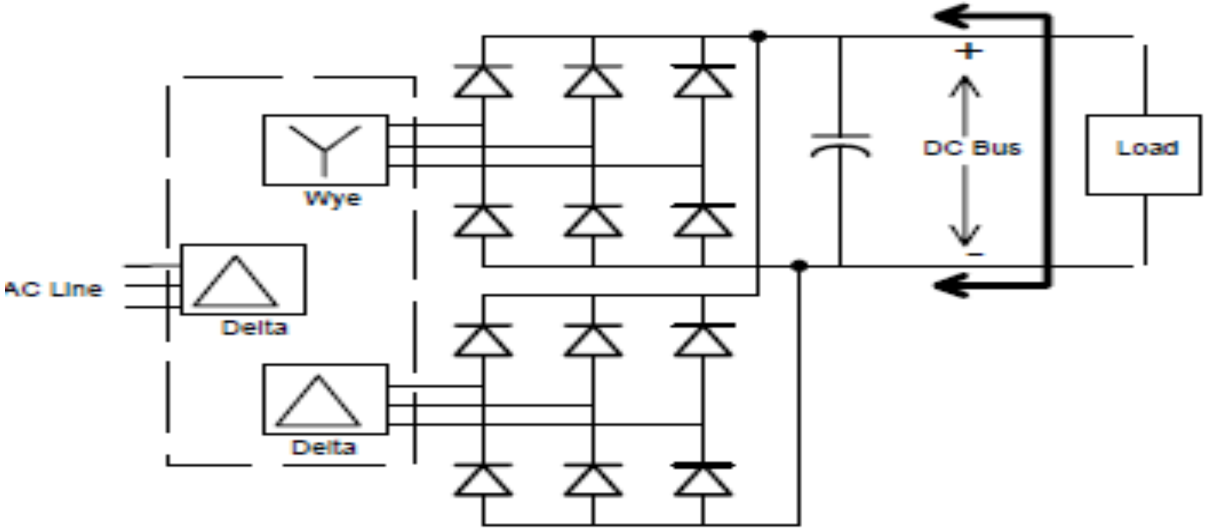
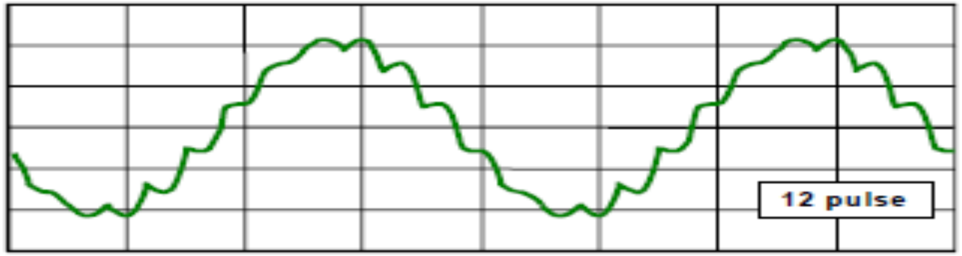
12 Pulse Converter





Externally mounted 3 winding transformer; more wire and cabling; complicated

Current slightly distorted TDD 8% to 15% (depending on network impedance

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18 Pulse Converter

Method

- 18-Pulse converter design which draws an almost purely sinusoidal waveform from the source

Benefits

- Meets the IEEE standards in every case
- Attenuates all harmonics up to the 35th
- Insensitive to future system changes
- Increases life of drive through incredibly stable DC bus voltage (18 small inputs instead of 6 large ones)

Concerns

- Not cost effective at small HP levels (50HP and smaller)

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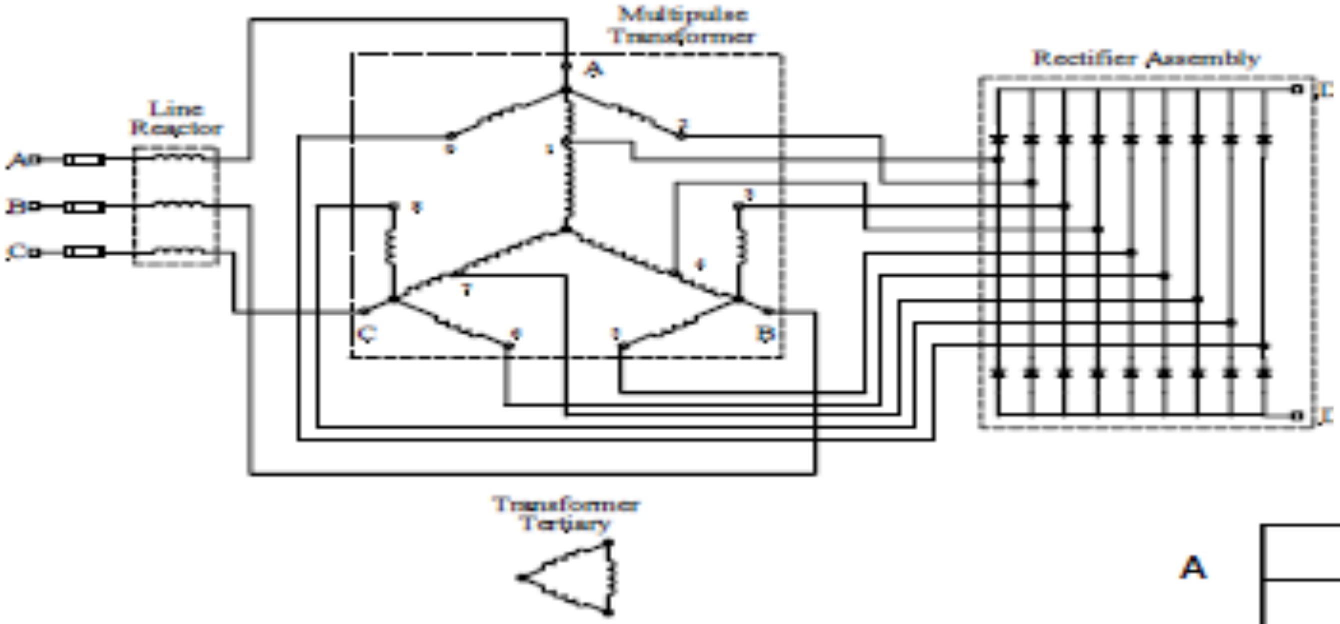
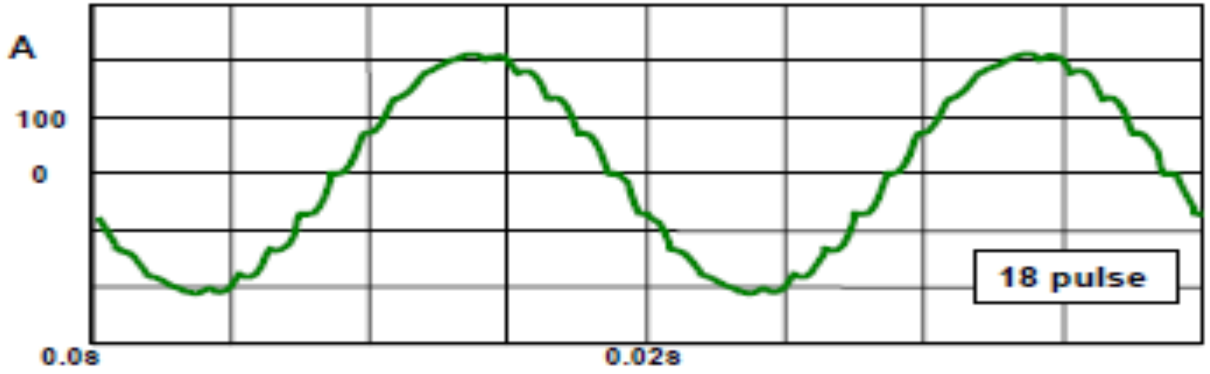
18 Pulse Converter



Current wave form good TDD 5% to 7% (depending on network impedance)



Larger footprint, more steel & copper (losses)

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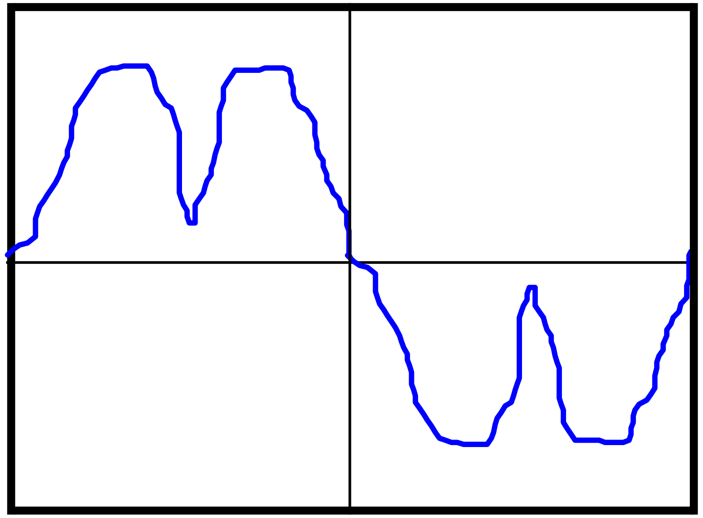
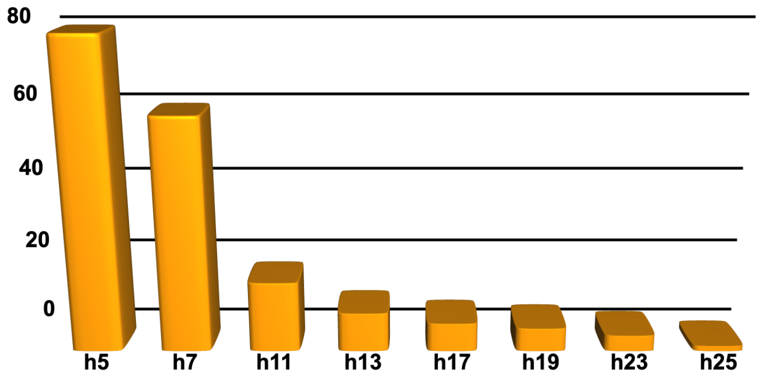
AC Drives & Harmonics

6-pulse converter without choke waveform:



Harmonic Content

h_5 = 79.5%
h_7 = 60.1%
h_{11} = 18.2%
h_{13} = 10.0%
h_{17} = 7.3%
h_{19} = 6.0%
h_{23} = 4.1%
h_{25} = 1.2%



Note that diode converter bridges produce harmonics according to the rule h = nk +/- 1, where *h* is the harmonic produced, *n* is the number of diodes and *k* is an integer. Note magnitude of lower order harmonics.

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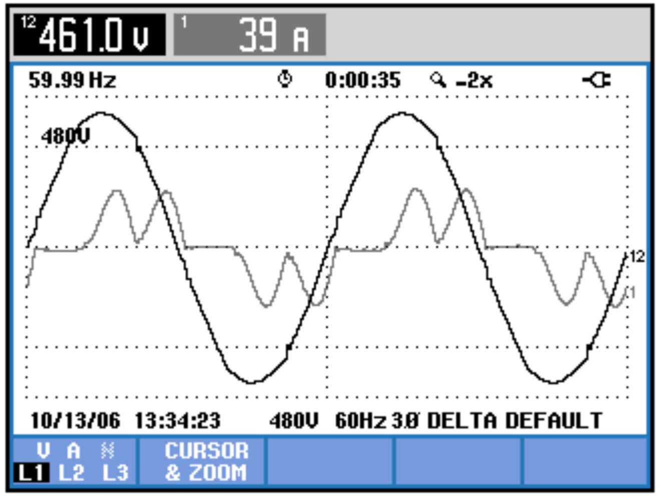
AC Drives & Harmonics

6-pulse converter with 3% Reactor waveform:

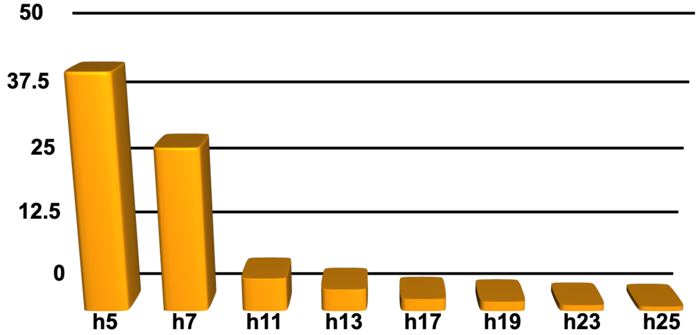


Note that diode converter bridges produce harmonics according to the rule h = nk +/- 1, where *h* is the harmonic produced, *n* is the number of diodes and *k* is an integer. Harmonic content is approximately 50% of that produced by a converter without choke.

Harmonic Content

h_5 = 42.5%
h_7 = 29.38%
h_{11} = 6.10%
h_{13} = 4.06%
h_{17} = 2.26%
h_{19} = 1.77%
h_{23} = 1.12%
h_{25} = 0.86%

Harmonic Distribution



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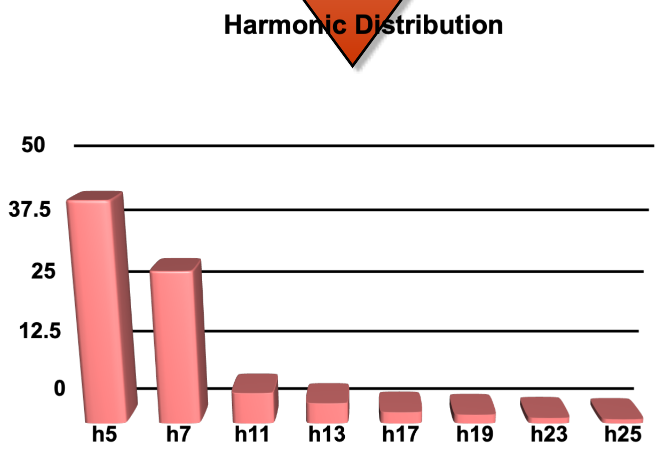
Harmonic Comparison of C-H Drives

6 Pulse Converter w/ reactor

35-50% I_{THD}

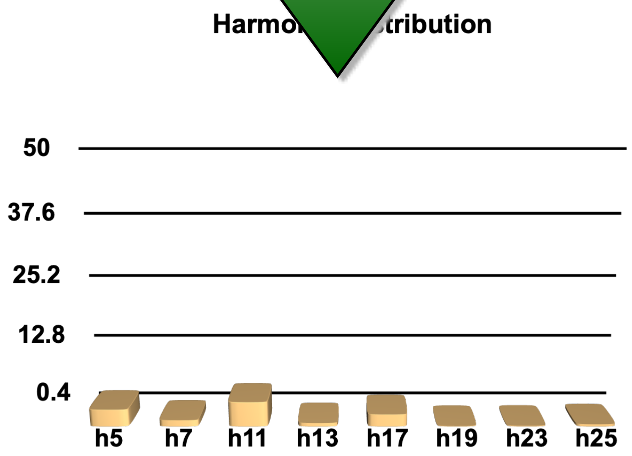
XYZ **Company**



12 Pulse Converter

8-15% I_{THD}

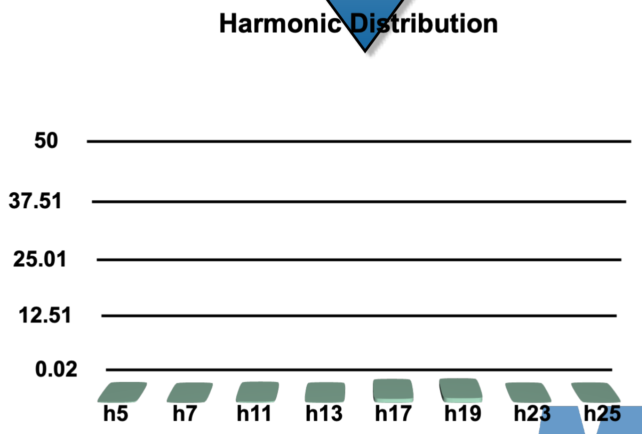
XYZ **Company**



18 Pulse Converter

5-7% I_{THD}

XYZ **Company**



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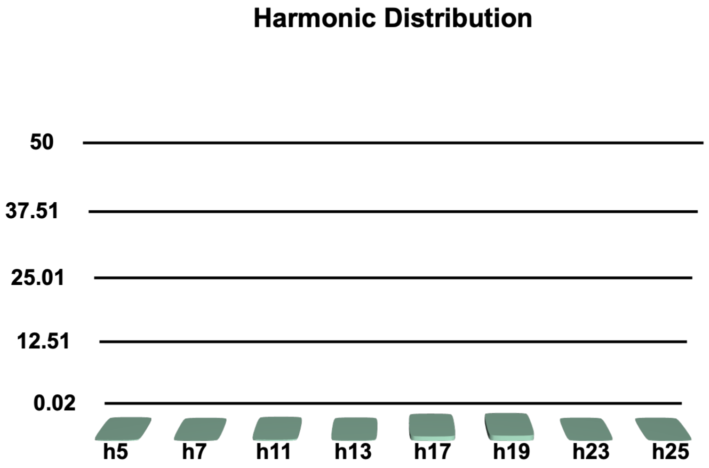
Harmonic Comparison of C-H Drives

Active Front End Drive

<5% I_{THD}

Z1000U



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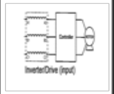
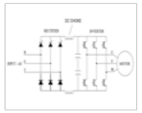
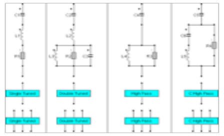
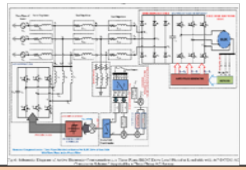
Comparisons

		Drive Options				Input Filter options			
		AC to AC	6 pulse	12 pulse	18 pulse	Line reactor (aka input reactor)	DC Link Reactor (aka dV/dt reactor)	tuned passive harmonic filter	active harmonic filter
									
Benefits	Reduces input line harmonics	yes	no	yes	yes	yes	yes	yes	yes
	protects drive from current spikes	yes	no	yes	yes	yes	yes	yes	yes
	reduces dv/dt and di/dt rates	yes	no	yes	yes	no	yes	no	yes
	reduces DC bus transient overvoltage	no DC bus	no	yes	yes	no	yes	no	no
	reduces common mode (shaft) currents	yes	no	yes	yes	n/a			
	optimized for ___ switching frequencies	yes	can be	yes	yes	no	no	yes	yes
Disadvantages	voltage drop	no	no	yes	yes	yes	no	no	no
	size & weight issues	no	no	yes	yes	no	no	yes	yes
	multiple connection	no	no	yes	yes	yes	no	yes	yes
	sensitive to unbalance	no	no	yes	yes!!!	no	no	no	yes
	All Nema 1 Configured								
mounting and cost	30 HP @ 480v	$ 7,856.00	$ 2,770.00	$ 10,085.00	$ 11,870.00			$ 3,234.00	Sized for corrective amps and will not
	Size & Weight	60"x22"x22" **285lb**	40"x9"x15" **70lb**	84"x38"x31" **440lb**	84"x38"x31" **440lb**			32"x18"x13"	be a standard. Usually built to order.
	40 HP @ 480v	$ 8,952.89	$ 3,290.00	$ 10,557.00	$ 12,421.00			$ 3,735.00	
	Size & Weight	60"x22"x22" **315lb**	40"x9"x15" **75lb**	84"x38"x31" **440lb**	84"x38"x31" **440lb**			32"x18"x13"	Usually not sized for individual drive
	50 HP @ 480v	$ 10,193.00	$ 4,012.00	$ 11,851.00	$ 13,942.00			$ 4,136.00	locations, applied to handle multiple
	Size & Weight	60"x22"x22" **325lb**	46"x11"x15.5" **94lb**	84"x38"x31" **593lb**	84"x38"x31" **602lb**			32"x18"x13"	non-linear loads connected to a single
	60 HP @ 480v	$ 11,388.00	$ 4,689.00	$ 13,211.00	$ 15,542.00			$ 4,588.00	power distribution system.
	Size & Weight	60"x22"x22" **340lb**	46"x11"x15.5" **108lb**	84"x38"x31" **614lb**	84"x38"x31" **633lb**			32"x18"x13"	
	75 HP @ 480v	$ 13,781.00	$ 5,334.00	$ 15,145.00	$ 17,818.00			$ 5,029.00	
	Size & Weight	60"x30"x22" **425lb**	46"x11"x15.5" **118lb**	84"x38"x31" **695lb**	92"x44x35" **755lb**			32"x18"x13"	
	100 HP @ 480v	$ 15,849.00	$ 6,740.00	$ 17,544.00	$ 20,642.00			$ 6,312.00	
	Size & Weight	60"x30"x22" **440lb**	43"x26"x19" **264lb**	92"x44x35" **755lb**	92"x44x35" **902lb**			32"x18"x13"	
	125 HP @ 480v	$ 18,487.00	$ 7,955.00	$ 19,799.00	$ 23,293.00			$ 7,417.00	
	Size & Weight	86"x41"x32" **765lb**	54"x34"x21" **439lb**	92"x44x35" **833lb**	84"x66"x31" **1107lb**			56"x18"x17"	

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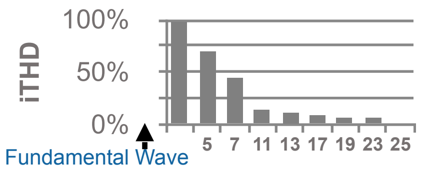
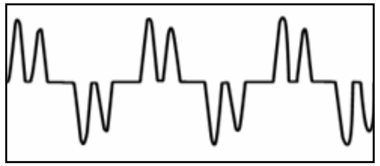
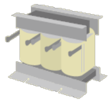
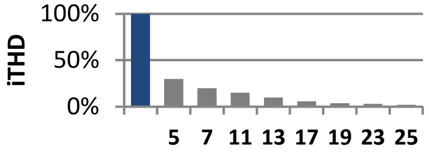
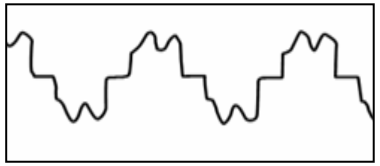
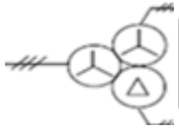
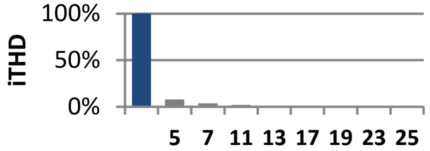
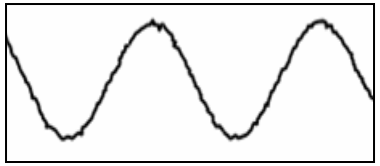
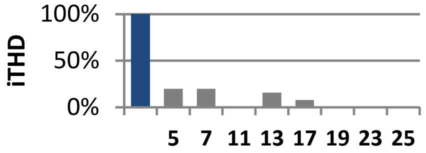
Harmonics Performance Comparisons

		Current Harmonics	Current Waveform	Current Distortion	True Power Factor*
Variable Frequency Drive without Reactor	VFD			88%	0.75
Variable Frequency Drive with DC Reactor	 VFD			33%	0.90
Variable Frequency Drive with Multi-Pulse	 VFD			3 to 5%	0.98
HVAC Matrix Variable Frequency Drive	HVAC Matrix			6 to 12%	0.95

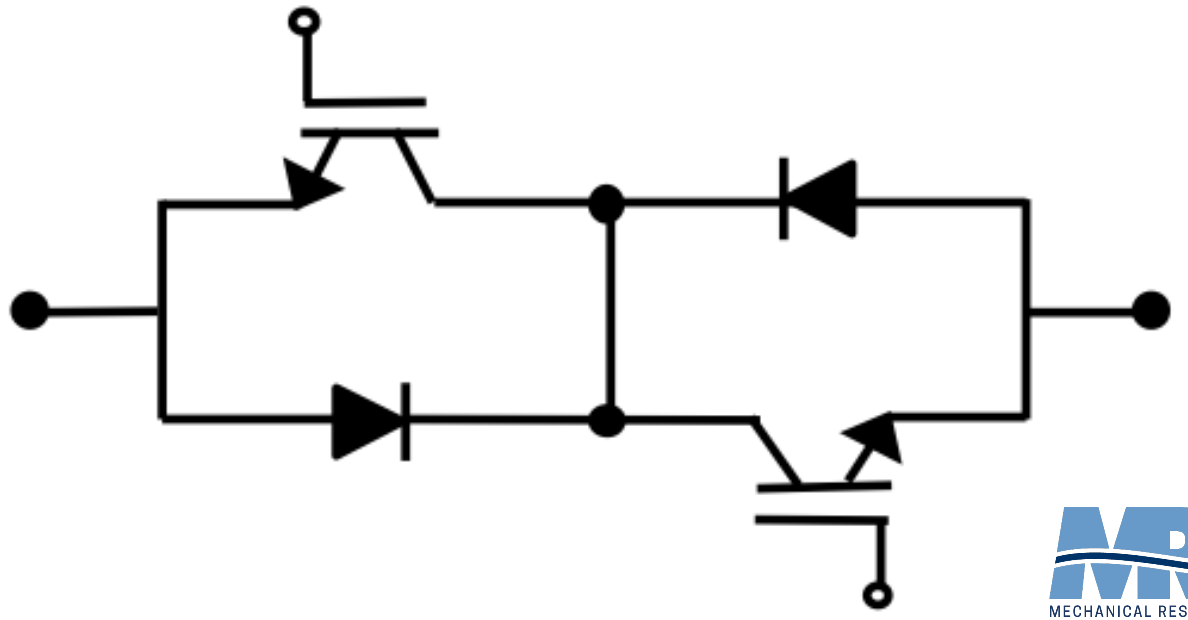
*60Hz at full load

MECHANICAL RESOURCE GROUP

Matrix IGBT Bi-directional Switch

Circuit of Insulated Gate Bi-Polar Transistors (IGBT) and diodes

- Enables bi-directional switching between input phases
- Switching produces simulated sine wave output
- Enables regenerative power back to the supply



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Matrix Drive Topology

AC input to variable frequency AC output

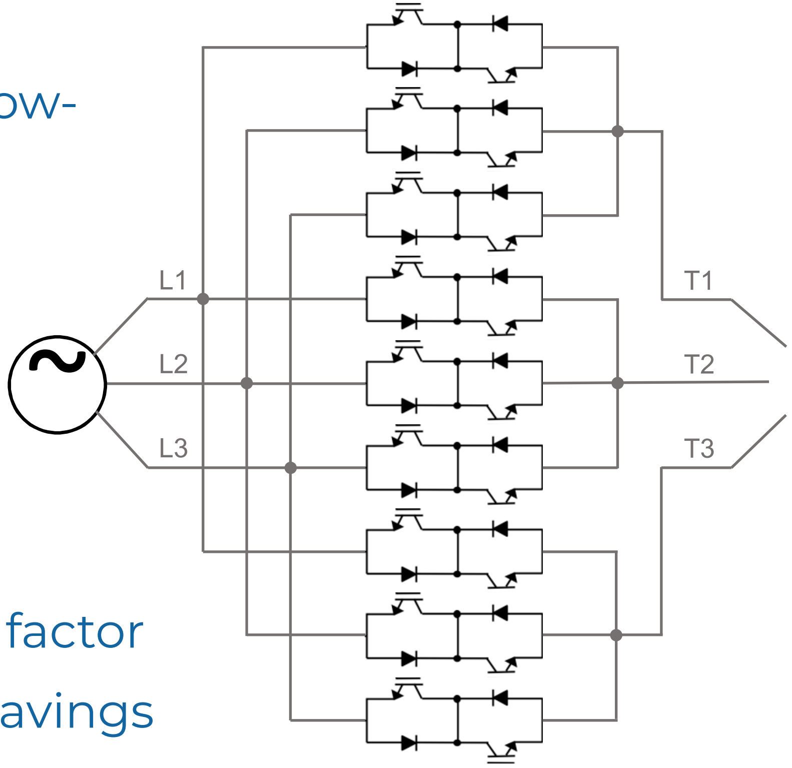
- Nine bi-directional switches
- No DC bus

Price

- Comparable to other low-harmonic solutions
- Not comparable to conventional drives

Advantages

- Ultra-low input harmonics
- Near-unity true power factor
- Regenerative energy savings
- Smaller than other harmonic solutions



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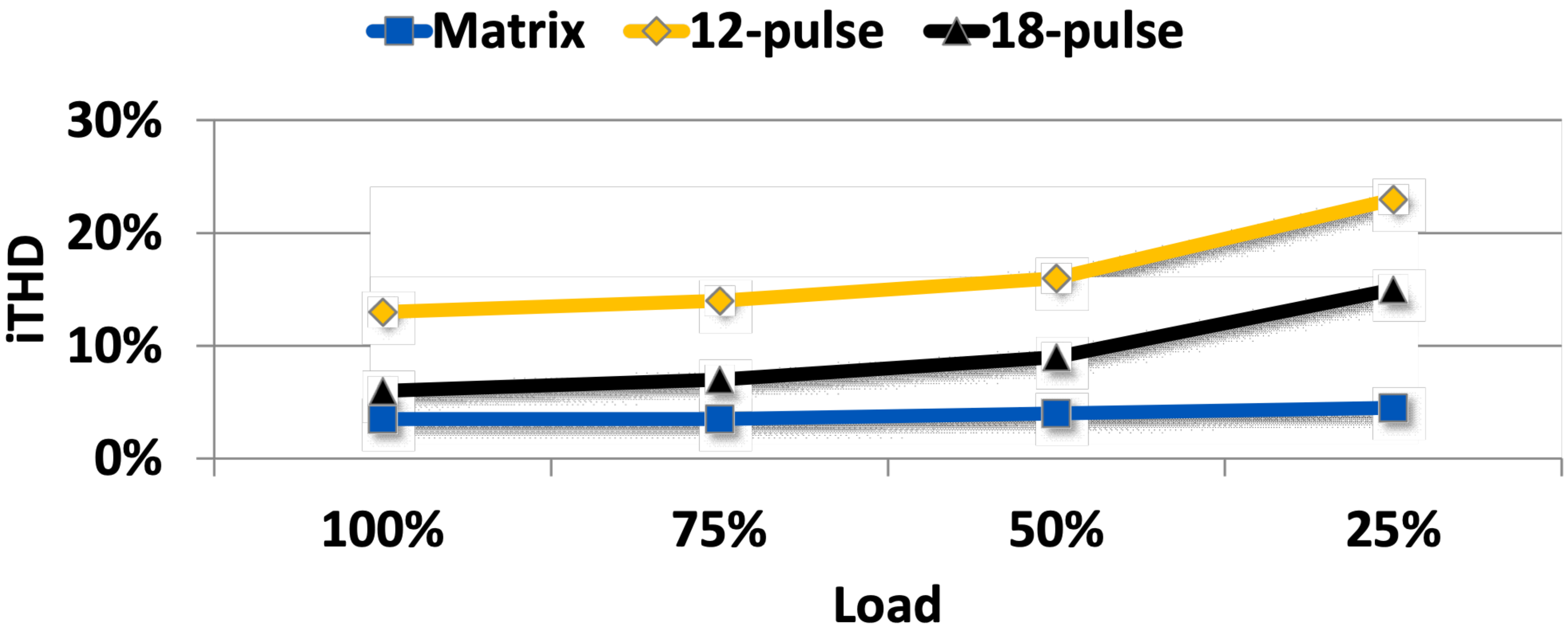
Z1000U vs. Multi-Pulse Harmonics Comparison

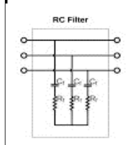
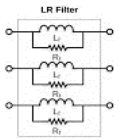
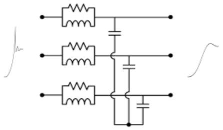
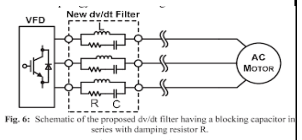
Excellent low harmonic performance over wide load range



Output Solutions

	All Nema 1 Configured		
mounting and cost	30 HP @ 480v	$ 4,672.00	$ 982.00
	Size & Weight	32"x18"x13"	12"x8"x 12"
	40 HP @ 480v	$ 4,672.00	$ 1,071.00
	Size & Weight	36"x19"x30"	12"x8"x 12"
	50 HP @ 480v	$ 5,785.00	$ 1,395.00
	Size & Weight	36"x19"x30"	12"x8"x 12"
	60 HP @ 480v	$ 5,852.00	$ 1,914.00
	Size & Weight	36"x19"x30"	12"x8"x 12"
	75 HP @ 480v	$ 6,250.00	$ 2,157.00
	Size & Weight	36"x19"x30"	16.5"x18"x30"
	100 HP @ 480v	$ 6,496.00	$ 2,157.00
	Size & Weight	36"x19"x30"	16.5"x18"x30"
	125 HP @ 480v	$ 7,327.00	$ 2,317.00
	Size & Weight	36"x19"x30"	16.5"x18"x30"

Output filter Options

		R-C Low Pass Filter	L-R Low Pass Filter	Sine-Wave Filter	dv/dt Filter (aka load reactors)	High frequency common-mode filters
						
Benefits	Reduces input line harmonics	Passes low frequency and reduces high frequencies				
	protects drive from current spikes			ok up to 150 m	ok up to 500 m	does not reduce stress on motor insulation
	reduces dv/dt and di/dt rates					
	reduces DC bus transient overvoltage					
	reduces common mode (shaft) currents			yes	yes	yes
	optimized for ___ switching frequencies		High	High	Low	
Disadvantages	voltage drop			typically 4-10% voltage drop	typically 0.5% voltage drop	n/a
	size & weight issues					
	multiple connection					
	sensitive to unbalance					

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Thank you! Ready to Learn More?

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