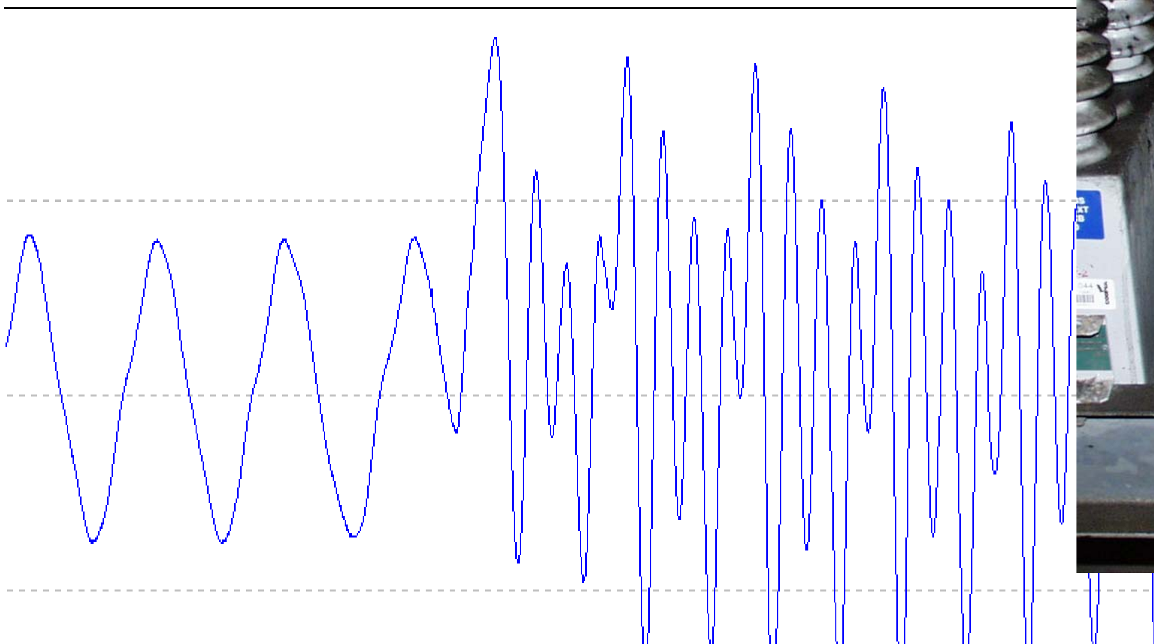

Harmonic Distortion from Variable Frequency Drives

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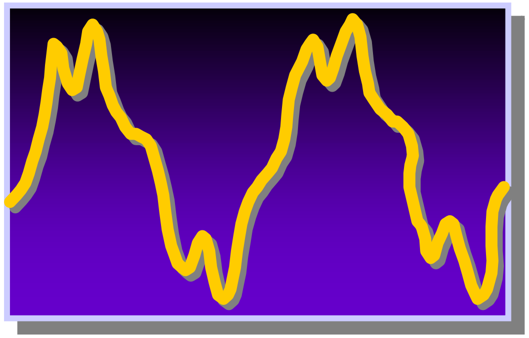
Harmonics

- Introduction to Harmonics
- Symptoms
- Expected Harmonics from VFD's
- Harmonic Resonance
- Understanding IEEE519-1992
- Harmonic Solutions for VFD's

Harmonic Distortion

- Harmonic problems are becoming more apparent because more harmonic producing equipment is being applied to power systems
  - VFD's
  - Electronic Ballasts
  - UPS
- Additionally, in many cases, these electronic based devices can also be more sensitive to harmonics



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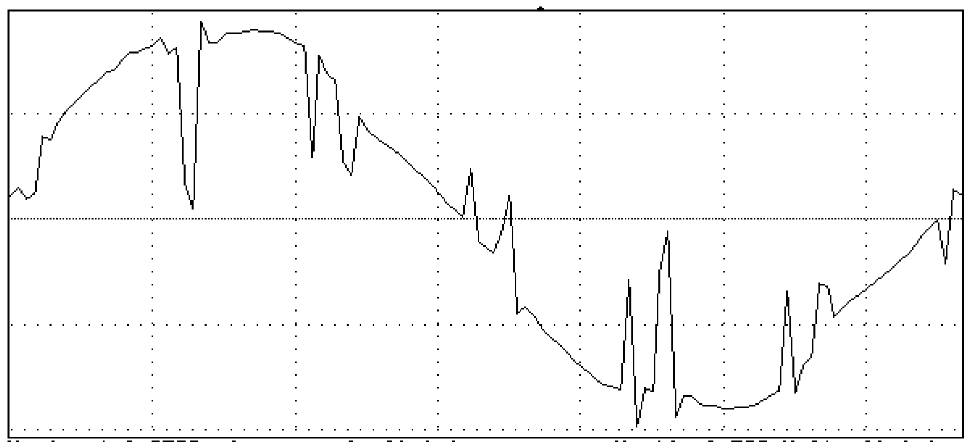
“Harmonics are not a problem unless they are a problem!”



Horizontal 2500 microseconds/division Vertical 500 Volts/division
Vrms: Prev=610.7, Min=605.5, Max=605.5 - Worst Imp= 0 Vpk, 0 deg

Harmonic Symptoms/Concerns

- Equipment Failure and Misoperation
  - Notching (electronic control malfunctioning, regulator misoperation)
  - Overheating/Failure (transformers, motors, cables/neutral)
  - Nuisance Operation (fuses, breakers, PC lock-ups)
  - Insulation deterioration
  - Capacitor resonance / failure

- Economic Considerations
  - Oversizing neutrals, transformers, generators
  - Losses/Inefficiencies/PF Penalties
  - Inconsistent meter reading
- Application of Power Factor Correction Capacitors
- Other Issues
  - Metering – do you really have a problem?
  - Marketing hype – buy my product!
  - "Specsmanship" - Misinterpretation of the IEEE-519 Standard

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Expected Harmonics

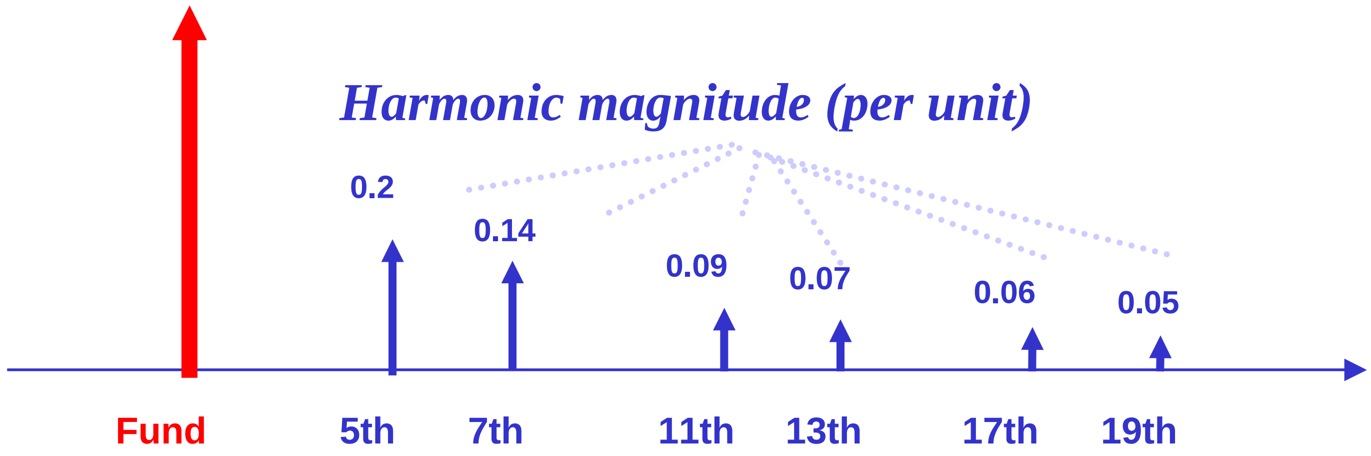
Source	Typical Harmonics*
6 Pulse Drive/Rectifier	5, 7, 11, 13, 17, 19…
12 Pulse Drive/Rectifier	11, 13, 23, 25…
18 Pulse Drive	17, 19, 35, 37…
Switch-Mode Power Supply	3, 5, 7, 9, 11, 13…
Fluorescent Lights	3, 5, 7, 9, 11, 13…
Arcing Devices	2, 3, 4, 5, 7...
Transformer Energization	2, 3, 4

* Generally, magnitude decreases as harmonic order increases

H = NP+/-1

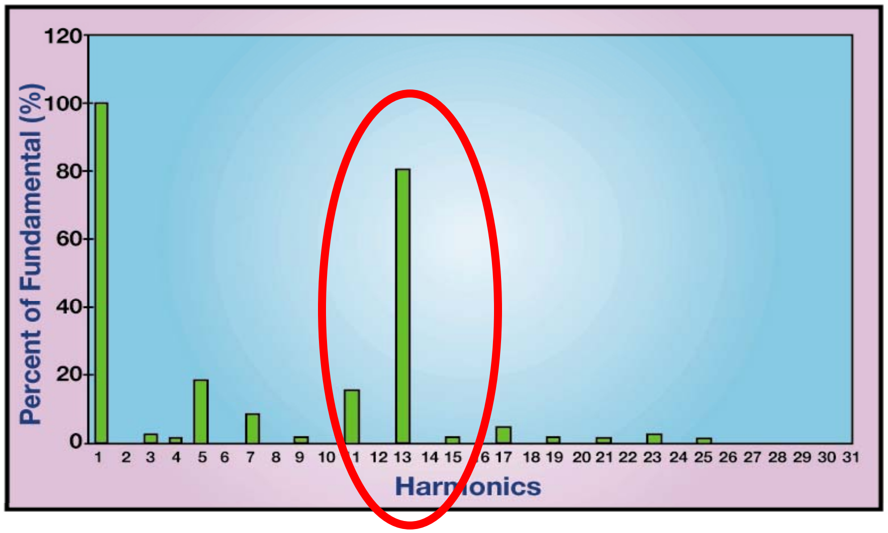
i.e. 6 Pulse Drive - 5, 7, 11, 13, 17, 19,…

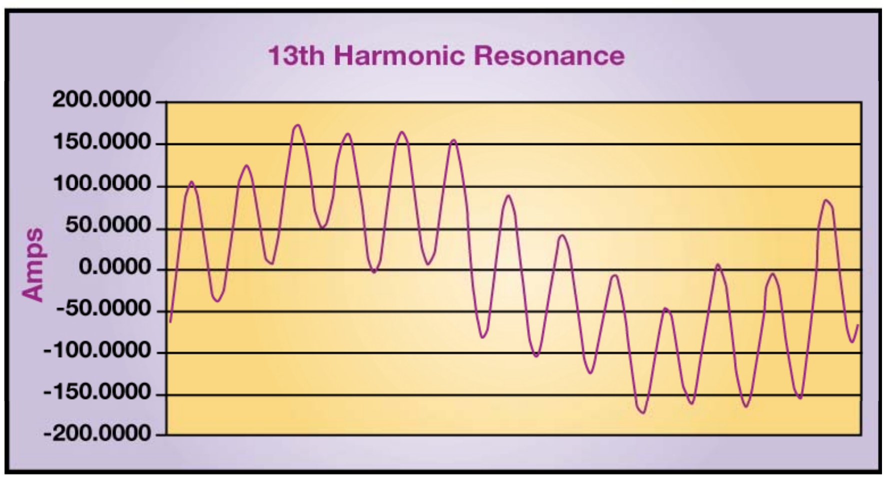
Harmonic Spectrum



- Normal VFD Harmonic Spectrum
  - Lower harmonic orders have the higher magnitudes
  - Magnitudes should decline as the harmonic order increases

Harmonic Spectrum





- If the harmonic spectrum exhibits abnormal magnitudes, it is a good sign of harmonic resonance
- Typically caused by interaction with Power Factor Correction Capacitors

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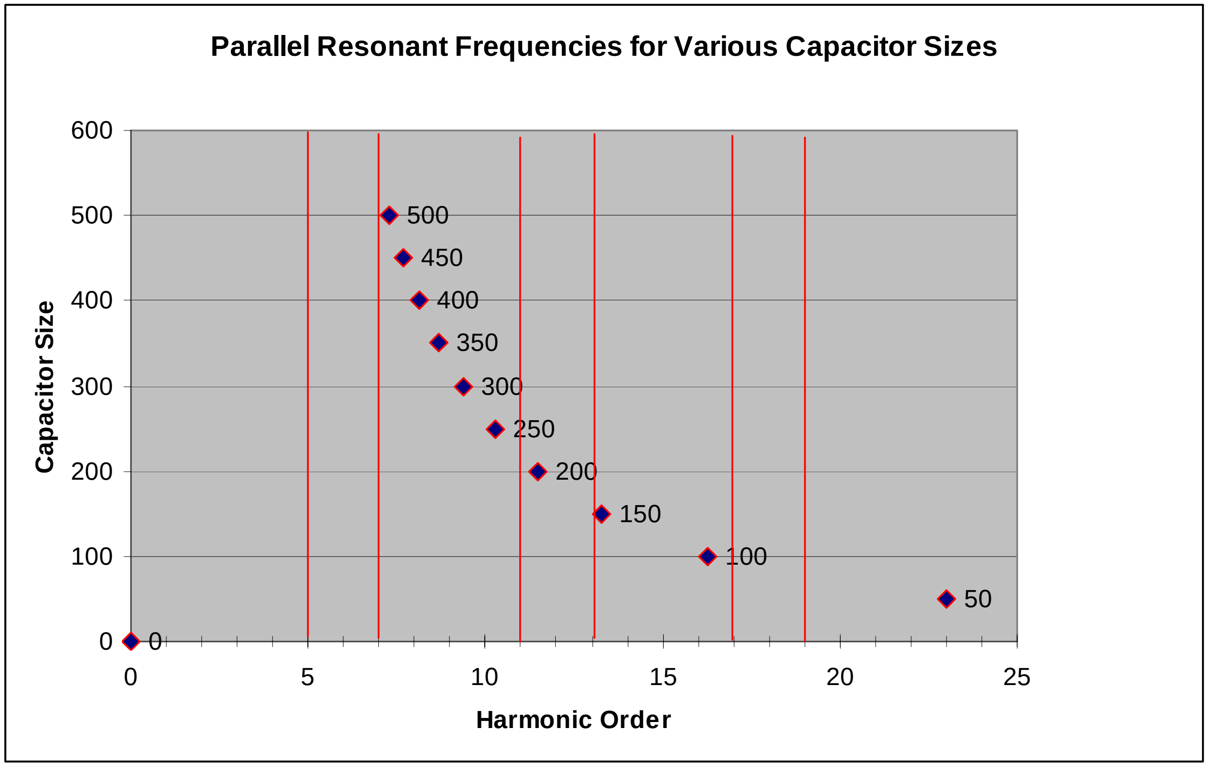
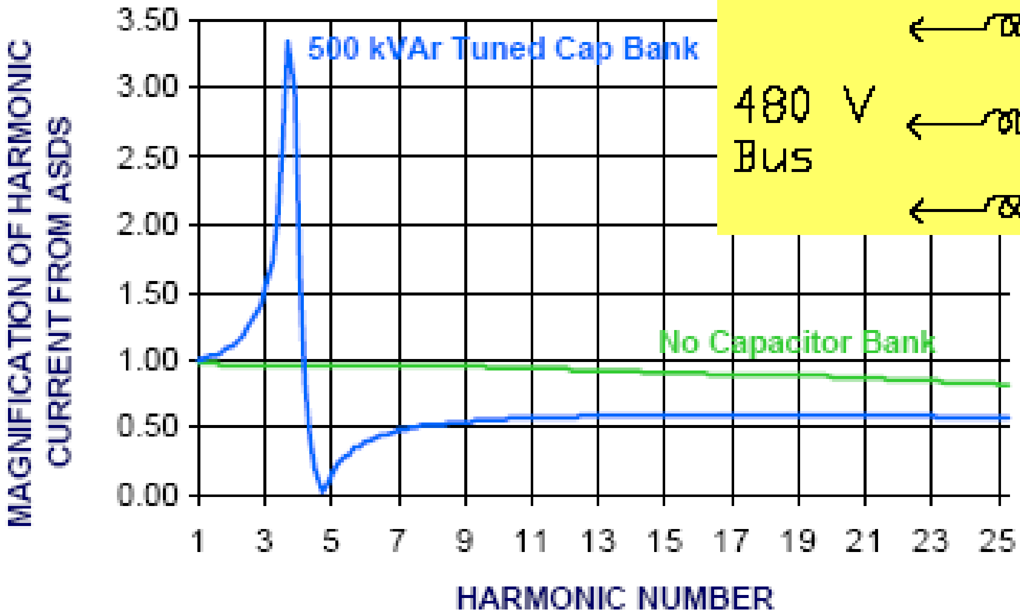
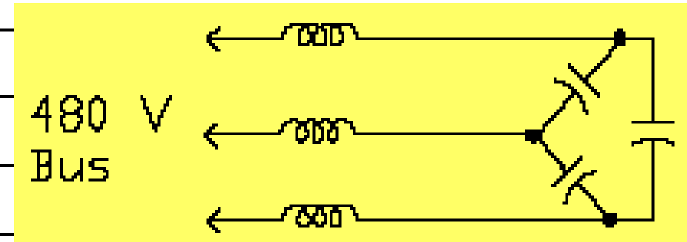
Power Factor Correction and Harmonics



- PFCC's change the resonant frequency of the distribution system
  - Depends on the size of the caps and the impedance of the system
- Can magnify any existing harmonics

Power Factor Correction and Harmonics





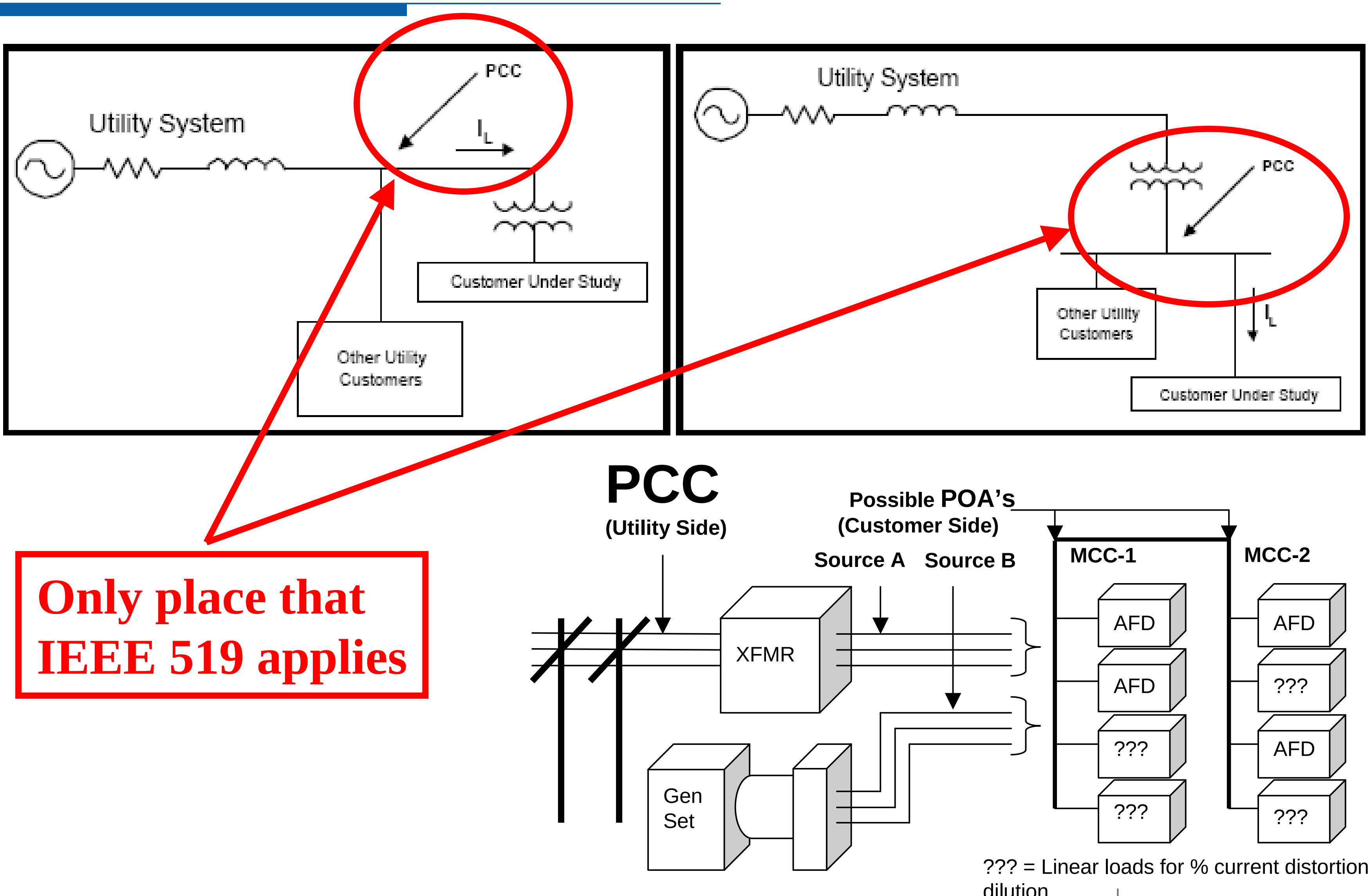
- Reactors can be added to the PFCC bank to create a tuned filter
  - Tuned to a ‘non-characteristic’ harmonic (i.e. 4.7^{th})
- Becomes a sink for 5^{th} harmonic currents

IEEE 519 - 1992

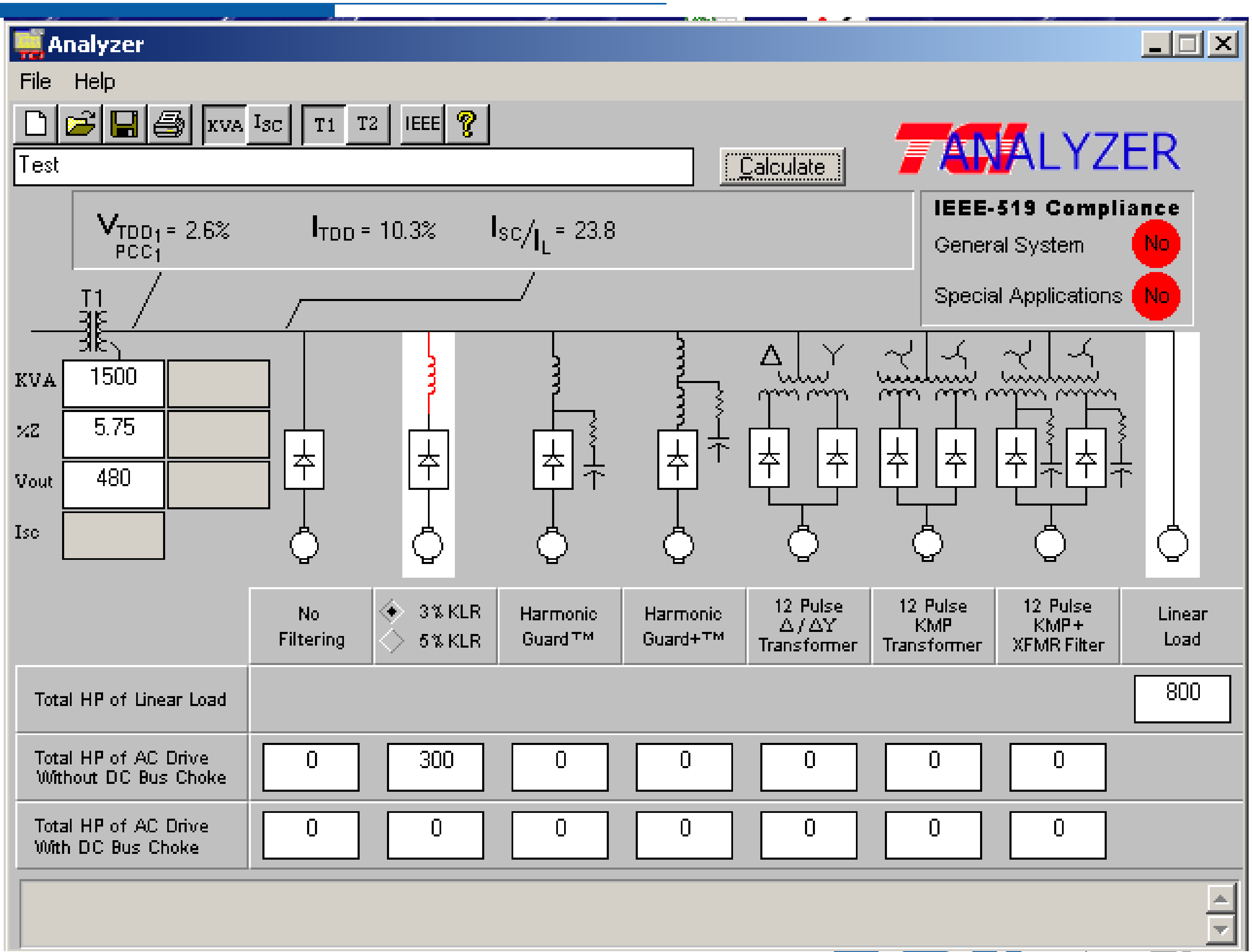
- It is currently the only recognized industry standard in North America for setting harmonic limits (voltage and current)
- Designed to limit utility harmonics as well as customer harmonic contribution to the utility grid
- Standard ONLY applies to the Point of Common Coupling (PCC)
  - The point where the utility connects to multiple customers
  - If a utility transformer is provided, the PCC is most likely on the LINE side of the transformer

IEEE 519 is widely misunderstood and misapplied in the industry

IEEE 519 – Point of Common Coupling (PCC)



Harmonic Calculators



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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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IEEE 519 - Voltage Distortion Limits

- IEEE 519 sets limits for both Voltage distortion and Current distortion

Harmonic Voltage Distortion Limits

Bus Voltage at PCC (V_n)	Individual Harmonic Voltage Distortion (%)	Total Voltage Distortion - THD_{V_n} (%)
$V_n \leq 69kV$	3.0	5.0
$69kV < V_n \leq 161kV$	1.5	2.5
$V_n > 161kV$	1.0	1.5

$$THD_{V_n} = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_n} \times 100\%$$

IEEE 519 - Current Distortion Limits

Not THD

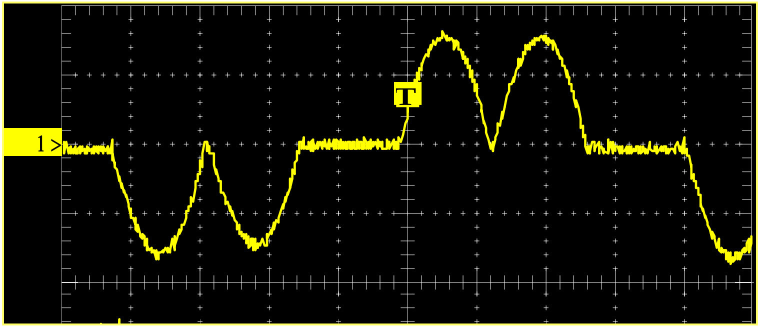
Harmonic Current Distortion Limits (I_h and TDD) in % of I_L (≤ 69kV)

I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	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**

- Current distortion limits are dependent on the “stiffness” of the source (I_{sc}/I_L)
  - A stiffer source has lower impedance = more distortion allowed
  - A softer source (i.e. generator) has higher impedance = less distortion allowed
- Current distortion limits are typically much more difficult to reach than Voltage distortion limits

THD vs. TDD

- THD(I)= Total Harmonic Current Distortion
  - *Measured* distortion on actual instantaneous current flowing
  - "Sinewave Quality Factor"
    - Lower the % THD, the closer the current waveform is to a true sinewave
  - Not used anywhere in IEEE 519



THD = 80%

Is this acceptable? Depends on system full load, % linear load, etc.

THD vs. TDD

- TDD(I) = Total Current Demand Distortion
  - *Calculated* harmonic current distortion against the full load (demand) level of the electrical system

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \times 100\%$$

Full load of the system

  - The greater the amount of Linear load, the less of an issue the current distortion becomes
  - Looks at the full capacity of the system
    - If non-linear loads are a small % of the full system current demand, the TDD is less

TDD vs THD

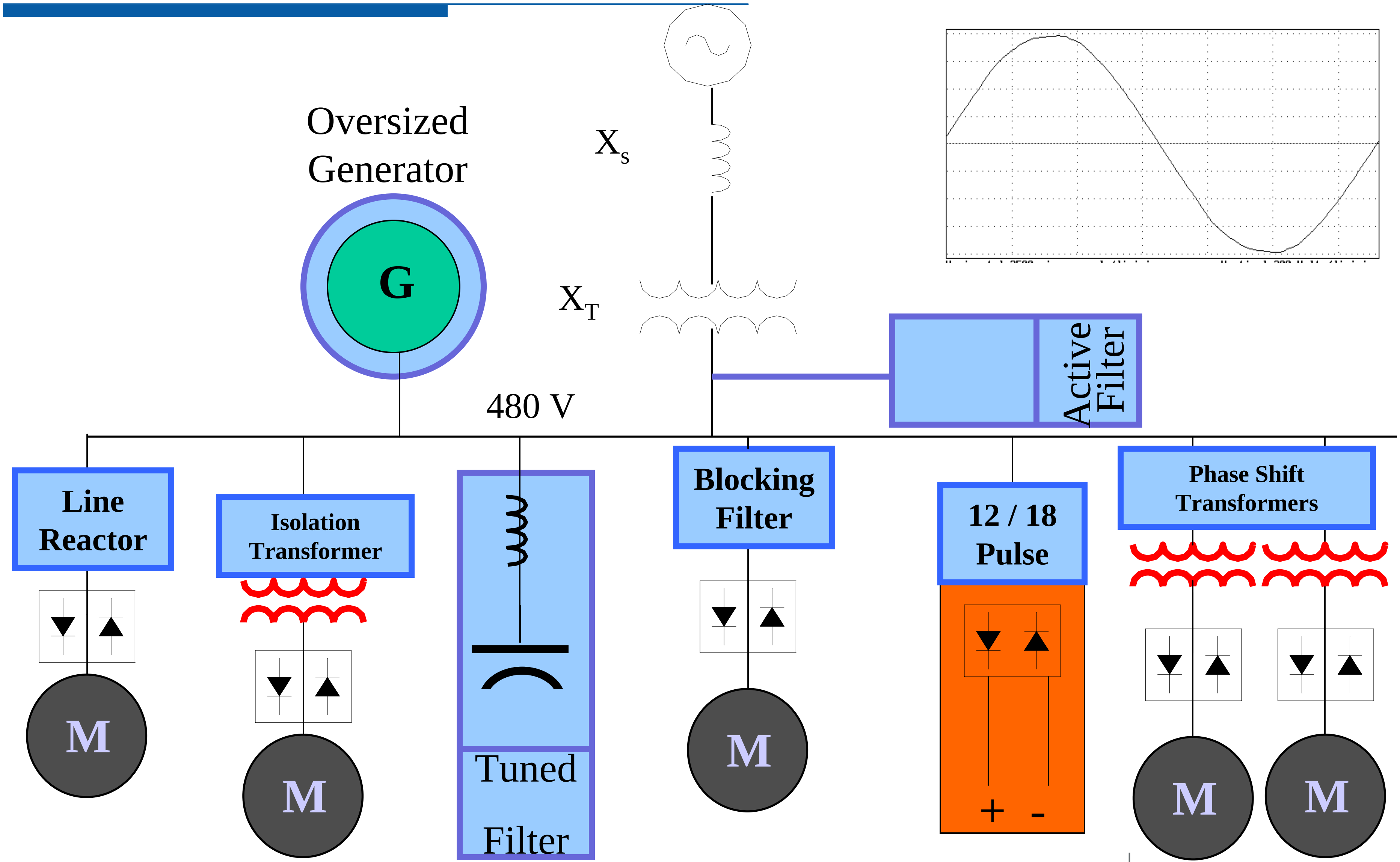
Example: With Harmonic Correction

	Measured				
	Total I, rms	Fund I, rms	Harm I, rms	THD(I)	TDD
Full load	936.68	936.00	35.57	3.8%	3.8%
	836.70	836.00	34.28	4.1%	3.7%
	767.68	767.00	32.21	4.2%	3.4%
	592.63	592.00	27.23	4.6%	2.9%
	424.53	424.00	21.20	5.0%	2.3%
	246.58	246.00	16.97	6.9%	1.8%
	111.80	111.00	13.32	12.0%	1.4%

Equal at full load

* As the load decreases,
TDD decreases while THD(I) increases.

Harmonic Solutions for VFD's



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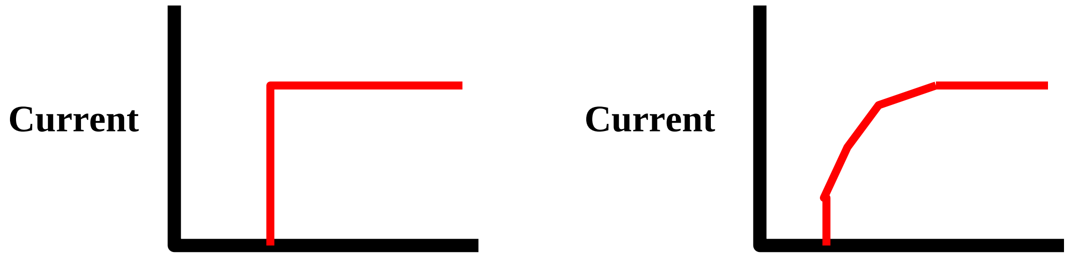
Harmonic Solutions for VFD's

- Line Reactors
- K-Rated / Drive Isolation Transformers
- Harmonic Mitigating Transformers/Phase Shifting
- 12-Pulse Converter
- 18-Pulse Converter
- Passive Parallel Tuned Filters
- Passive Series Tuned Filters
- Active Filters
- Active Rectifier (Regenerative VFD's)

Line Reactors

- Line Reactor = *Inductor*
- An *inductor* slows down the rate of rise of current.



- Impedance of an inductor increases as frequency increases

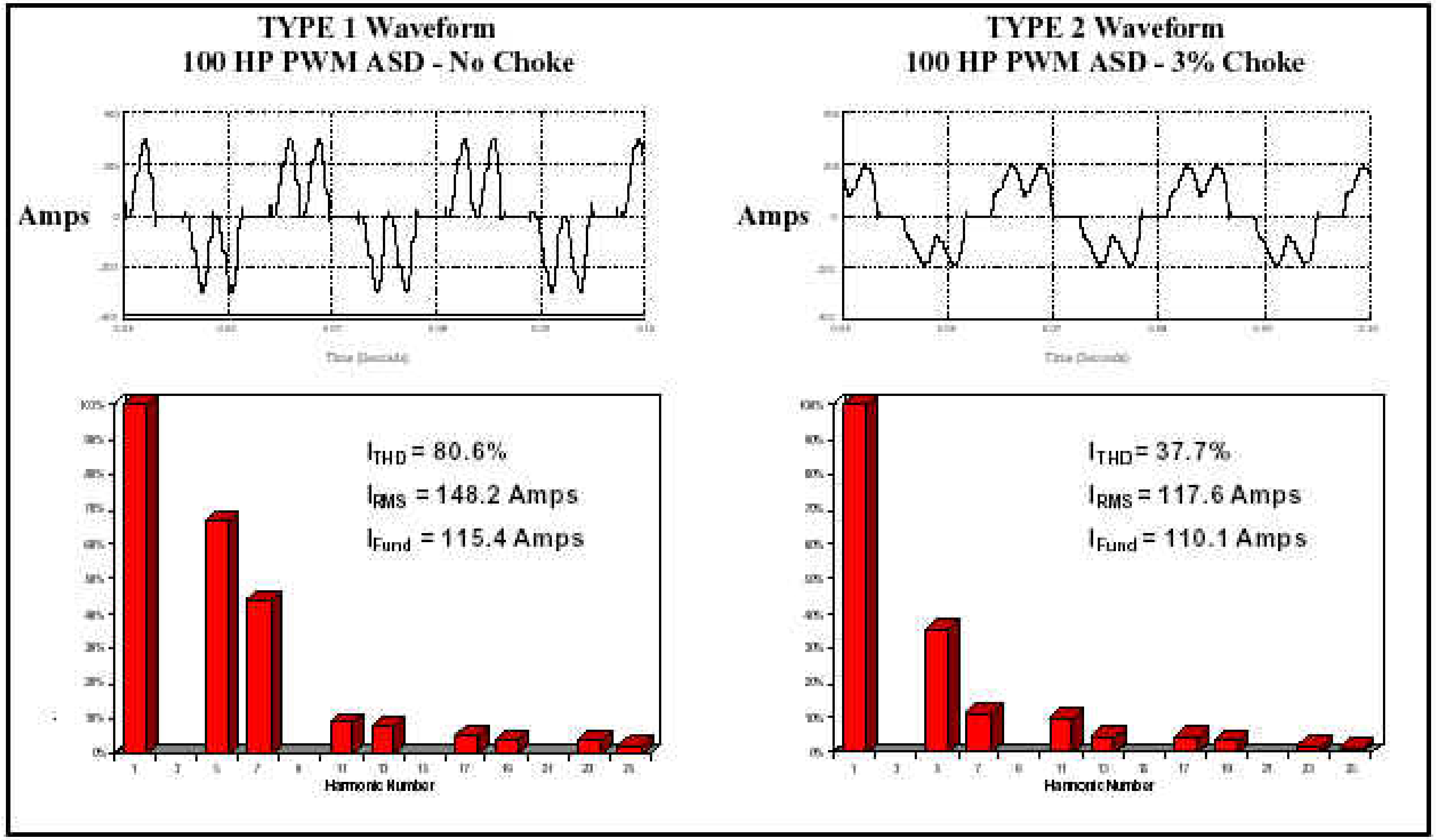
$$X_L = 2\pi f L \qquad Z = \sqrt{R^2 + X_L{}^2}$$

where: f=freq (Hz)

L=inductance (H)

- Reactors have more impedance the higher the harmonic order

Effect of Drive Line Reactors



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Effect of Drive Line Reactors

Harmonic Order	Reactor Size				
	0.5%	*1.0%*	*3.0%*	*5.0%*	*10.0%*
5^{th}	80.0%	60.0%	40.0%	32.0%	23.0%
7^{th}	60.0%	37.0%	16.0%	12.0%	7.5%
11^{th}	18.0%	12.0%	7.3%	5.8%	4.0%
13^{th}	10.0%	7.5%	4.9%	3.9%	2.8%
17^{th}	7.3%	5.2%	3.0%	2.2%	0.4%
19^{th}	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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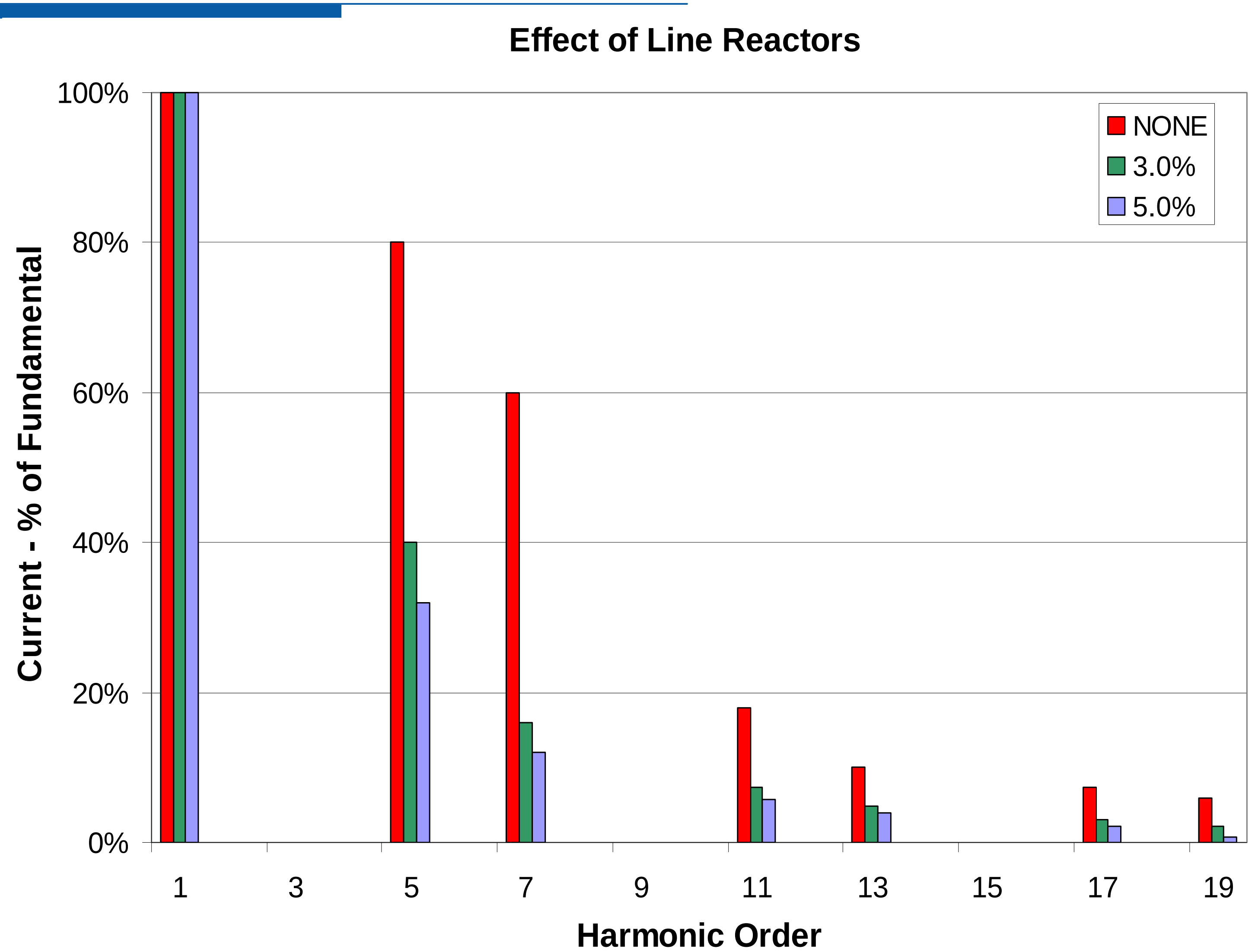
Effect of Drive Line Reactors



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Line Reactor Ratings

- Reactors are rated in %Z for the rated voltage system (i.e. 3%, 5%, 8%, etc.)
- Line reactors greater than 5% are not recommended due to voltage drop
- Example: A 3% line reactor will cause a 3% voltage drop when passing full rated current

    480v*3% = 14.4 volts

    480v*5% = 24 volts

    480v*8% = 38.4 volts
- Higher % reactors may cause VFD undervoltage nuisance trips

Drive Line Reactors

Advantages

- Lowest cost
- Moderate reduction in harmonics
- Provides increased protection for AFD
- Insensitive to system changes

Disadvantages

- May require larger enclosure / separate mounting
- Harmonic reduction may not be sufficient
- Possible voltage drop issues
- Produce heat

Drive Isolation Transformers

Provide the similar benefits as Line Reactors. Isolation transformers are like a 3.5 - 6% line reactor. (Transformer %Z)

Advantages

- Moderate reduction in harmonics
- Isolation from Ground
- Moderate cost (compared to some other attenuation methods)

Disadvantages

- Large footprint
- Separate mounting
- Harmonic reduction may not be sufficient
- No increased protection for VFD

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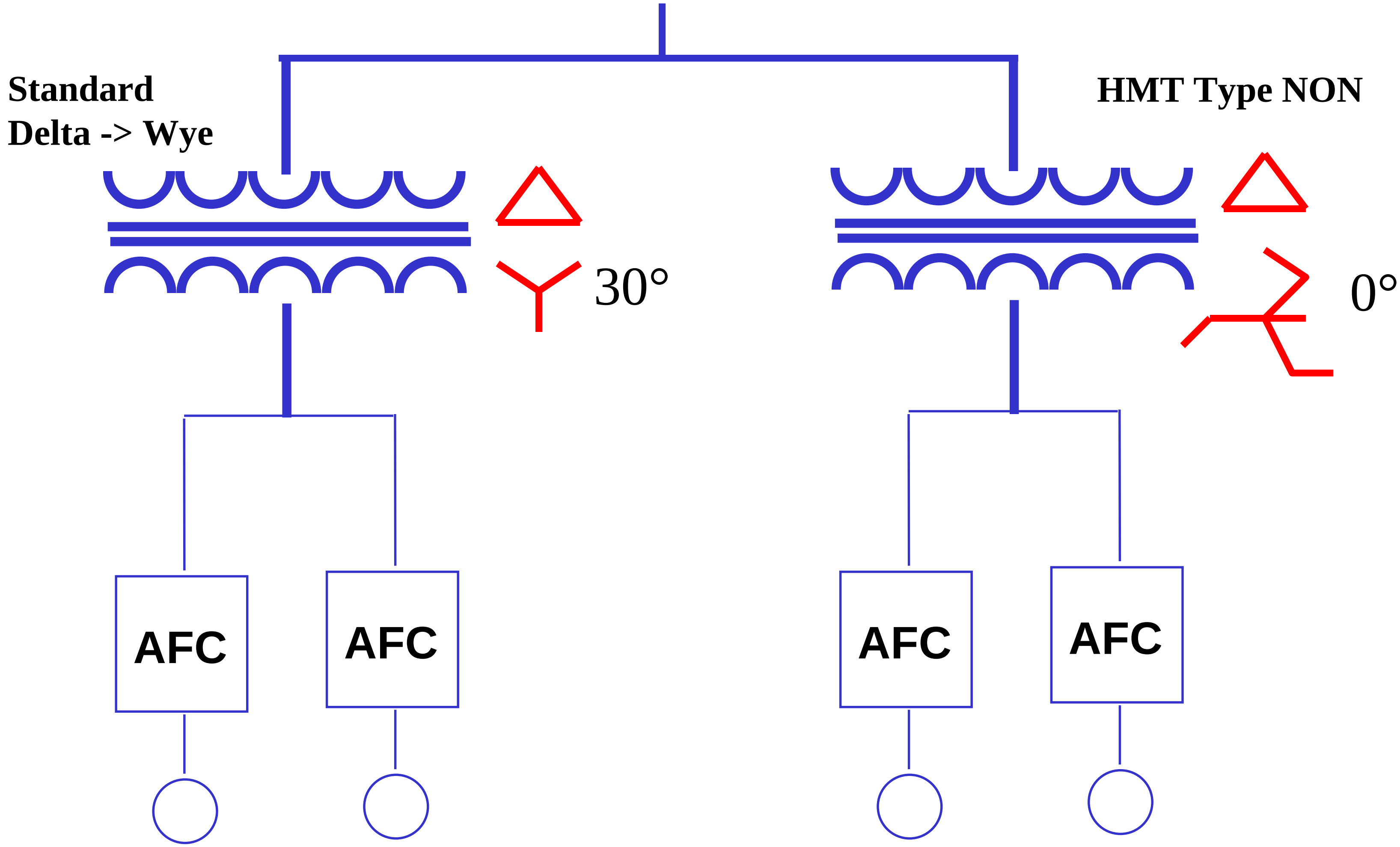
Phase Shifting – Harmonic Mitigating Transformers (HMT)

- Special wound transformers (typically zig-zag) that use phase shifting to cancel harmonics
- Application depends on the targeted harmonics
- Triplen harmonics (3^{rd}, 9^{th}, etc.) can be cancelled with single transformer
- VFD harmonics (5^{th}, 7^{th}, etc.) are cancelled using pairs of transformers.
  - Delta -> Wye transformers have 30° phase shift
  - HMT's have various degrees of phase shifting depending on manufacturer - 0°, +15°, 15°, etc.

Phase Shifting – Harmonic Mitigating Transformers (HMT)



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Phase Shifting – Harmonic Mitigating Transformers (HMT)

Advantages

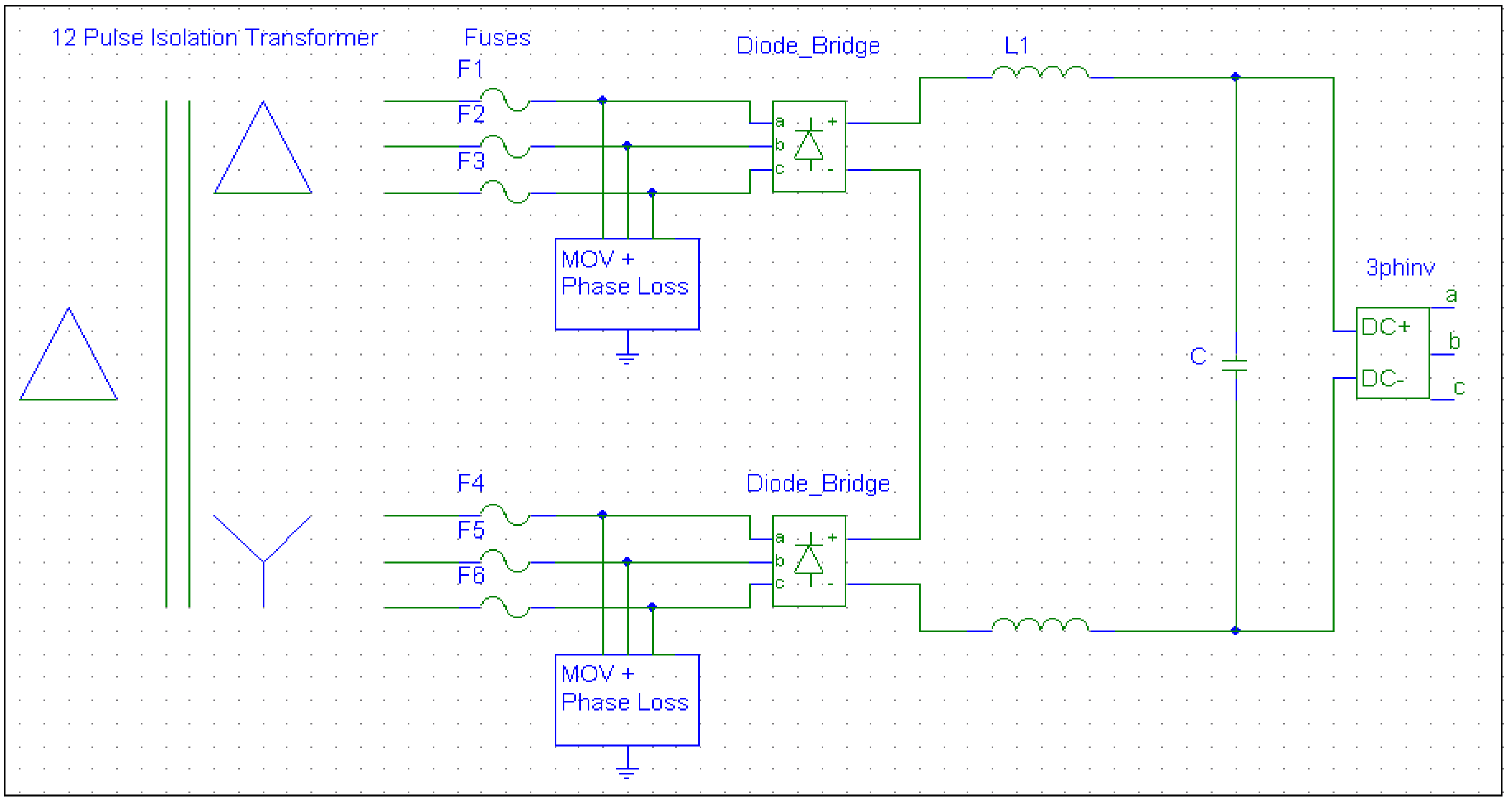
- Energy Savings
- Heat reduction
- Can provide additional 3th harmonic attenuation
- Cancels harmonics in primary system
- No derating of transformer
- Typically include additional electrostatic shielding
- Highly reliable (no electronic components)
- No maintenance
- Simple installation

Disadvantages

- Engineering intensive solution. (Difficult to retrofit)
- Multiple transformers needed to target 5^{th}, 7^{th}, 17^{th}, 19^{th}, etc.
- Load must be balanced between transformer pairs. (Only the balanced load gets attenuated.)
- May need supplemental harmonic reduction to meet IEEE 519

Multi-Pulse VFD's – 12 Pulse

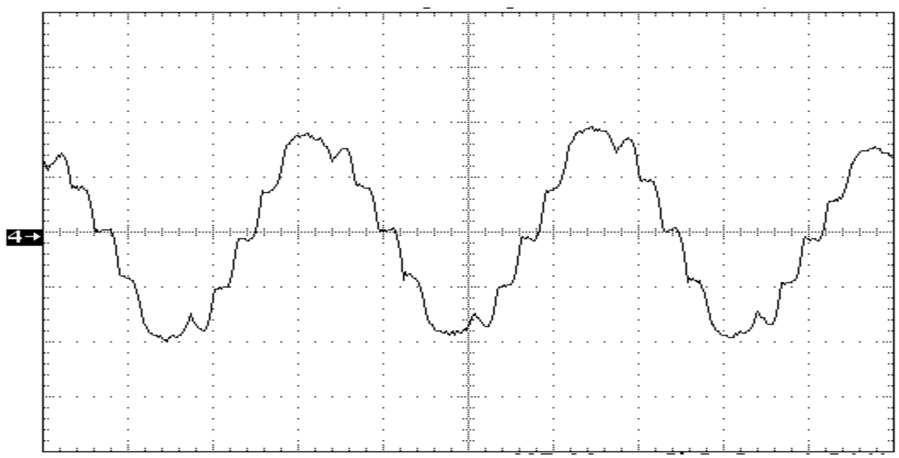
- Phase shifting isolation transformer provides dual outputs that go to (2) separate rectifiers. (12 diodes)
- Turns 3-phase power into "6-Phase" power



Multi-Pulse VFD's – 12 Pulse

- Phase shifting isolation transformer provides dual outputs that go to (2) separate rectifiers. (12 diodes)
- Turns 3-phase power into "6-Phase" power

Expanded 12 Pulse Current Waveform



Multi-Pulse VFD's – 12 Pulse

Advantages

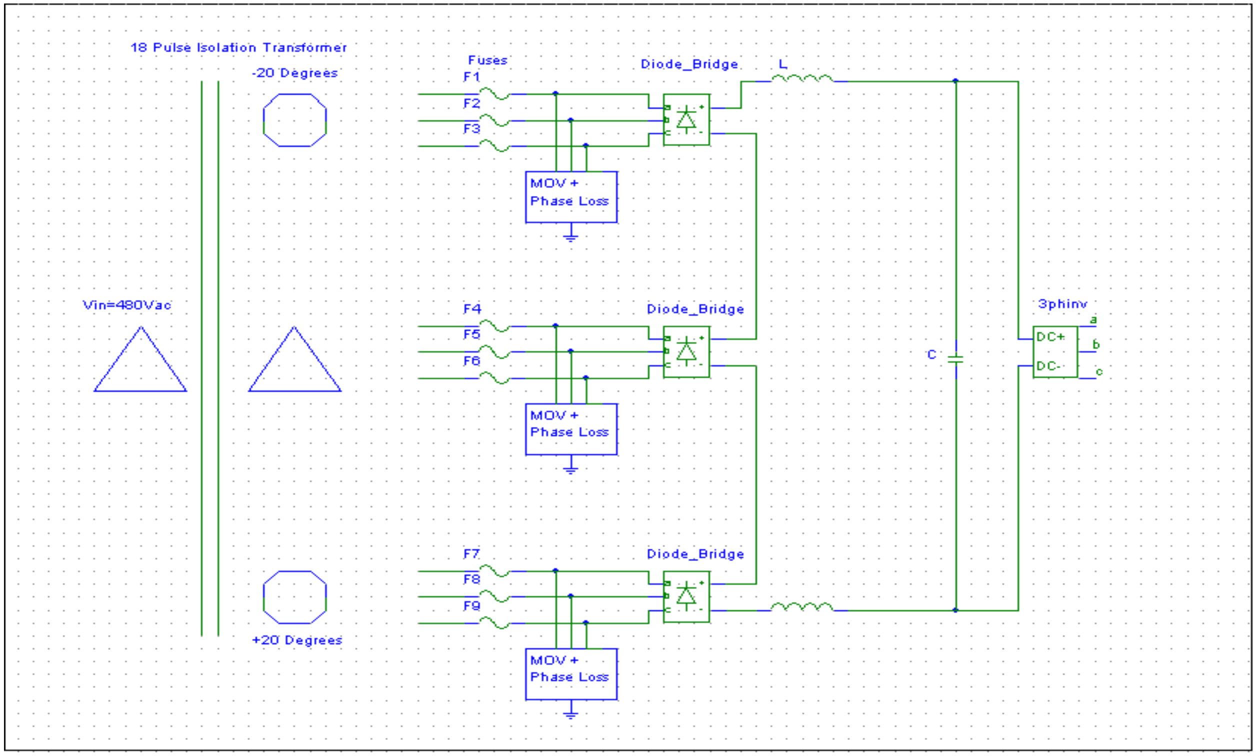
- Cost varies
- Substantial reduction in harmonics
  - THD(I) = 9% @ full load
    11% @ ½ load
- Almost complete cancellation of 5th and 7th harmonics
- Insensitive to system changes

Disadvantages

- Cost varies
- Increased size and weight
- More complexity
- Current distortion is load dependent
- Doesn't guarantee compliance with IEEE 519

Multi-Pulse VFD's – 18 Pulse

- Phase shifting isolation transformer provides dual outputs that go to (3) separate rectifiers. (18 diodes)
- Turns 3-phase power into "9-Phase" power



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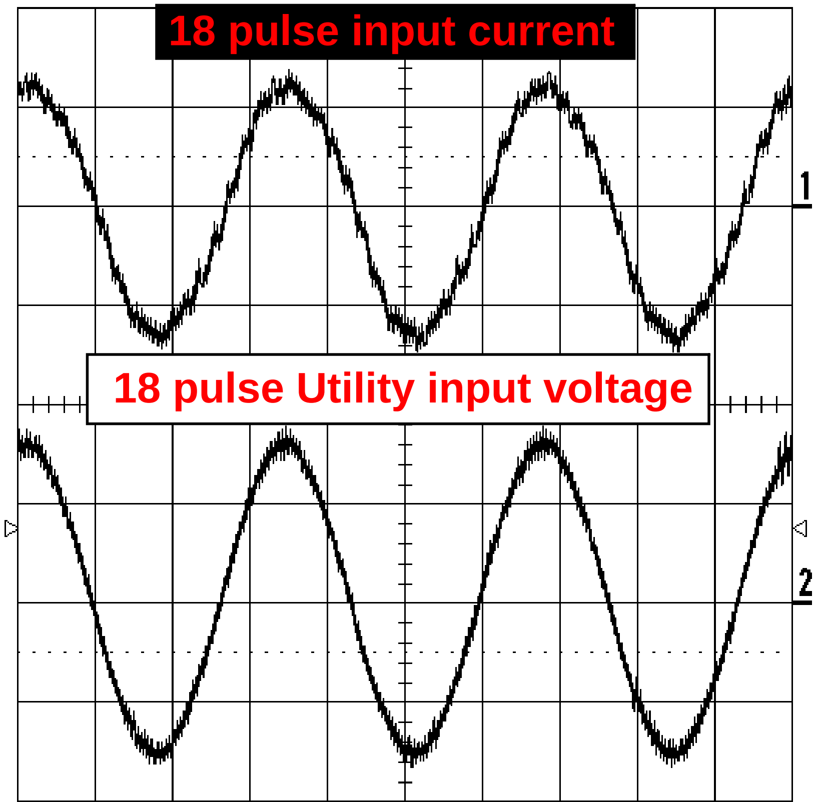
Multi-Pulse VFD's – 18 Pulse

• Phase shifting isolation transformer provides dual outputs that go to (3) separate rectifiers. (18 diodes)

• Turns 3-phase power into "9-Phase" power



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Multi-Pulse VFD's – 18 Pulse

Advantages

- Guarantees compliance with IEEE 519 at the drive terminals
- Up to 4x the reduction of 12 pulse
- Excellent for large drives
- Substantial reduction in harmonics
  - THD(I) = 3.5% @ full load
    6% @ no load
- Almost complete cancellation of 5th, 7th, 11th, and 13th harmonics
- Insensitive to system changes

Disadvantages

- Higher Cost
- Must be applied to each VFD
- Increased size and weight
- More complexity

Multi-Pulse VFD’s – 18 Pulse

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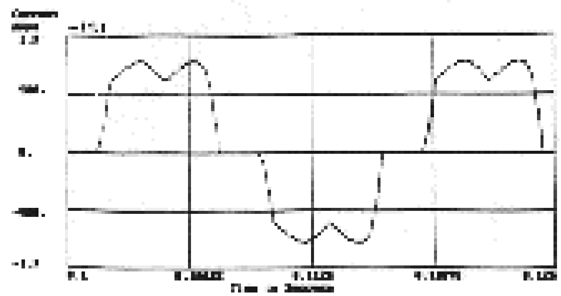
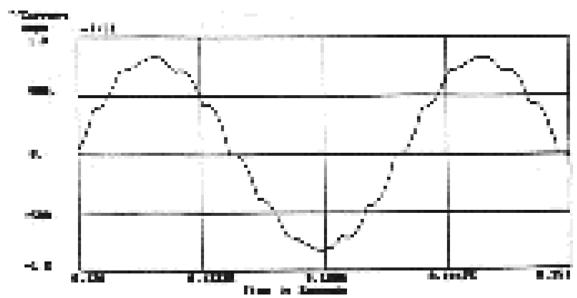
Multi-Pulse VFD’s

6-pulse converter



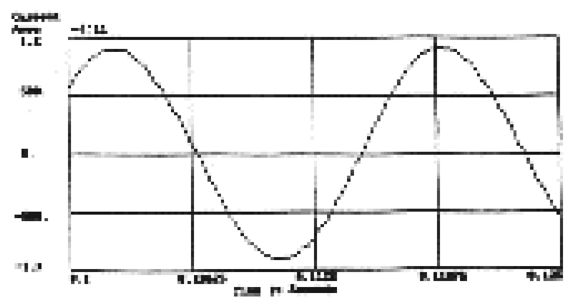
25% - 40% Current THD

12-pulse converter



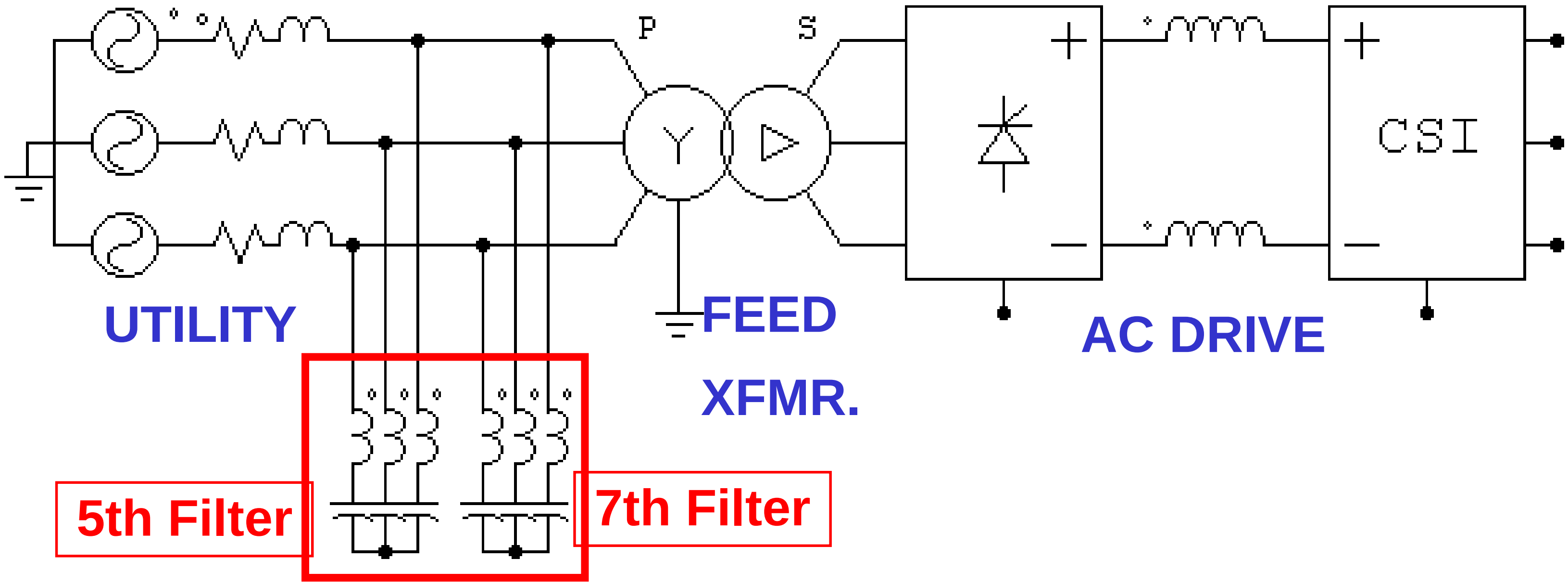
9% - 11% Current THD

18-pulse converter



3% - 4% Current THD

Passive Filters (Parallel / Tuned)



- Consists of LC combinations tuned to a specific frequency (Typically the 5th or 7th)
- Act as a shunt (or trap) for harmonics
- Applied close to harmonic generating loads

Passive Filters (Parallel / Tuned)

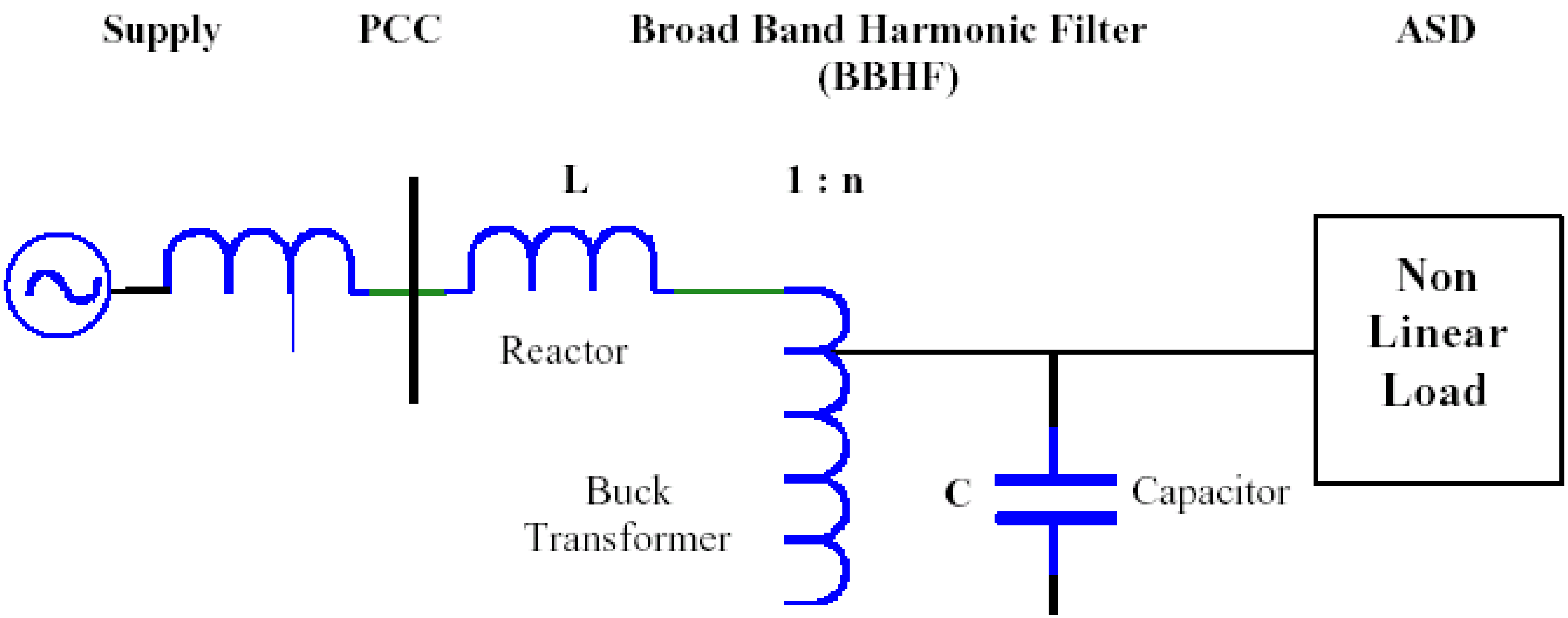
Advantages

- Allows higher VFD content
- Single filter for multiple drives
- Can target specific "trouble" harmonics
- Can be designed to guarantee compliance with IEEE 519

Disadvantages

- Higher cost
- Engineering intense solution
- Separate mounting and protection
- May require multiple "steps" to meet IEEE 519
- Must design to avoid overload, excessive voltage rise
- Interact with all plant and utility non-linear loads
- May change as load profile changes

Passive Filters (Series / Broadband)



Passive Filters (Series / Low Pass)

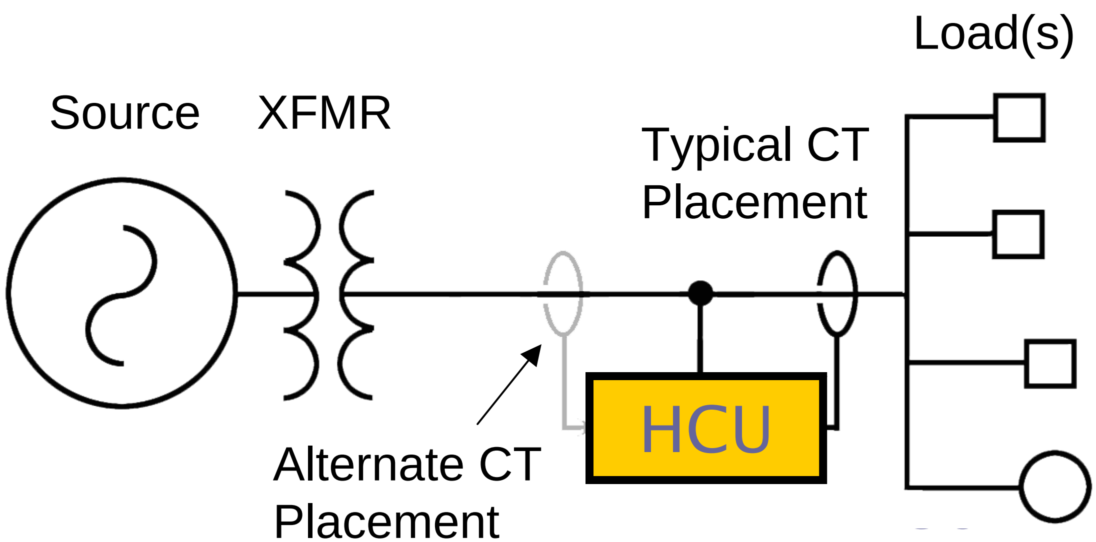
Advantages

- Allows higher VFD content
- Increased protection for VFD
- Power factor correction
- Simple configuration that doesn't require detailed analysis

Disadvantages

- High cost
- Increased size
- One filter required per drive
- Could result in leading power factor when lightly loaded
- Possible resonance

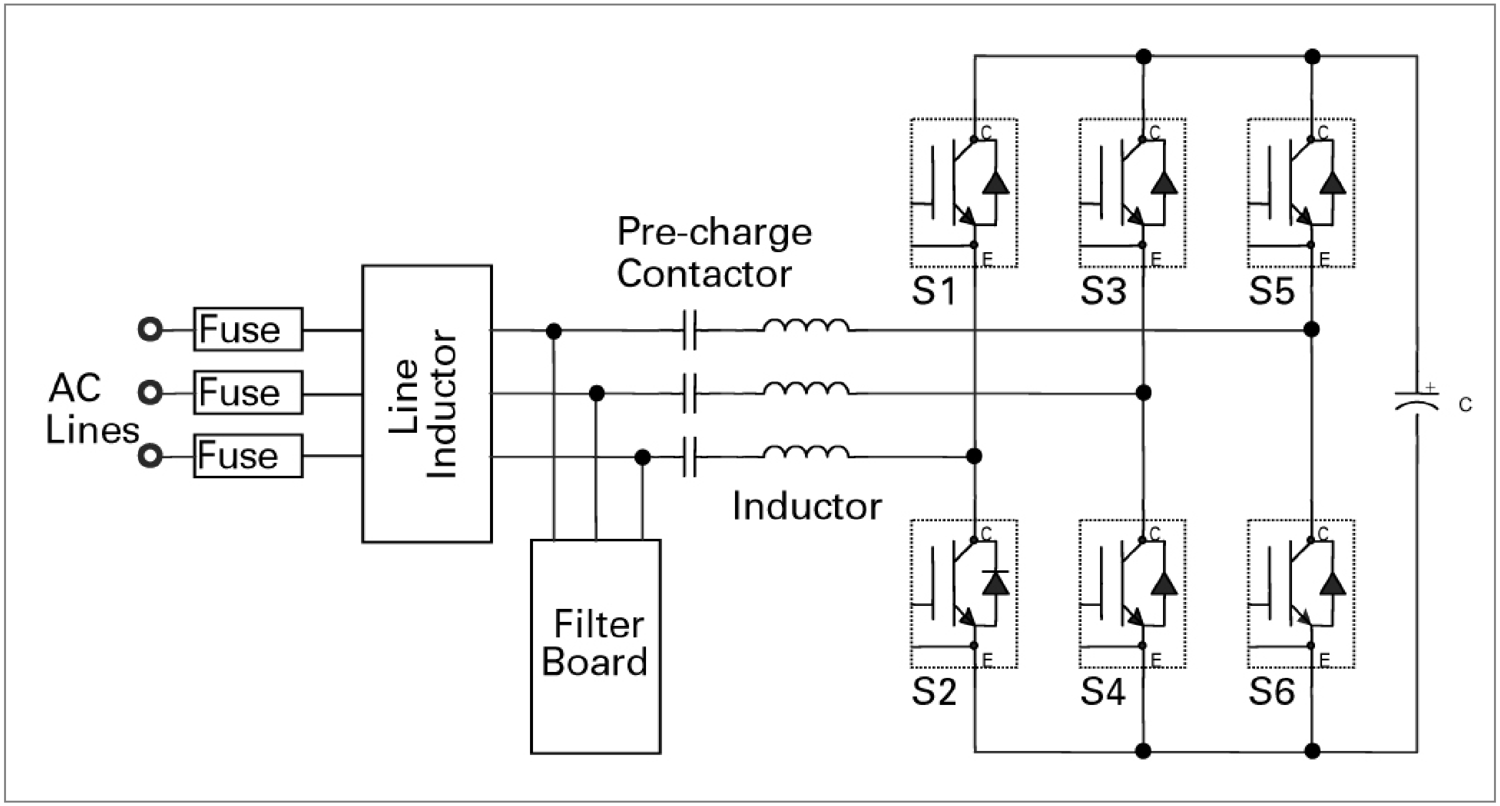
Active Filters



- Actively senses harmonics
- Injects equal and opposite currents to cancel harmonic currents
- Multiple units operate in parallel to get additional capacity
- Can also use extra capacity to correct power factor

Active Filters

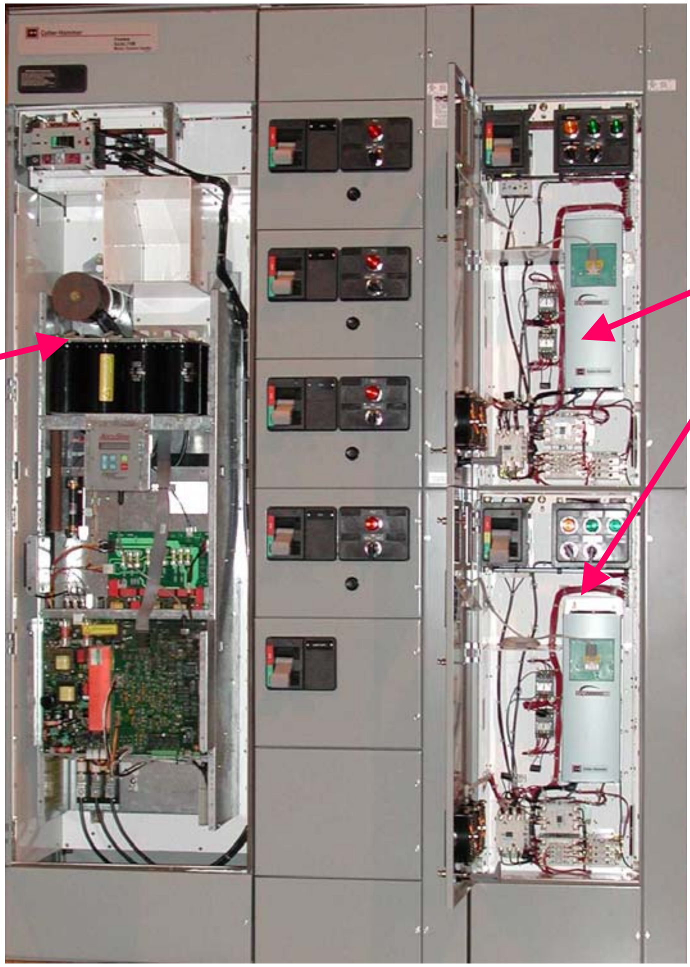
Power Schematic



Active Filters

Integration into Motor Control Center

Active Harmonic
Correction Unit



Non-linear
AC Drive Loads

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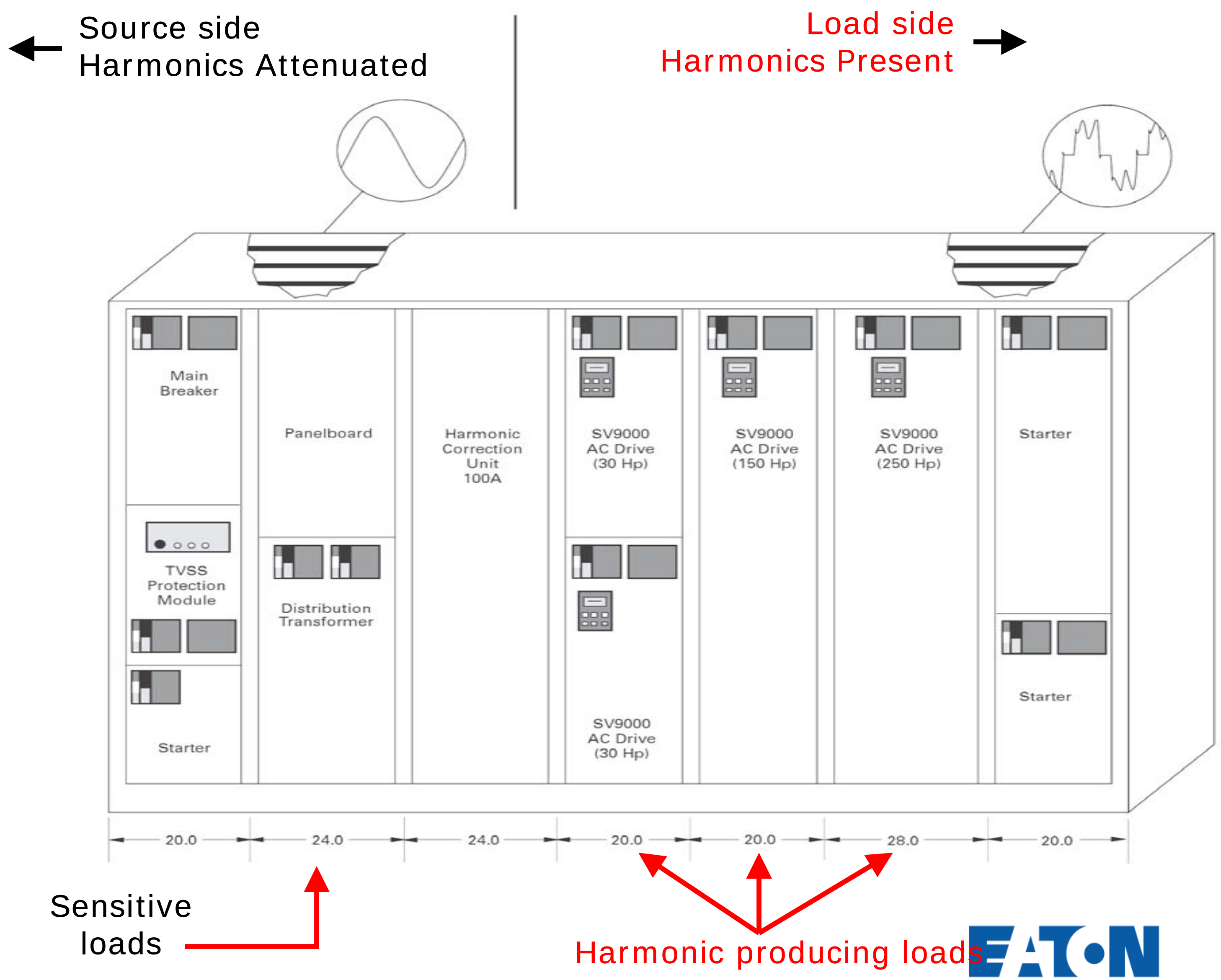
Active Filters



Harmonic Correction can be configured for load or source sensing.

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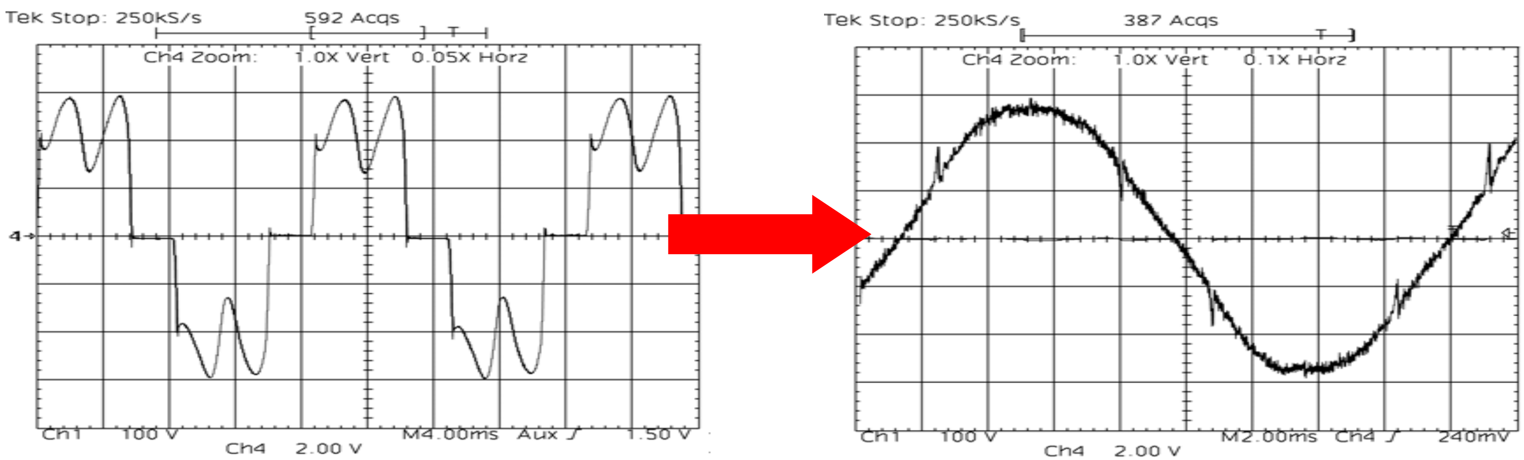
Active Filters



- Highly accurate control and monitoring
- Flexible harmonic control
    - system can grow as customer's needs change
    - size based on actual running loads vs. provision
    - can be applied within MCC with integral drives <u>or</u> feeders

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Active Filters

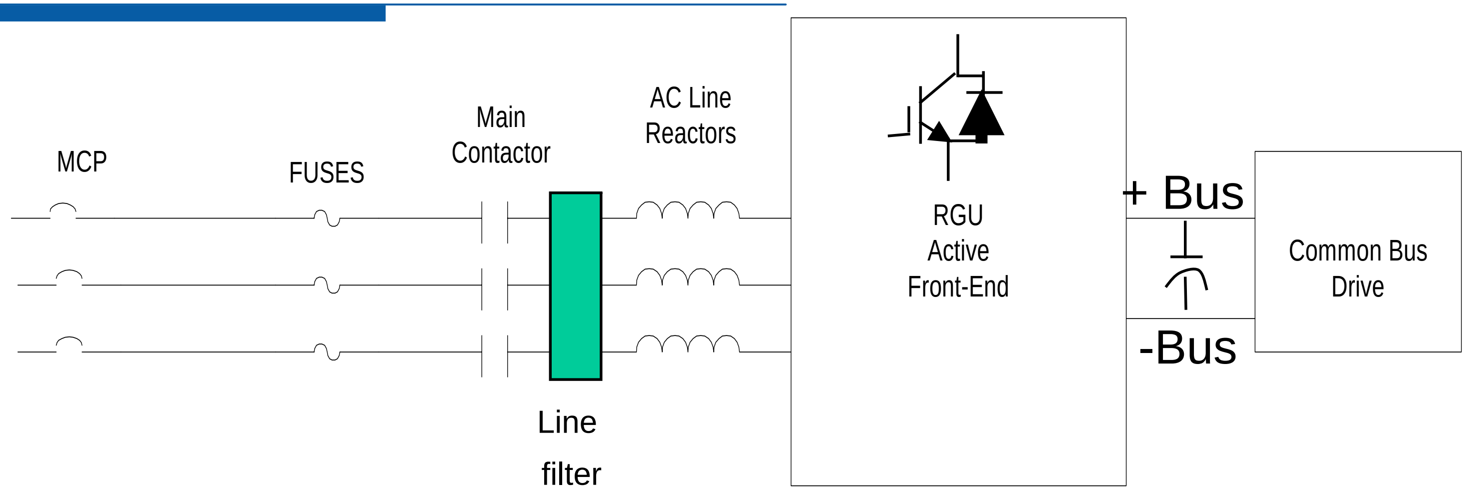
<u>Advantages</u>

- Can be sized to guarantee IEEE 519 compliance
- Shunt design cannot be overloaded
- Cancels 2nd-50th harmonic
- Provides 60 Hz reactive current (PF correction)
- Can be incorporated in MCC to compensate for multiple AFDs
- Fast response to varying loads
- Expandable

<u>Disadvantages</u>

- Typically more expensive than other methods
  - More competitive where redundant VFD's are used
- Size
- More complex

Regenerative VFD's (Active Rectifier)



- Active front end rectifier
- IGBT devices replace diode in rectifier
- High frequency switching
- Supplies forward power to DC bus drive system
- Regenerates excess power back to the 3-phase AC line with sinusoidal input currents

Regenerative VFD's

Advantages

- Creates little harmonic distortion
- Regenerates excess power back to AC line
- Fast response to varying loads

Disadvantages

- Not widely used
- Most complex
- Very expensive solution
  - More competitive for large regenerative loads
- Requires large line reactor
- Not as efficient in forward driving mode

Mitigation Technique vs. Installed Cost

A 6 pulse

B 6 pulse with 3% reactor

C 6 pulse with 5% reactor

D Phase Shifting Transformer

E 12 Pulse

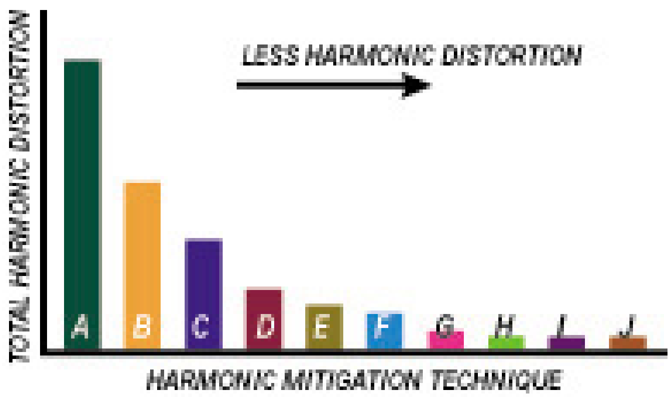
F Series Low Pass Filter

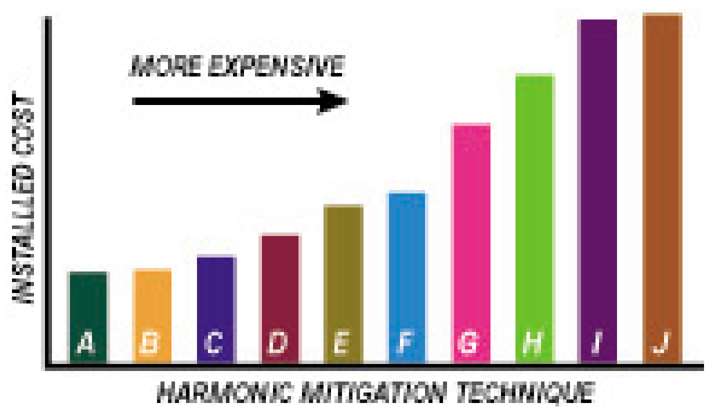
G 18 Pulse

H Parallel Tuned Filter

I Active Filter

J Regenerative active front end





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Summary

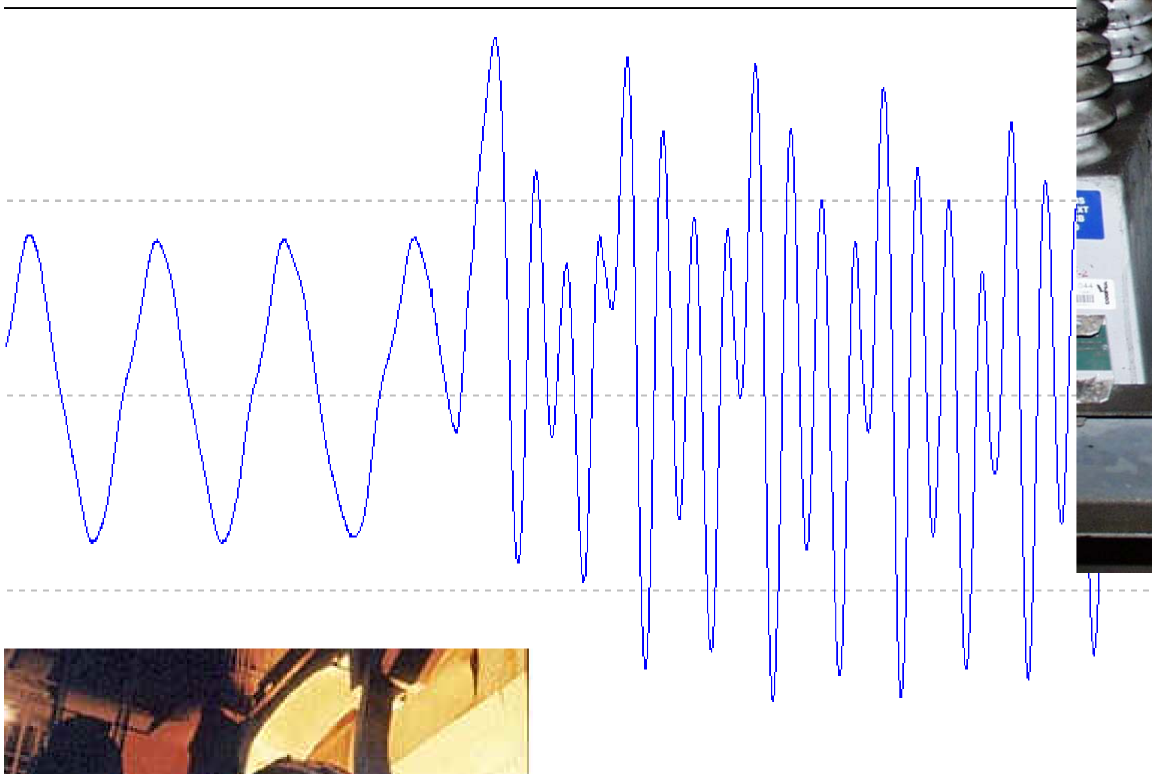
There are a wide variety of solutions

Different solutions are appropriate in different situations

Appropriate solutions depend on numerous factors

1. Number of VFD's
2. Redundancy
3. Existing or New Construction
4. Linear load
5. Facility type
6. Future growth

Best solution is determined from a complete system analysis considering all available filtering methods



Thank You!

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