Merlin Gerin
Square D
Telemecanique

The Facts About Harmonics and Power Factor

Power Quality: Harmonics & Power Factor Correction

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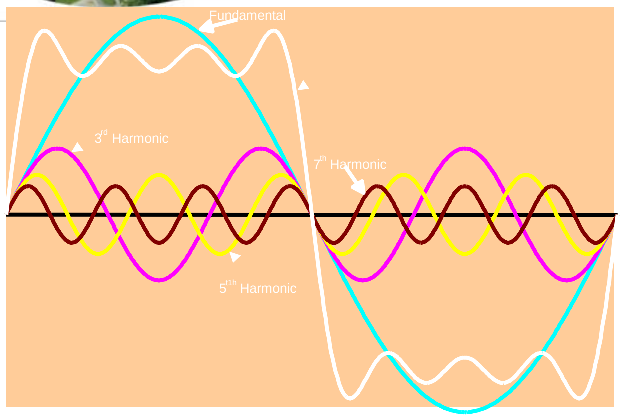
Agenda

- I. Harmonic Basics
- II. Harmonic Mitigation Methods
- III. Active Harmonic Filters
- IV. Applications
- V. Specification Recommendations
- VI. Summary



Harmonic	Frequency	Sequence
1	60Hz	+
2	120Hz	0
3	180Hz	0
4	240Hz	0
5	300Hz	-
6	360Hz	0
7	420Hz	+
:	:	:
19	1140Hz	+

Harmonic Basics

- What are harmonics?
  - Proliferated by power semiconductor devices
    - Converts power (AC to DC)
  - A harmonic is a component of a periodic wave having a frequency that is an integer multiple of the fundamental power line frequency
    - Characteristic harmonics are the predominate harmonics seen by the power distribution system
  - Predicted by the following equation:
    - h_C = characteristic harmonics to be expected
    - n = an integer from 1,2,3,4,5, etc.
    - p = number of pulses or rectifiers in circuit

$$H_c = np +/- 1$$

Multi-pulse Converters

$H_n = np +/- 1$

H_n = characteristic harmonic order present

n = an integer

p = number of pulses

Harmonic Orders Present

Harmonics present by rectifier design					
	Type of rectifier				
Hn	1 phase 4-pulse	2 phase 4-pulse	3 phase 6-pulse	3 phase 12-pulse	3 phase 18-pulse
3	x	x			
5	x	x	x		
7	x	x	x		
9	x	x			
11	x	x	x	x	
13	x	x	x	x	
15	x	x			
17	x	x	x		x
19	x	x	x		x
21	x	x			
23	x	x	x	x	
25	x	x	x	x	
27	x	x			
29	x	x	x		
31	x	x	x		
33	x	x			
35	x	x	x	x	x
37	x	x	x	x	x
39	x	x			
41	x	x	x		
43	x	x	x		
45	x	x			
47	x	x	x	x	
49	x	x	x	x	

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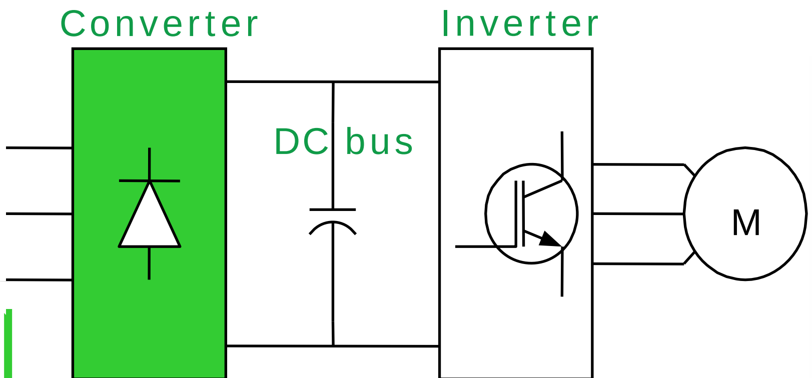
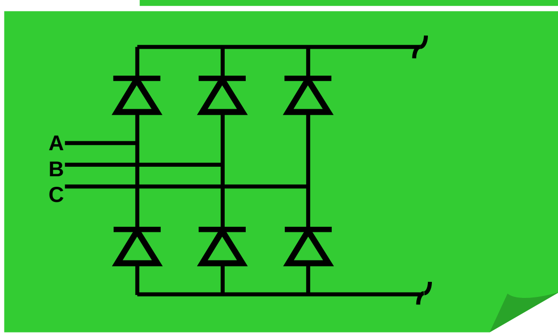
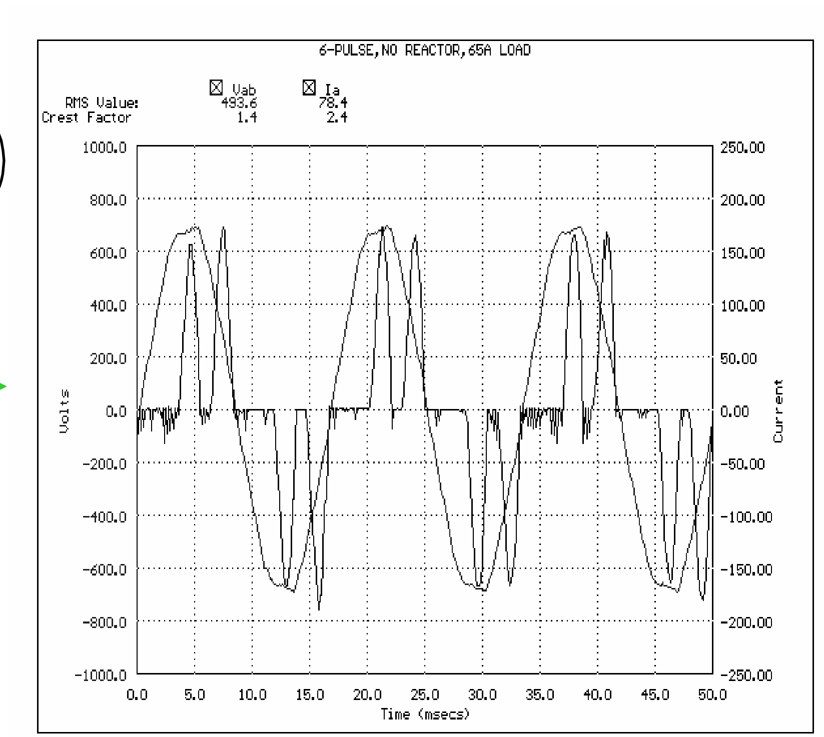
Harmonic Basics

- Nonlinear loads draw harmonic current from source
- Example: 6-Pulse VFD

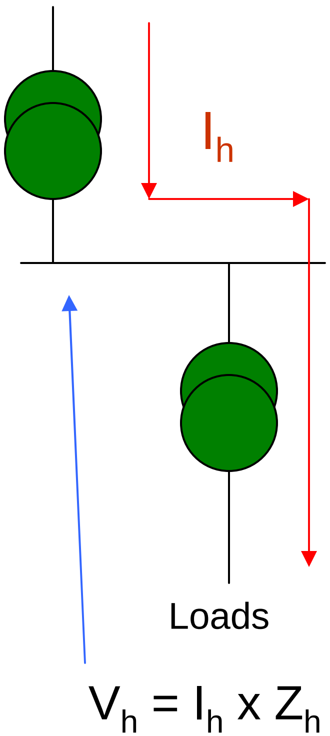






Harmonic Basics

- Why a concern?
  - Current distortion
    - – Added heating, reduced capacity
      - – Transformers
      - – Conductors and cables
      - – Nuisance tripping of electronic circuit breakers (thermal overload)
  - Voltage distortion
    - – Interference with other electronic loads
    - – AC Motor winding & bearing failures
  - Potential resonance condition (PF caps)
    - – Excessive voltage
    - – Overheating of PF correction capacitors
    - – Tripping of PF protection equipment
    - – Shutdown / damage to electronic equipment



Total Power Factor

$$TPF = (DPF) \times (\text{Distortion factor})$$

$$DPF = \frac{KW}{KVA_f} = \cos \phi$$

$$\text{Distortion Factor} = \frac{1}{\sqrt{1 + THD(I)^2}} = \cos \delta$$

TPF = Total or true power factor

DPF = Displacement power factor

Distortion Factor = Harmonic power factor

Total Power Factor Example

- Variable frequency drive (PWM type)
  - DPF = .95
  - THD(I) = 90%
    - (no DC choke & no input line reactor)
  - Distortion Factor = $\frac{1}{\sqrt{1 + .9^2}} = .7433$
- TPF = .95 x .7433 = .7061

Harmonic Mitigation Methods

- Typically applied per device
  - Line reactors/DC bus chokes/isolation transformers
  - 5th harmonic filters (trap filters)
  - Broadband filters
  - Multi-pulse transformers/converters
  - Active front end (AFE) converter

- System solution
  - Active harmonic filter

Harmonic mitigation methods (Applied per VFD)

Solution	Advantage	Disadvantage	Typical % TDD	Typical Price Multiplier*
Increase short circuit capacity	Reduces THD(V)	■Increases TDD ■Not likely to occur**	Dependent upon SCR***	Cost of transformer and installation change out
C-Less Technology	■Lower TDD ■Simplified design ■Less cost	■Compliance is limited ■Application limited ■Size limited	30 - 50% TDD	0.90 - 0.95
Impedance (3% LR or 5% DC choke)	■Low cost adder ■Simple	■Compliance difficult	30 - 40% TDD	1.05 - 1.15
5th Harmonic filter	Reduces 5th & total TDD	■Does not meet harmonic levels at higher orders^	18 - 22% TDD	1.20 - 1.45
Broadband filter	Reduces TDD (thru 13th)	■Large heat losses ■Application limited	8 - 15% TDD	1.25 - 1.50
12-pulse rectifiers	■Reduces TDD ■Reliable	■Large footprint/heavy ■Good for >100 HP	8 - 15 % TDD	1.65 - 1.85
18-pulse rectifiers	■Reduces TDD ■Reliable	■Large footprint/heavy ■Good for >100 HP	5 - 8% TDD	1.65 - 1.85
Active front end converter	■Very good TDD ■Regeneration possible	■Large footprint/heavy ■Very high cost per unit ■High heat losses	< 5% TDD	2.0 - 2.5

* Price compared to a standard 6-pulse VFD.

** Utilities and users are not likely to change their distribution systems.
*** Increasing short circuit capacity (lower impedance source or larger KVA capacity) raises TDD but lowers THD(V).
^ Can be said for all methods listed.

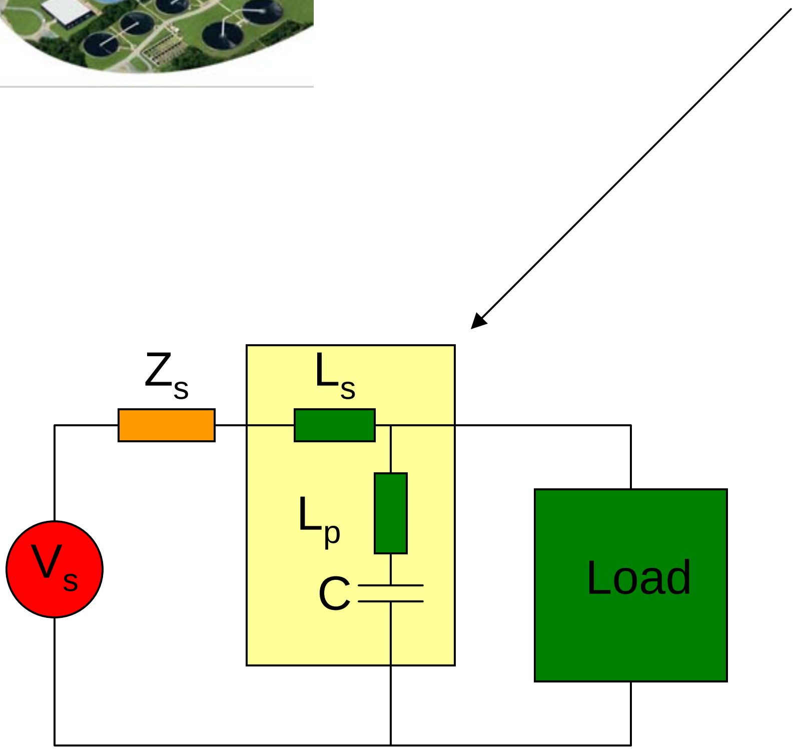
Inductors/Transformers/DC Bus Chokes

Description:

Converter-applied inductors, DC bus chokes, or isolation transformers

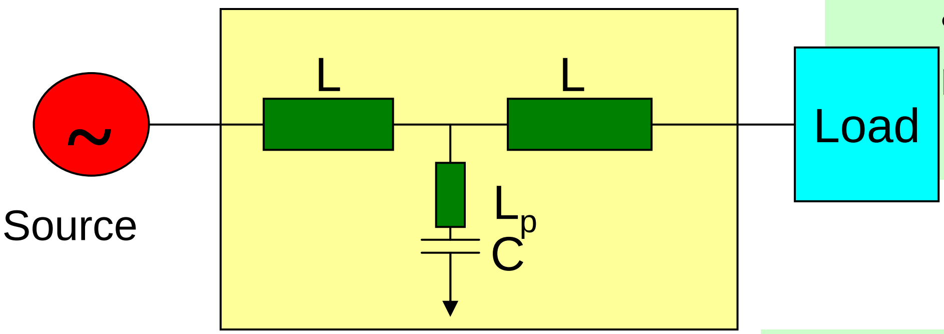
- Pros:
  - Inexpensive & reliable
  - Transient protection for loads
  - 1st Z yields big TDD reduction (90% to 35% w/3% Z)
- Cons:
  - Limited reduction of TDD at equipment terminals after 1st Z
  - Reduction dependent on source Z

5th Harmonic Filter (Trap Filter)



- Inductor (L_p) and Capacitor (C) provide low impedance source for a single frequency (5^{th})
  - Must add more tuned filters to filter more frequencies
- Inductor L_s required to detune filter from electrical system and other filters
  - If L_s not present, filter is sink for all 5^{th} harmonics in system
  - If L_s not present, resonance with other tuned filters possible
- Injects leading reactive current (KVAR) at all times – may not need

Broadband Filters



Mitigates up to 13th order or higher
- Each inductor (L) > 8% impedance
  - V drops ~ 16% at load
  - Trapezoidal voltage to load
    - Can only be used on diode converters
  - Prevents fast current changes (only good for centrifugal loads)
  - When generators are present, re-tuning may be required

- Capacitor (C) designed to boost V at load to proper level (injects leading VARs)
- Physically large
- High heat losses (>5%)
- Series device

Multi-Pulse Drives

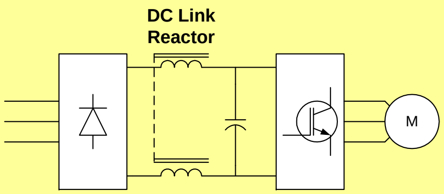
Description: Drives/UPS with two (12 pulse) or three (18 pulse) input bridges fed by a transformer with two or three phase shifted output windings.

- Pros:
  - Reduces TDD to 10% (12 pulse) & 5% (18 pulse) at loads
  - Reliable
- Cons:
  - High installation cost with external transformer
  - Large footprint (even w/autotransformer)
  - Series solution with reduction in efficiency
  - One required for each product
  - Cannot retrofit

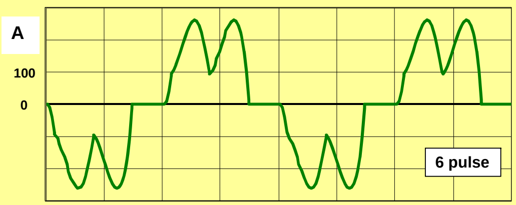
Harmonic mitigation methods

VFD mitigation topologies

6-Pulse converter

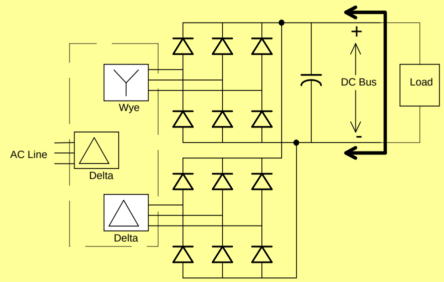


“C-less” or 3% reactance min (if included); small footprint, simplified cabling

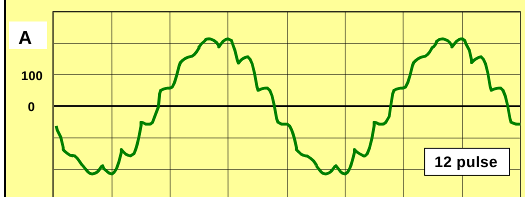


Current waveform distorted
TDD 30% to 40% with 3% reactor (depending on network impedance)

12-Pulse converter

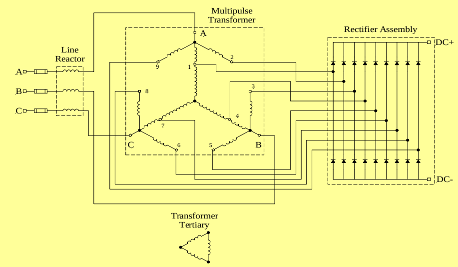


Externally mounted 3 winding transformer; more wire and cabling; complicated

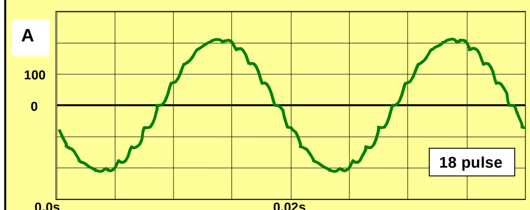


Current slightly distorted
TDD 8% to 15% (depending on network impedance)

18-Pulse converter



Large footprint, more steel & copper (losses)



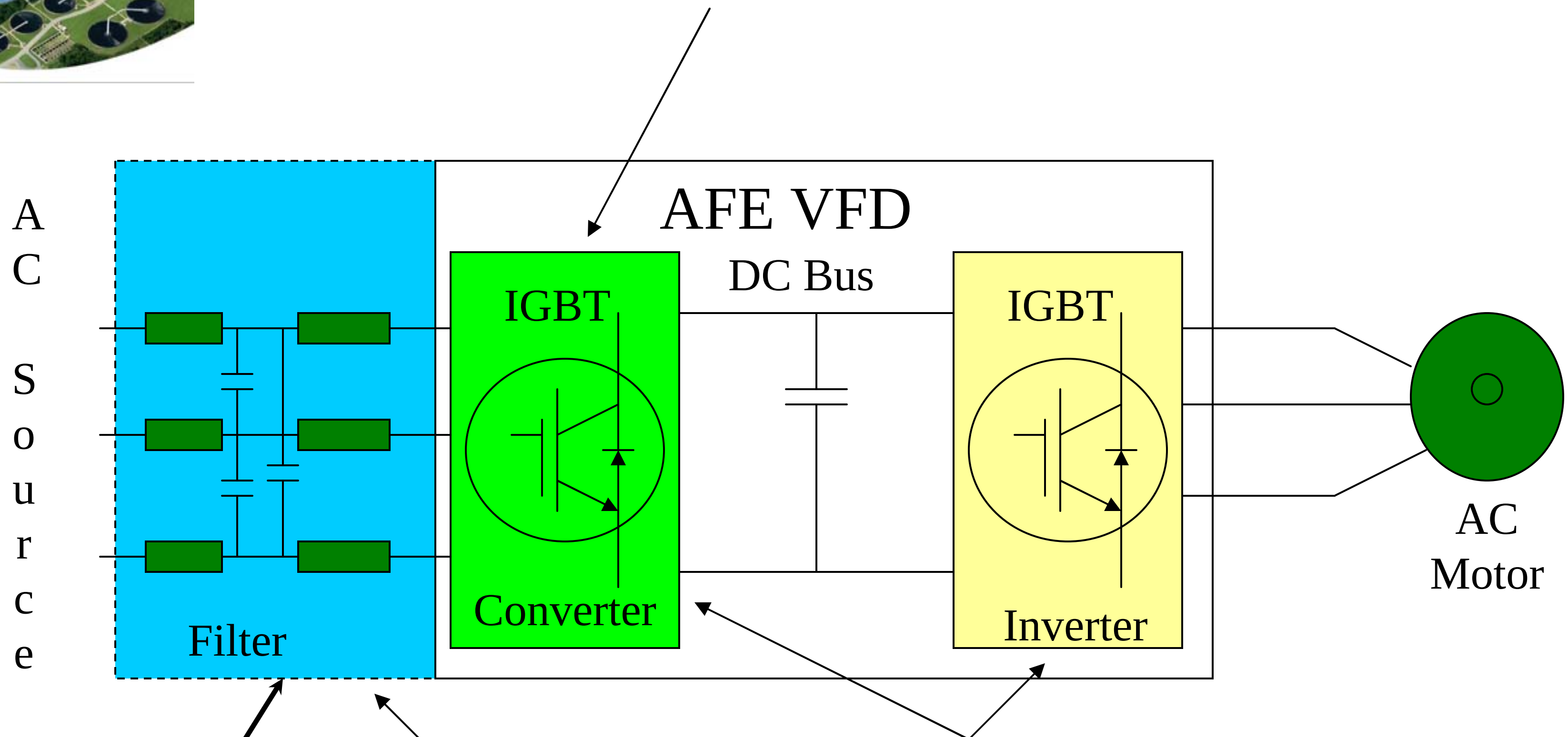
Current wave form good
TDD 5% to 7% (depending on network impedance)

AFE Converters

- Used in UPS and VFD
- Replaces diode converter with IGBT converter

- THE HYPE
  - Permits current smoothing on AC lines (< 5% TDD)
  - Permits 4-quadrant operation of VFD
  - Maintains unity TOTAL PF

Active Front End Converter



Required to limit THDv on mains to <=5%

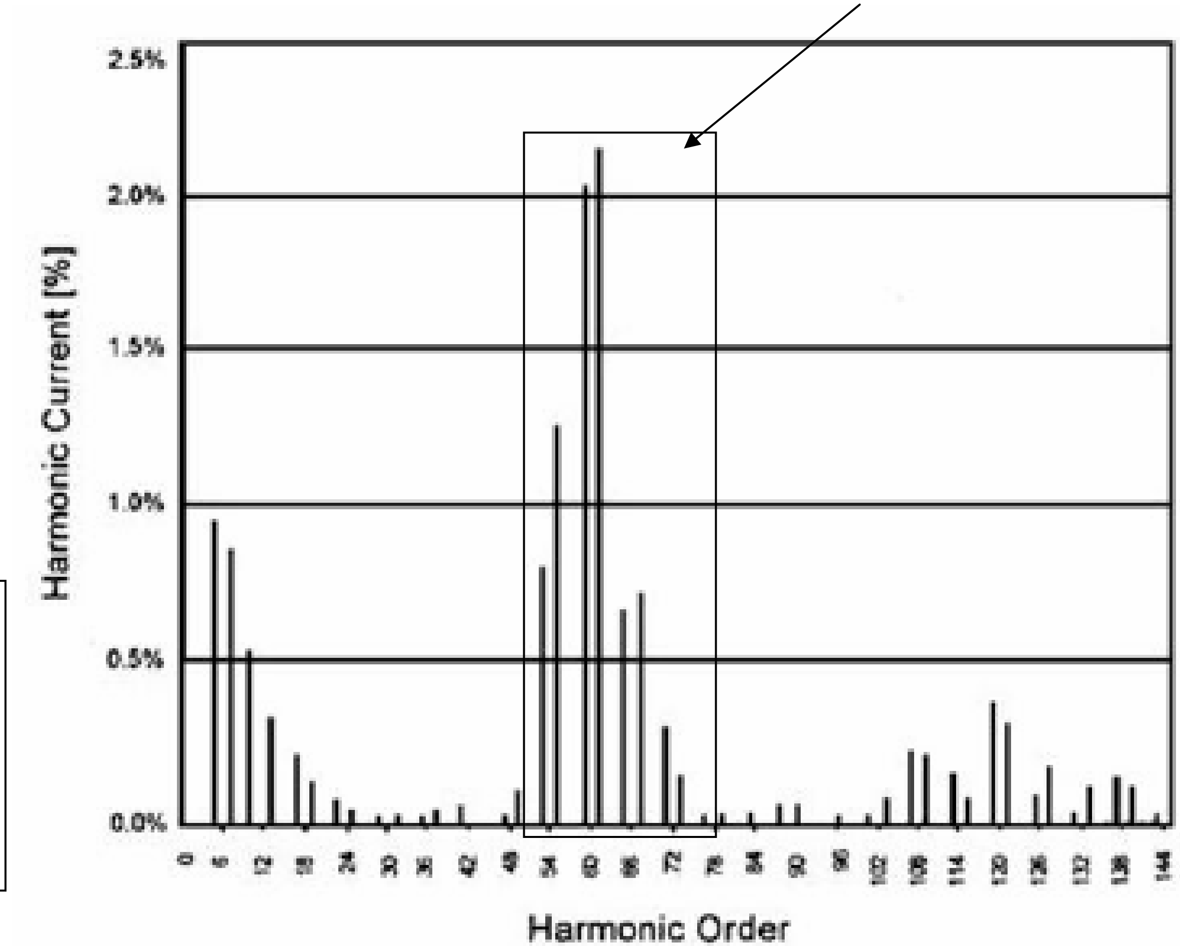
Losses - ~5% of rated

Losses – 1.5 to 2% of rated

AFE Converters

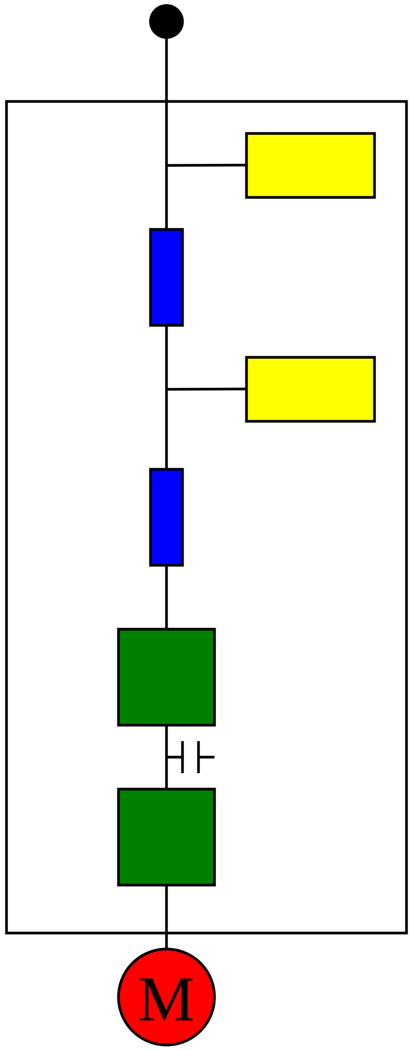
Significant harmonics above 50th order

American Bureau of Shipping (ABS) requires examination to 100th order when AFE applied



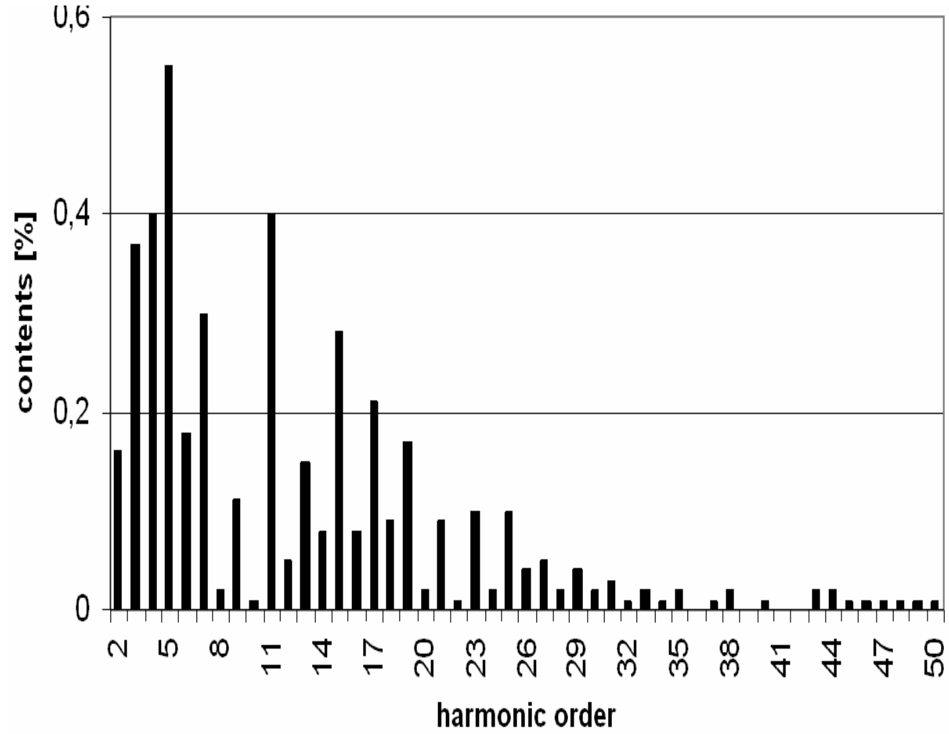
Higher frequencies yield higher heating of current path & potential resonance with capacitors

AFE Converters



- PCC
- EMC Filter
- Mains Choke Reactance, 4%
- Mains Filter
- Mains Filter Reactance, 12%
- Mains Pulse Converter, IGBT
- DC Bus
- Motor Pulse Inverter, IGBT
- Motor

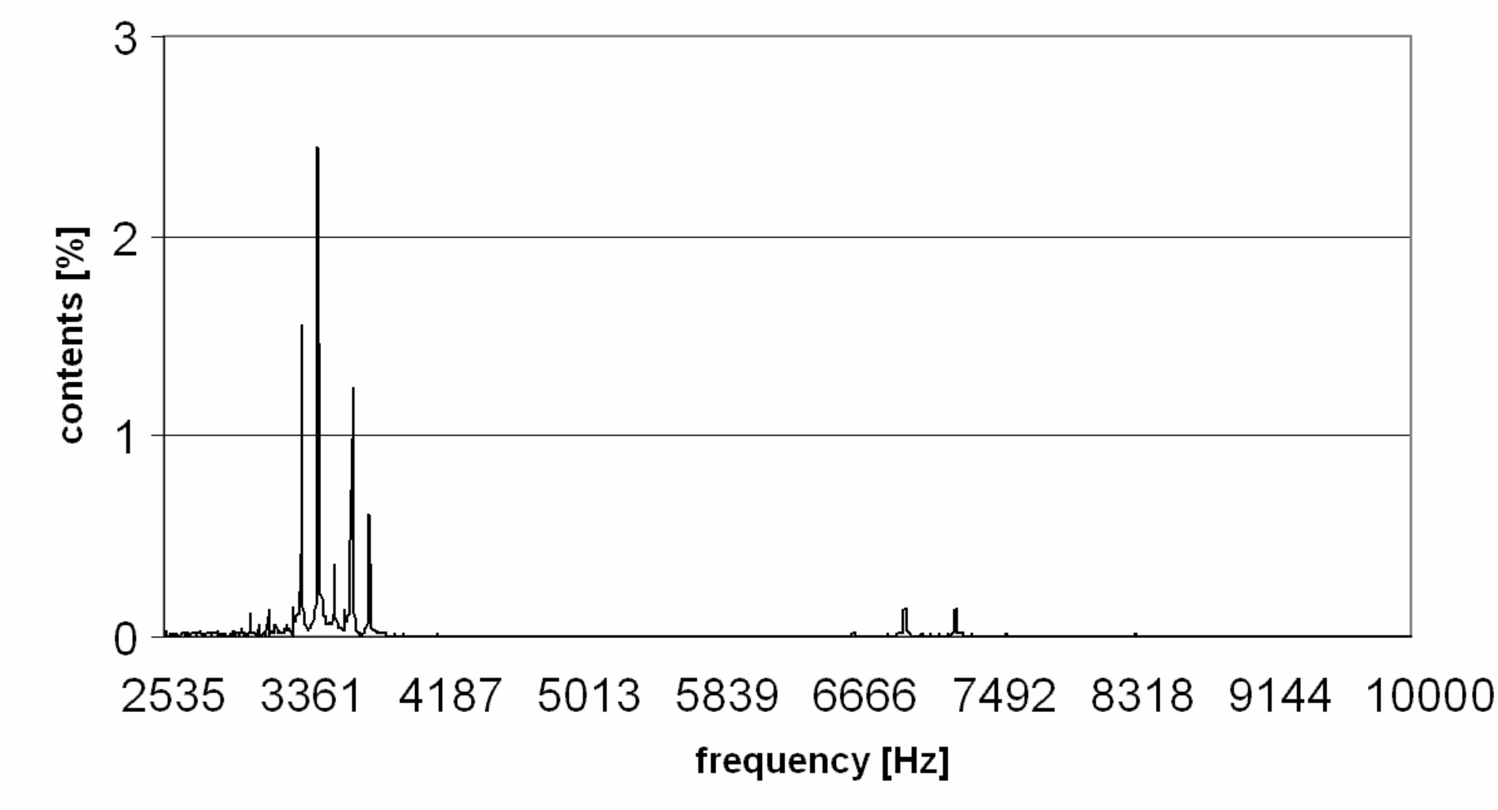
AFE THDv < 50th
(Measurements on vessel)



The selected example of the 400V voltage spectrum (THD=3.32%).

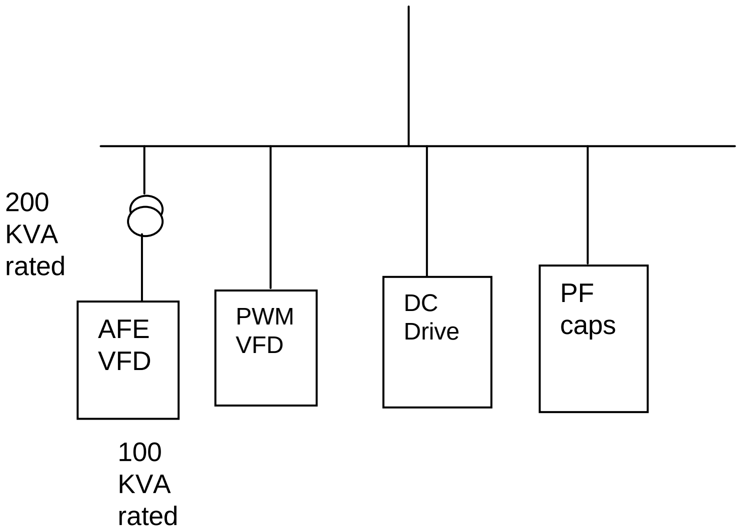
AFE THDv > 50th

(Measurements on vessel)



The result is a Vthd >50Hz of around 3.25%; almost as much as below! Total Vthd is ~ 4.65%!

AFE Converters



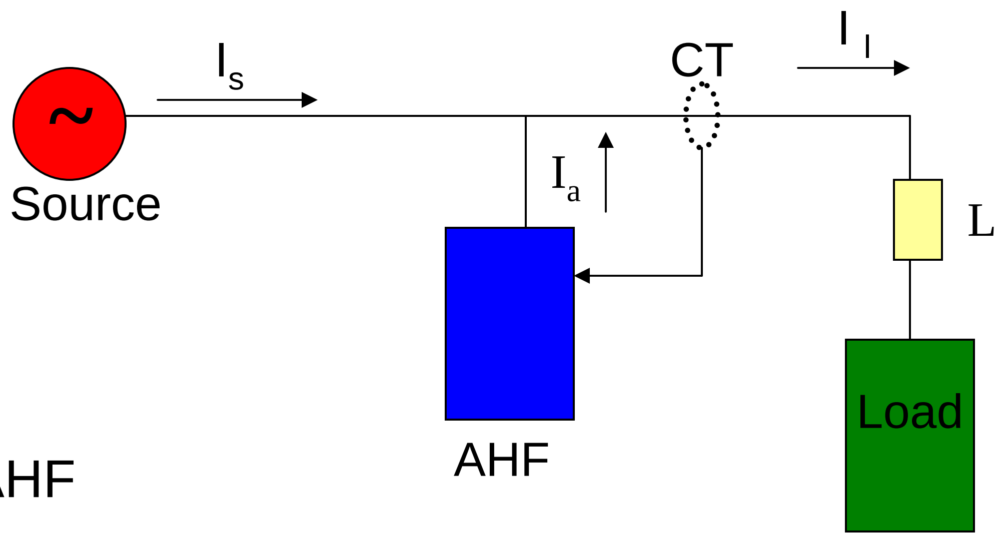
- Cons
  - Larger & more expensive than 6 pulse drives
    - Approximately twice the size & price
  - Larger & more expensive than 18-p VFD
  - High heat losses (~8%) per VFD
  - Mains voltage must be free of imbalance and voltage harmonics
    - Generates more harmonics
  - Without mains filter THD(V) can reach 40%
  - Requires short circuit ratio $\geq$ 40 at PCC
  - Switched mode power supplies prohibited
  - Capacitors prohibited on mains
  - IGBT & SCR rectifiers prohibited on same mains
    - No other nonlinear loads permitted
  - Cause high DC bus ripple & pumps up the DC voltage at low loads to trip unit

System Solution

Active Harmonic Filter

- Applied to one or many nonlinear loads
  - VFD, UPS, UV, DC drives, DC power supplies
- Provides DPF correction
- More cost effective for multiple loads
- Saves space
- Lower heat losses
- Not critical to operation

Active Harmonic Filter



AHF

•Parallel connected

•$\vec{I}_s + \vec{I}_a = \vec{I}_l$

- •Ia includes 2nd to 25/50th harmonic current
- •I_s <5% TDD

Active Harmonic Filters

- Advantages
  - Highly effective (2nd to 25/50th orders cancelled)
  - Parallel connected – not critical for equipment operation
  - Scalable
    - Parallel units as needed
  - Universal solution
    - Handles many loads
    - Many types of loads at same time
  - Can be installed as convenient
  - Best cost for multiple loads
  - Smallest footprint with std VFD/UPS
  - Lowest system heat losses
- Disadvantages
  - Heat from high speed switching of IGBT
  - Cost issues possible for single load
- Considerations
  - Load must have input impedance (3%)
    - Protects load
    - Limits size of AHF
  - Need branch circuit protection

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System Solution

AHF Sizing Example

- A 125 HP variable torque 6-pulse VFD with 3% LR
  - Required AHF filtering capability = 47.5 amperes
- Two 125 HP VT 6-pulse VFD w/3% LR
  - Required AHF size = 84.4 amps
- Three 125 HP VT 6-pulse VFD w/3% LR
  - Required AHF size = 113.5 amps
- Six 125 HP VT VFD w/3% LR
  - Required AHF size = 157.6 amps
    - (not 6 x 47.5 = 285 amps)

ANSI Standard
IEEE 519-1992

- Chapter 11
  - Addresses THD(V) delivered by utility to user
  - THD(V) must be < 5% [< 69 KV systems]
- Chapter 10
  - Defines the amount of TDD a user can cause
  - Based upon size of user in relation to power source
  - Table 10.3 for systems < 69 kV
  - Defines limits for voltage notches caused by SCR rectifiers – Table 10.2
- Defines PCC (point of common coupling)

IEEE 519-1992 Table 10.2

Limits on Commutation Notches

(Applies to SCR rectifiers – only)

Table 10.2
Low-Voltage System Classification and Distortion Limits

	*Special Applications	General System	**Dedicated System
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area, μVs	16,400	22,800	36,500

Note: Notch area for other than 480 V systems should be multiplied by V / 480.

***Special Applications** – Airports, Hospitals*

***** Dedicated System** – Dedicated exclusive to converter loads*

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IEEE 519-1992

- Defines current distortion as TDD
  - Total Demand Distortion
    - – Largest amplitude of harmonic current occurs at maximum load of nonlinear device – if electrical system can handle this it can handle all lower amplitudes
    - – Always referenced to full load current
    - – Effective meaning of current distortion
- Defines voltage distortion as THD
  - Total harmonic voltage distortion
- Does not use THD(I)
  - Total harmonic current distortion
  - Instrument measurement (instantaneous values)
  - Uses measured load current to calculate THD(I)

IEEE 519-1992

•TDD and THD(I) are not the same except at 100% load

Example: with AHF operating

	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%

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

IEEE 519-1992 Table 10.3

Current Distortion Limits for General Distribution Systems (<69 kV)

Isc/Iload	<11	11<=h<17	17<=h<23	23<=h<35	h>=35	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%	0.2%	1.0%	15.0%
>1000	15.0%	7.0%	6.0%	2.5%	1.4%	20.0%

Isc = short circuit current capacity of source

Iload = demand load current (fundamental)

TDD = Total Demand Distortion

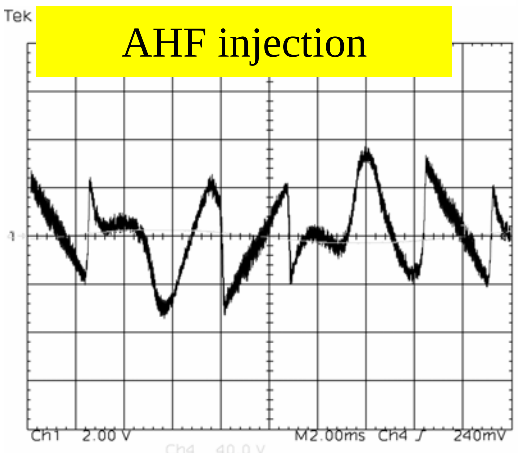
(TDD = Total harmonic current distortion measured against fundamental current at demand load.)

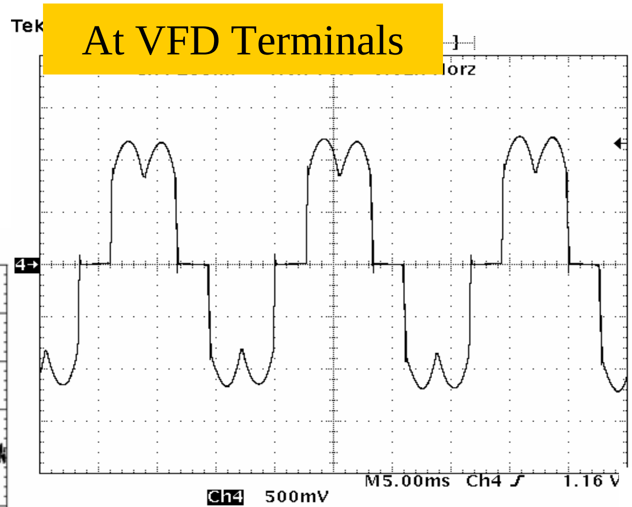
Harmonic Standards

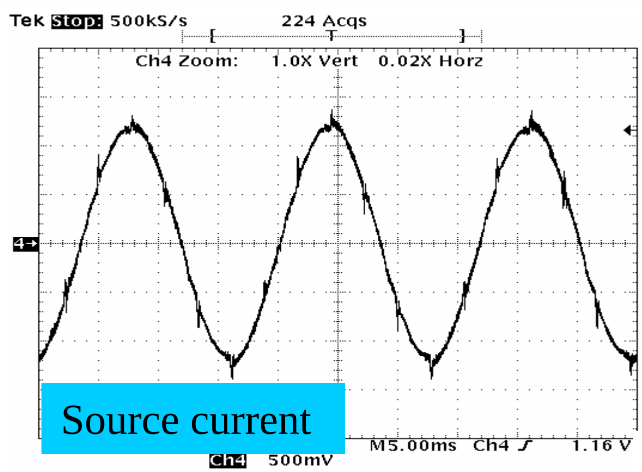
- Most harmonic problems are not at PCC with utility
    - Occurs with generators & UPS
    - Occurs where nonlinear loads are concentrated
    - Occurs inside the plant

- Need to protect the user from self by moving the harmonic mitigation requirements to where harmonic loads are located

AHF Harmonic Performance







Order	AS off % I fund	AS on % I fund
Fund	100.000%	100.000%
3	0.038%	0.478%
5	31.660%	0.674%
7	11.480%	0.679%
9	0.435%	0.297%
11	7.068%	0.710%
13	4.267%	0.521%
15	0.367%	0.052%
17	3.438%	0.464%
19	2.904%	0.639%
21	0.284%	0.263%
23	2.042%	0.409%
25	2.177%	0.489%
27	0.293%	0.170%
29	1.238%	0.397%
31	1.740%	0.243%
33	0.261%	0.325%
35	0.800%	0.279%
37	1.420%	0.815%
39	0.282%	0.240%
41	0.588%	0.120%
43	1.281%	0.337%
45	0.259%	0.347%
47	0.427%	0.769%
49	1.348%	0.590%
% THD(I)	35.28%	2.67%

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Active Harmonic Filter

Dual Mode Operation

$$I_{as} = \sqrt{I_h^2 + I_r^2}$$

I_{as} = rms output current of AHF PCS

I_h = rms harmonic current

I_r = rms reactive current

Examples		
Ias	Ih	Ir
100.0	10.0	99.5
100.0	20.0	98.0
100.0	30.0	95.4
100.0	40.0	91.7
100.0	50.0	86.6
100.0	60.0	80.0
100.0	70.0	71.4
100.0	80.0	60.0
100.0	90.0	43.6
100.0	95.0	31.2

Typical W/WW Applications

- Pumping Stations
  - Potable
  - Wastewater
- Wastewater Plants
- Water Purification (potable)

Typical W/WW Applications

- Pumping Stations Applications
  - VFD for pump control
    - Simple/repeatable control
      - Remote control made easy
    - Energy savings over discharge, on/off, & inlet flow control

Typical W/WW Applications

- Wastewater Plants
  - Many pumps for fluid movement (VFD)
    - VT
      - Centrifugal pumps
    - CT
      - Progressive cavity pumps (semi-solids)
  - Solids handling (VFD)
    - Conveyors
  - Aeration blowers (VFD)
    - CT & VT types
  - Disinfectant
    - UV systems (ultraviolet)
      - Electronic ballasts – 3Φ
    - Ozone generators (SCR power supplies)
  - HVAC

Typical W/WW Applications

- Water Purification
  - Many pumps (VFD)
  - UV systems (electronic ballasts)
  - Reverse osmosis
    - Centrifugal pumps (VFD)
  - Ozone generators

Specification Recommendations for System Solution

- Write TDD specs not THD(I)
- Separate harmonic spec from nonlinear load spec
  - Place AHF spec in Section 16 by itself
  - Write standard nonlinear load specification
    - Eliminates vendor hassles
    - Need 3% impedance on each nonlinear load
- Universal solution
  - Good for all nonlinear loads
  - Apply AHF per electrical bus (best economics)
- Can attain 5% TDD per load or bus inside the plant
  - Guarantees elimination of harmonic problems – both TDD and THD(V)

Summary

- Know the solution
  - What does it accomplish harmonically
  - Know the benefits and cautions
    - Every device requires different considerations
- Make comparisons
  - First cost
  - Floor space required
  - Heat losses/cooling requirements
  - Cost of operating
- Select what you really need
  - All 6-p rectifiers should have at least a 3% line reactor
    - Reduces TDD to ~1/3
    - Protects diode rectifiers from transients
    - Reduces voltage notch of SCR rectifiers
- Write the specification required
  - Meet the standard at utility
  - Protect the user from self

Thank You

Questions?