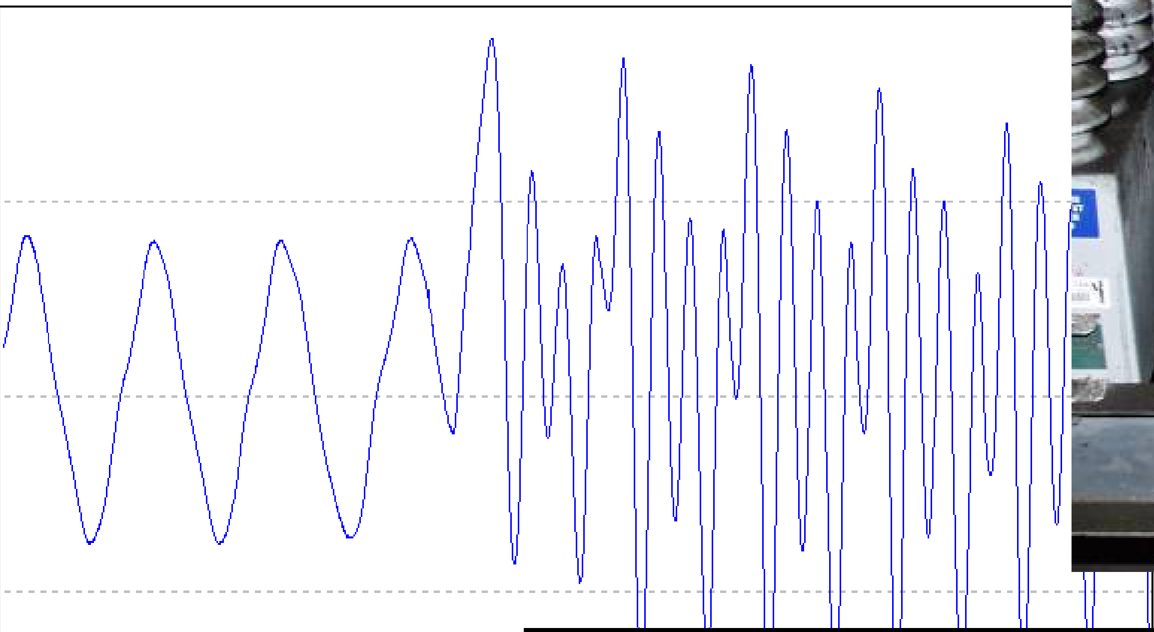


Harmonic Sources and Solutions

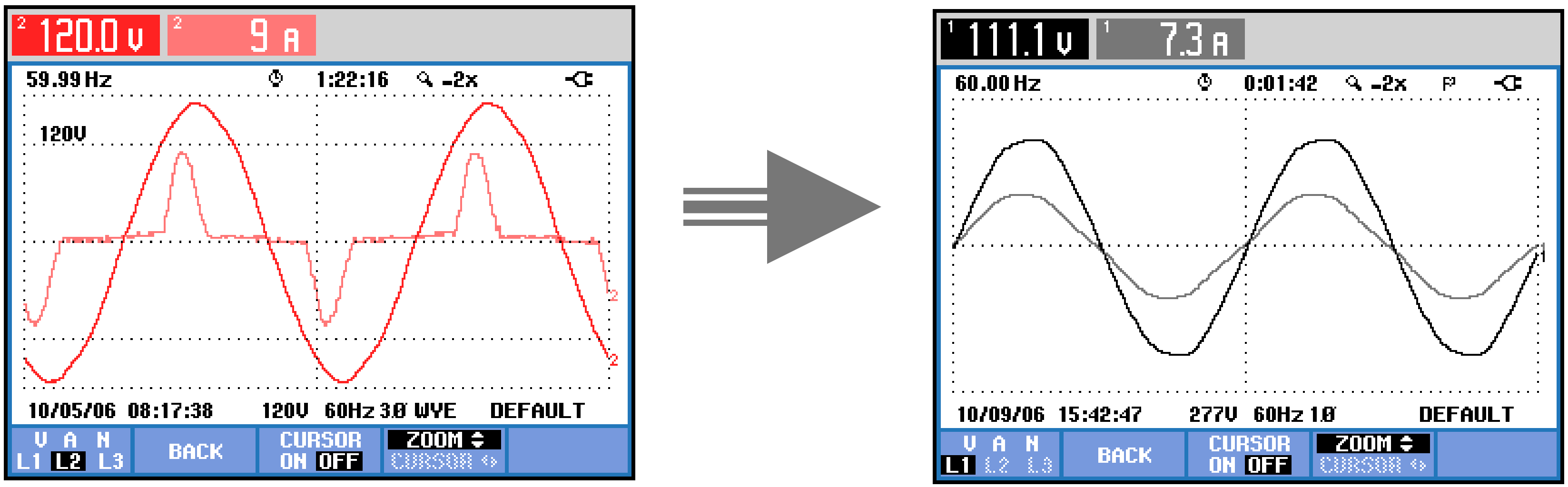
For IEEE San Antonio

Harmonics

- **Introduction to Harmonics**
- Symptoms
- Characteristic Harmonics from non-linear loads
- Harmonic Resonance
- Understanding IEEE 519-1992
- Harmonic Solutions

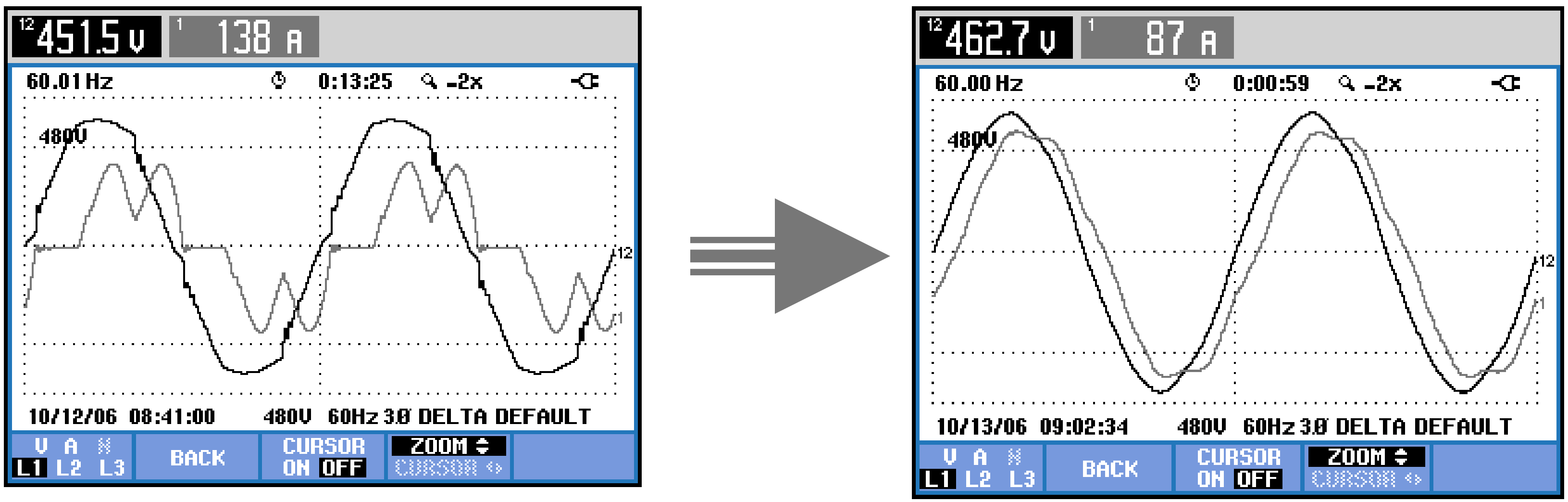
Harmonics – Who Cares!

- Recent technology changes
  - Switch Mode Power Supplies (SMPS) change over to PF Corrected Power Supplies



Harmonics – Who Cares!

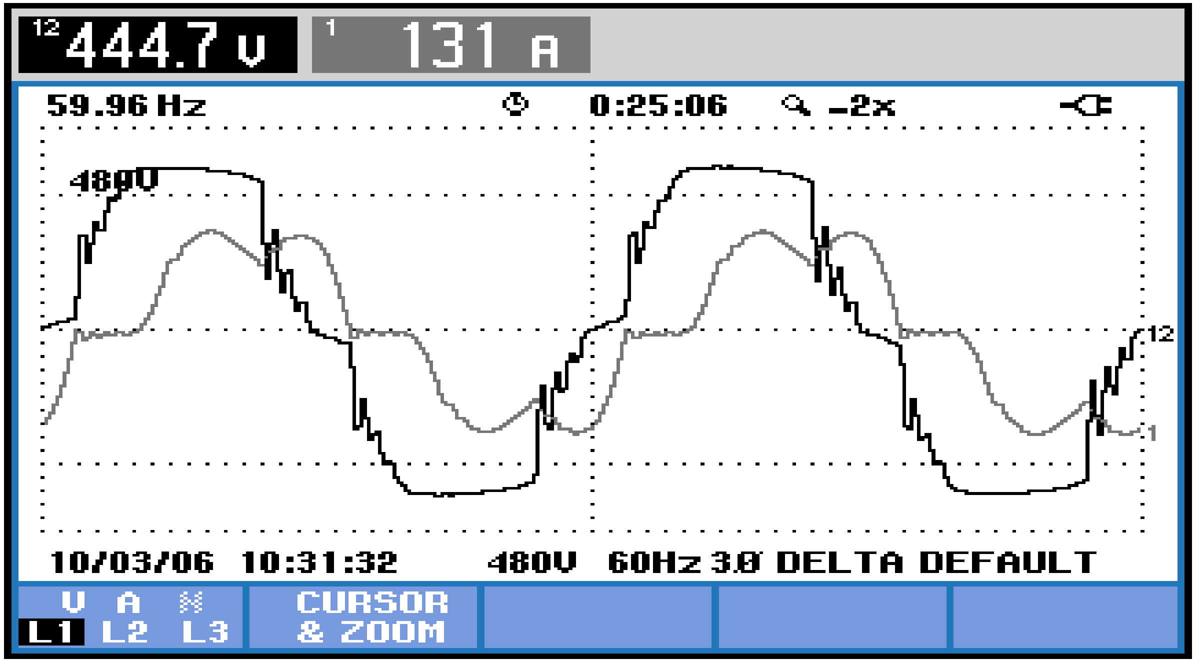
- Recent technology changes
  - Active front end on UPS and some drives



Harmonics – Who Cares!

- What remains – why are we here?
  - What level of harmonics is a problem?

"Harmonics are not a problem unless they are a problem!"



Harmonics

- Introduction to Harmonics
- **Symptoms**
- Characteristic Harmonics from non-linear loads
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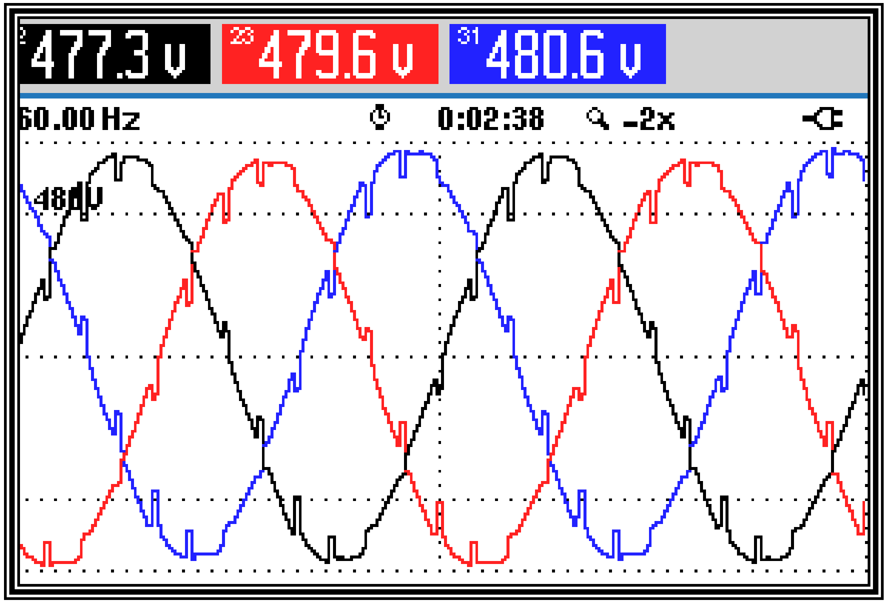
- Understanding IEEE 519-1992
- Harmonic Solutions

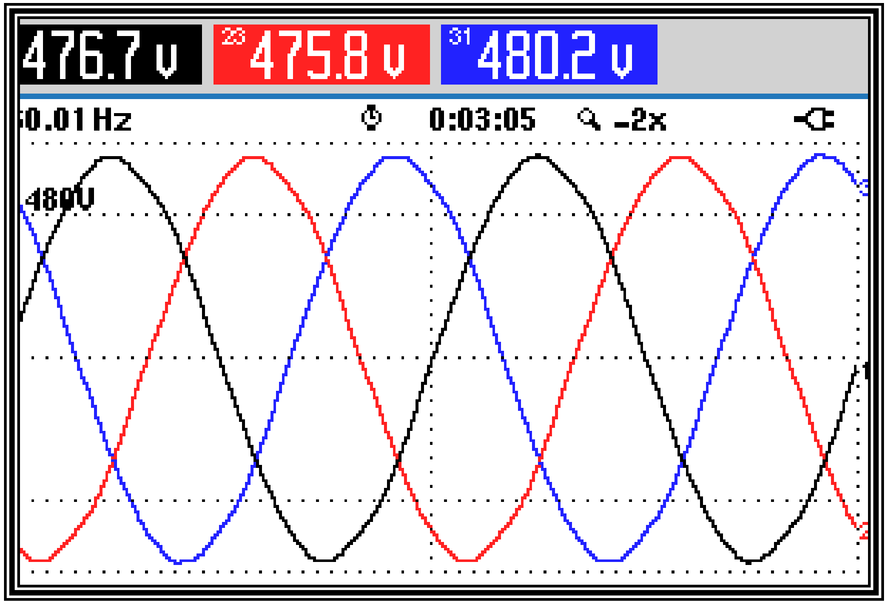
Harmonic Symptoms

– Generator Sync Failure

- Generator 1 (Loaded)



Generator 2 (Unloaded)

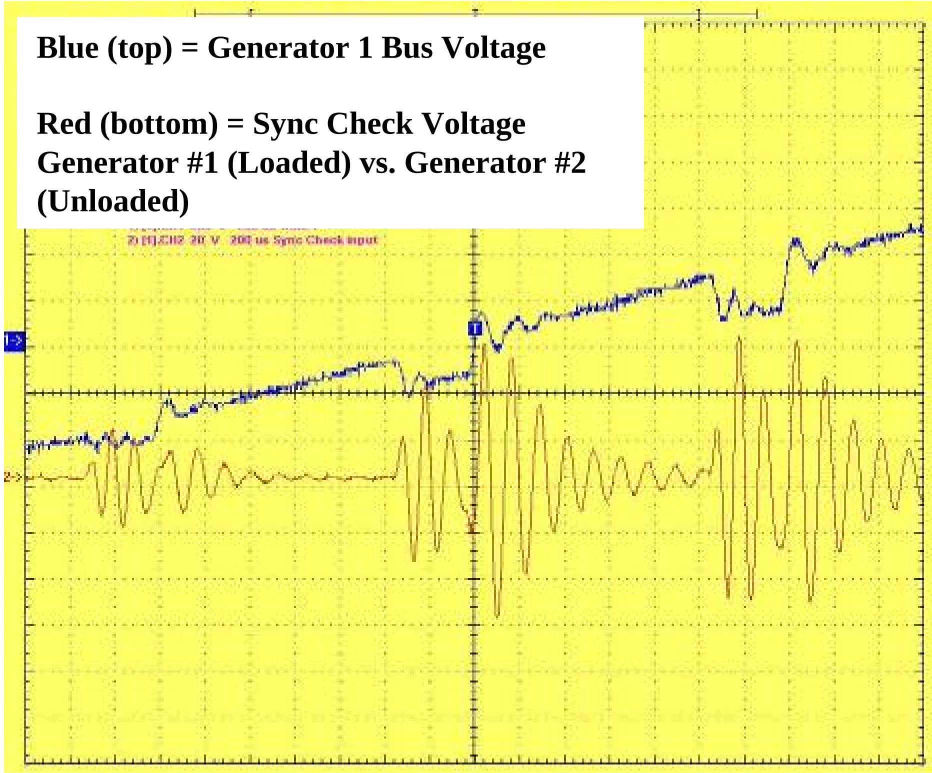


Harmonic Symptoms

Generator Sync Failure

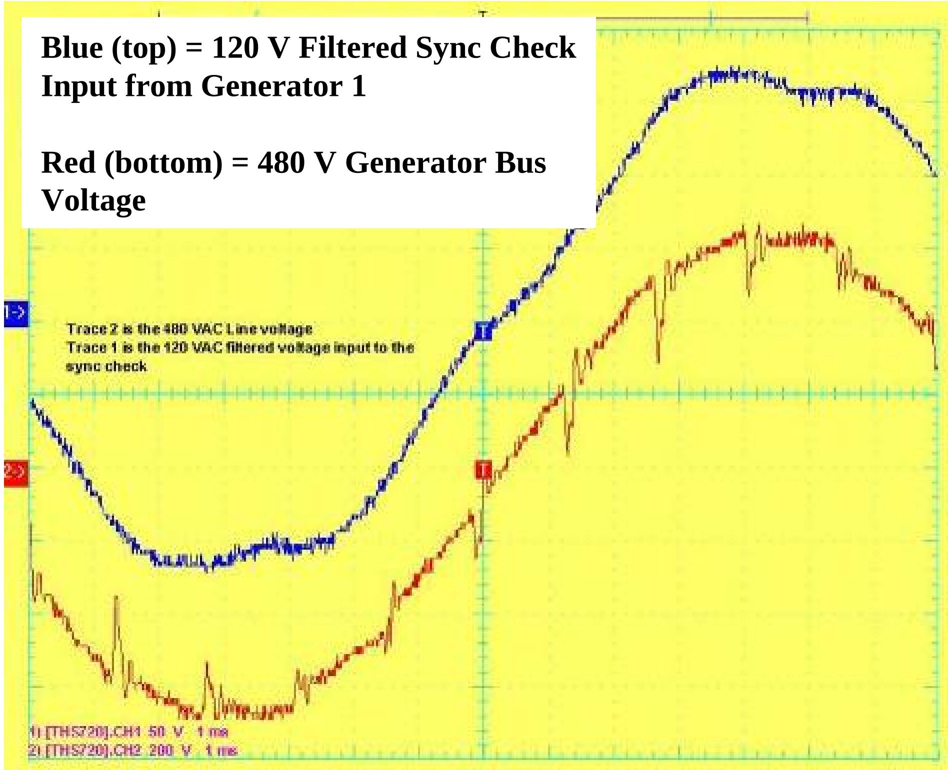
Blue (top) = Generator 1 Bus Voltage

Red (bottom) = Sync Check Voltage Generator #1 (Loaded) vs. Generator #2 (Unloaded)



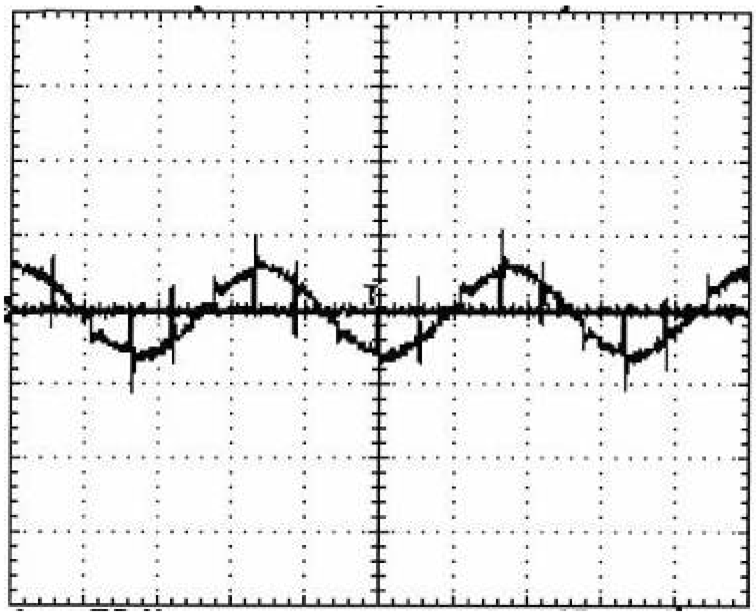
Blue (top) = 120 V Filtered Sync Check Input from Generator 1

Red (bottom) = 480 V Generator Bus Voltage



Harmonic Symptoms

Transfer Switch Frequency Sync Check Failure



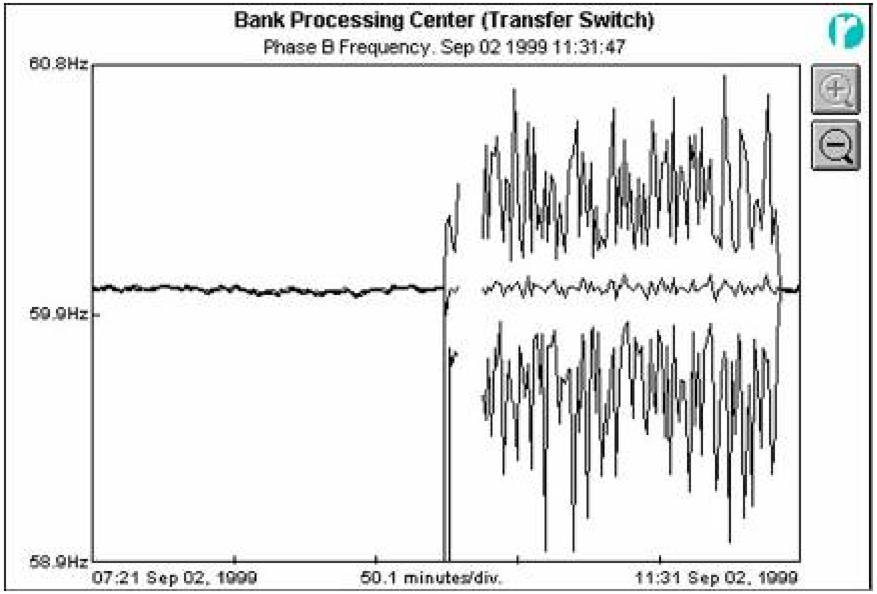
- Notching from UPS rectifier
- Transfer switch indicated > 99 Hz on generator source
- Could not re-synchronize with utility
- Batteries depleted

Solution: (Temporary) Disable over-frequency check

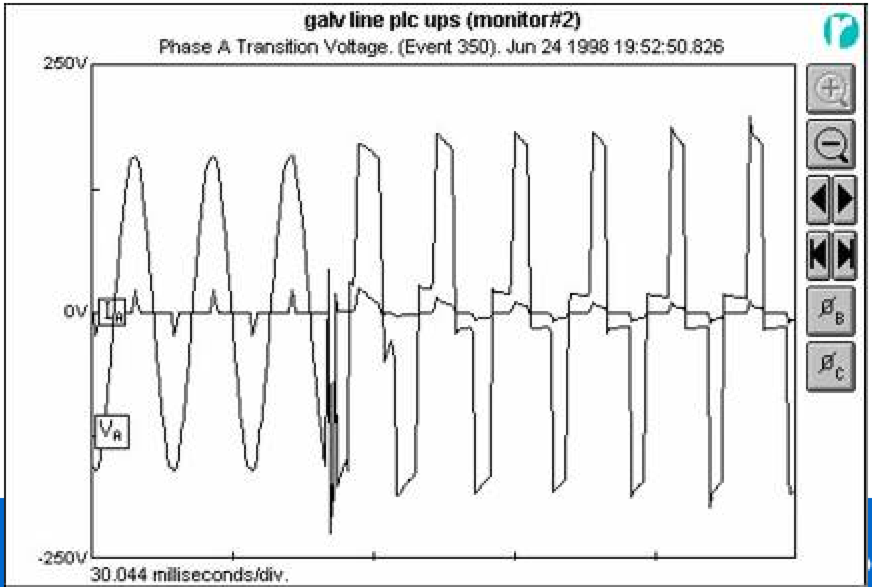
Solution: (Permanent) 480 V UPS Filter or Notch Filter

Harmonic Symptoms

- UPS reporting "UPS not synchronized to input power"
- Frequency/slew rate issue
- Undersized generator
- **Solution:** Increase generator size (i.e. lower impedance)

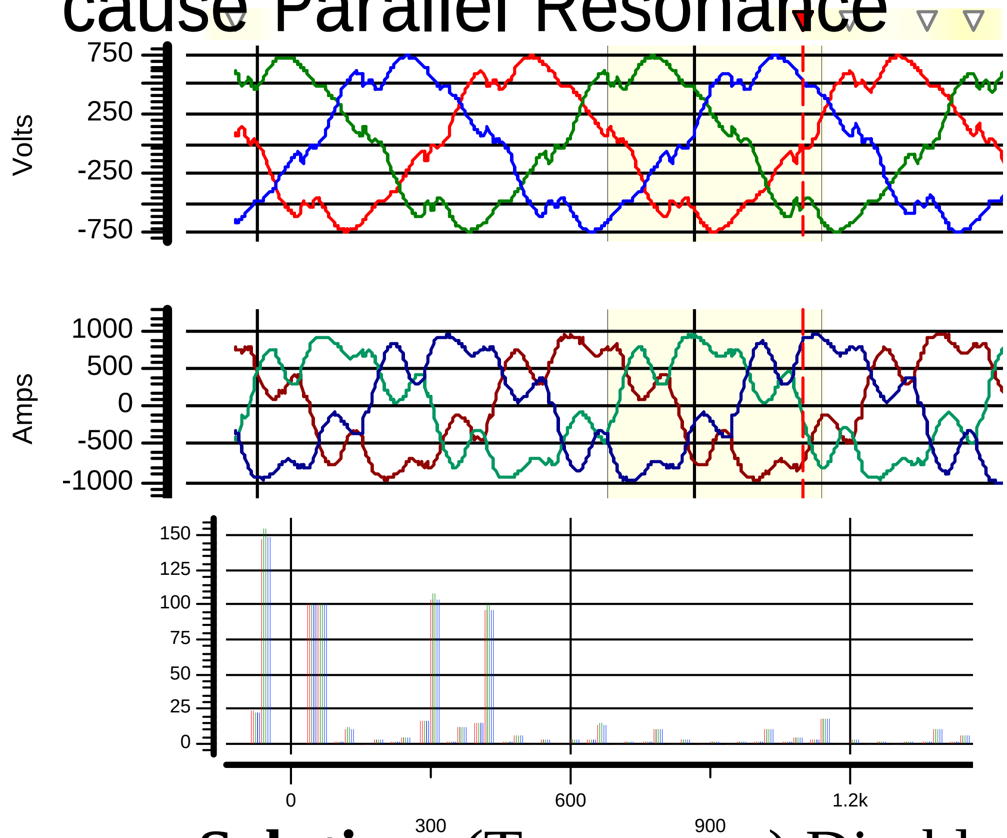


- Control (PLC) could not tolerate square wave voltage
- Standby UPS
- **Solution:** Apply sine wave output UPS



Harmonic Symptoms

Softstart Starter on Generators cause Parallel Resonance



- System with large UPS system (11th harmonic filter), undersized generators and soft starts on HVAC
- Parallel resonant point of UPS filter shifts on generator causing amplification of 5th and 7th harmonics from S.S.
- High harmonic distortion causes misfiring of the UPS rectifiers further aggravating instability.

Solution: (Temporary) Disable UPS Filter(s)

Solution: (Permanent) Replace w/Active Filter(s)

Harmonics

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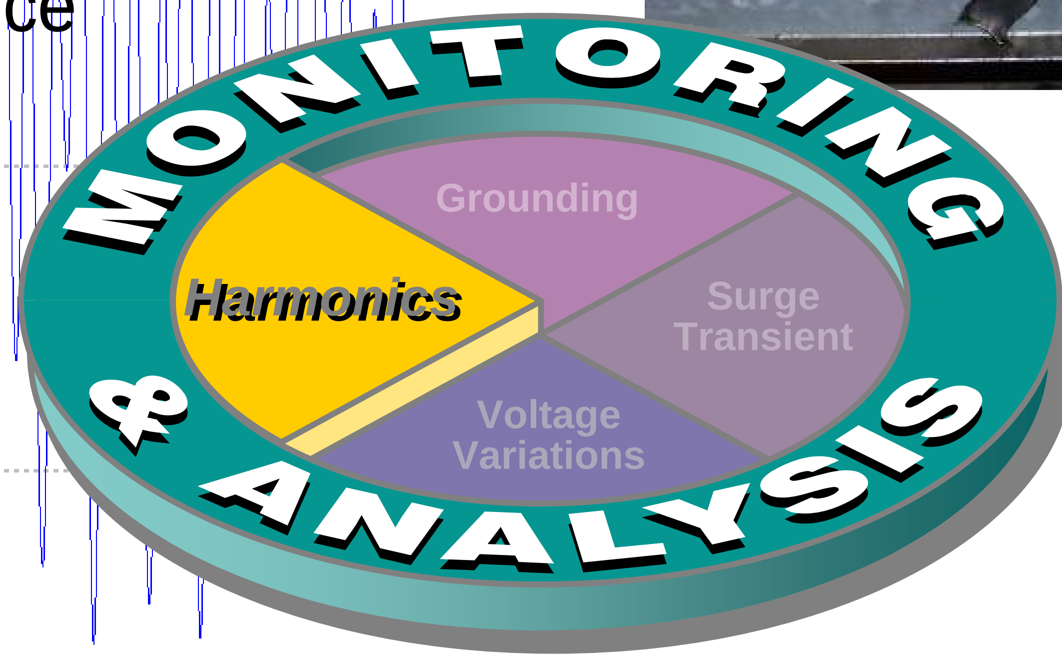
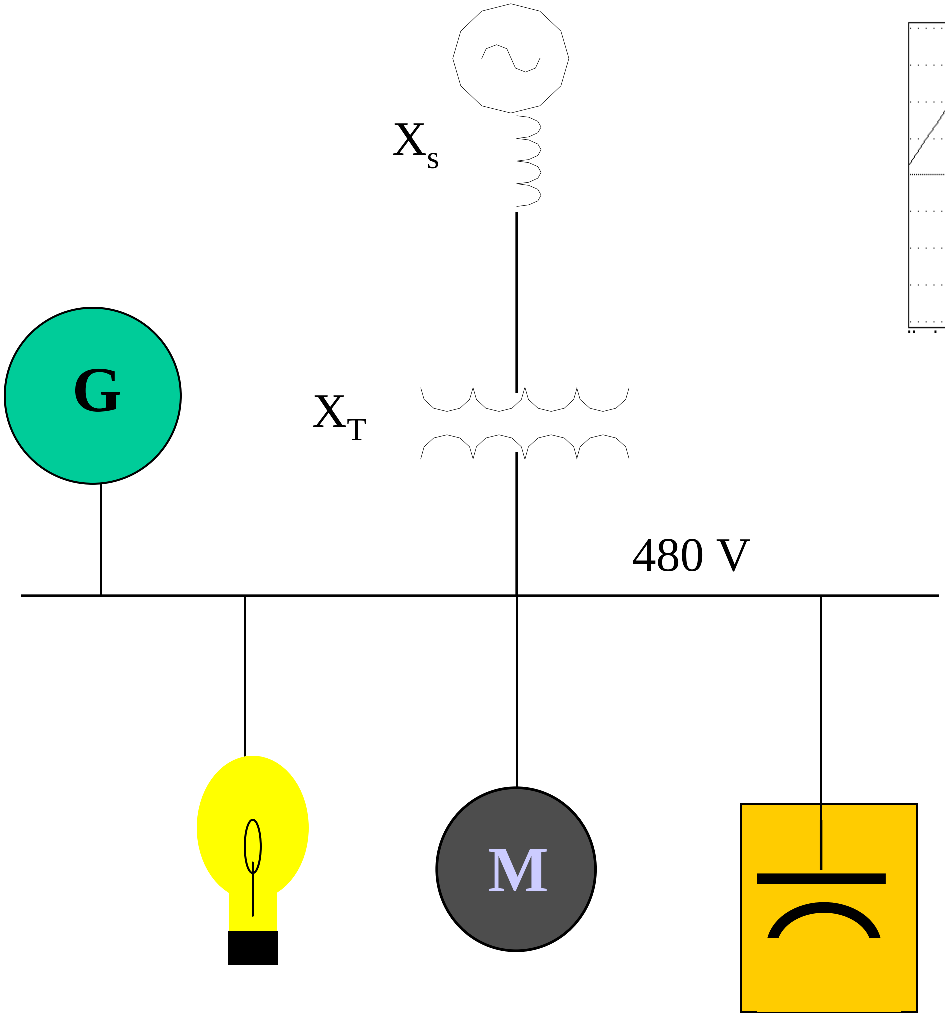
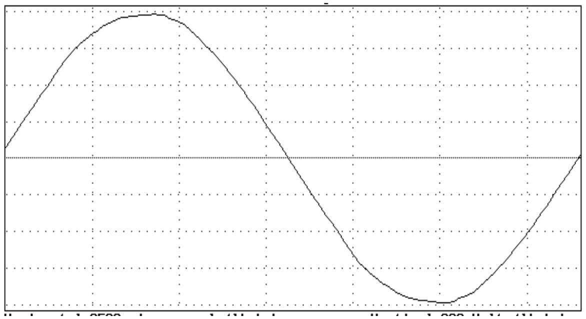
Harmonic Distortion

- Harmonic problems are becoming more apparent because more equipment that produce harmonics are being applied to power systems



Harmonics Yesterday





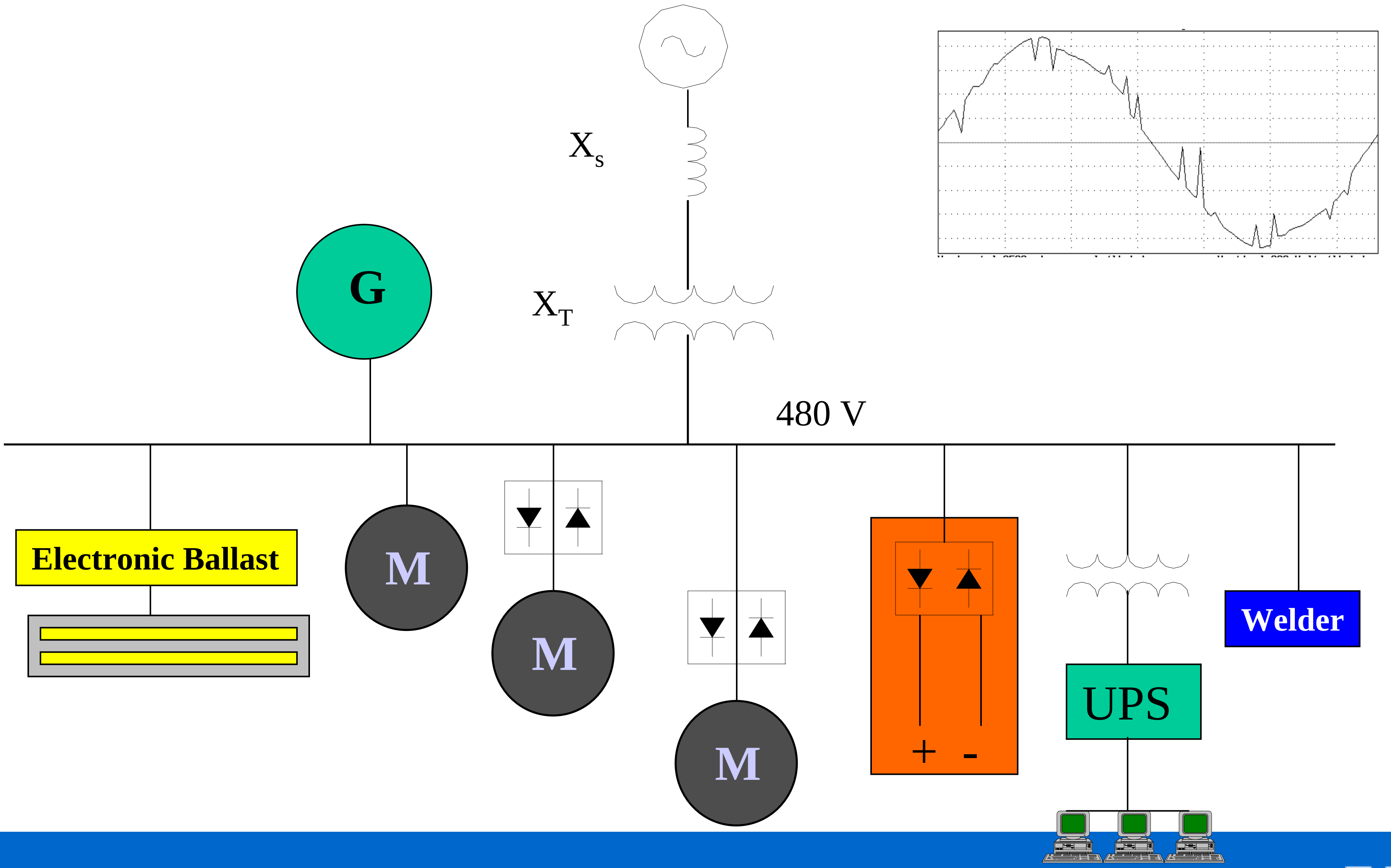
Which came first?.....

Voltage Distortion

Current Distortion

- In this case...the Egg!
  - **Current distortion causes Voltage distortion**
  - **Voltage distortion is created by pulling <u>distorted current</u> 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**

Harmonics Today

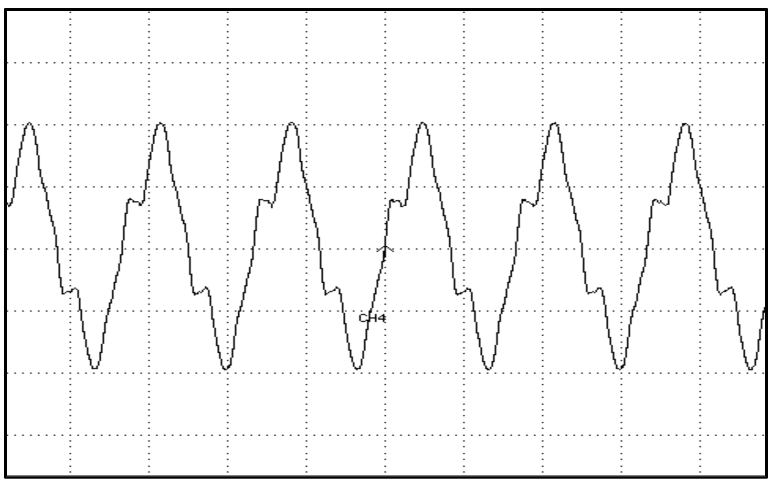


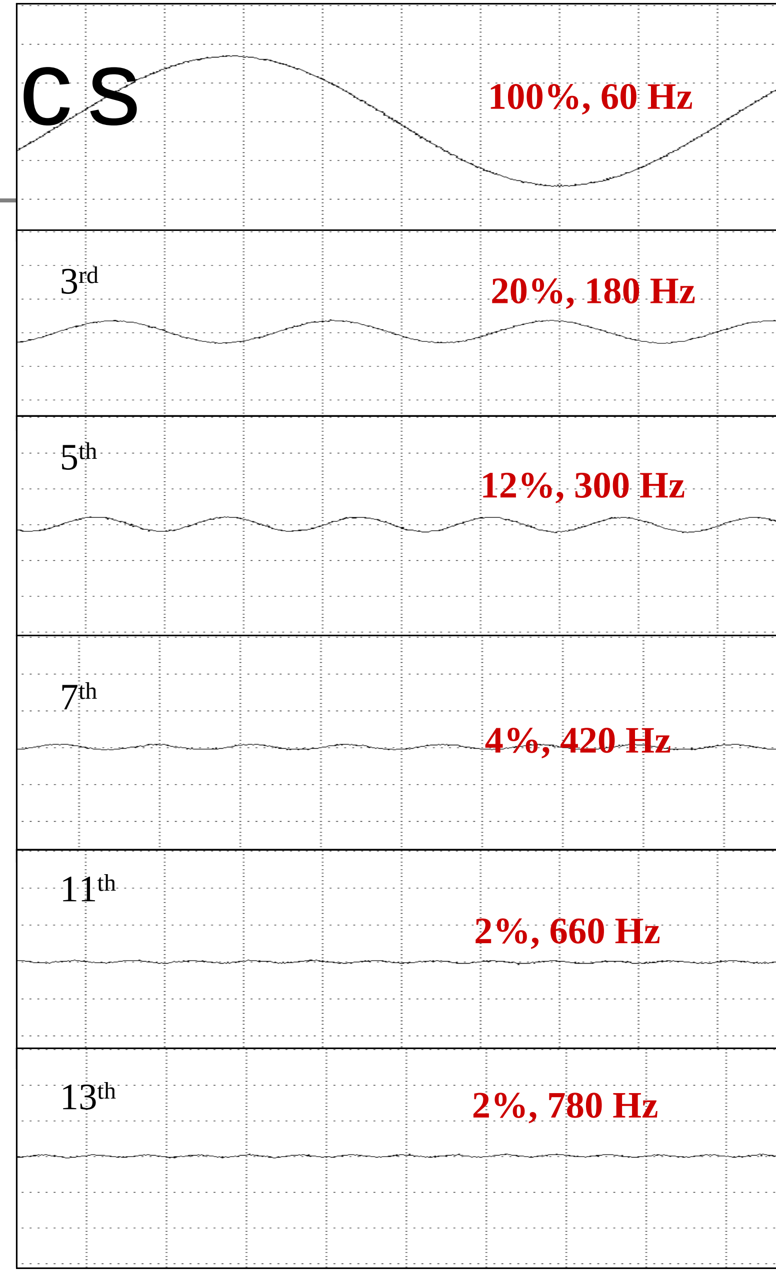
Harmonics

Total Harmonic Distortion (THD) – (voltage or current) represents a ratio of the root-mean-square of the harmonic content to the fundamental quantity, expressed as a percent of the fundamental.

$$\%THD_I = \frac{\sqrt{I_2{}^2 + I_3{}^2 + I_4{}^2 + \ldots}}{I_1} \times 100\%$$

relays_cd_07072008.zip





Expected Harmonics

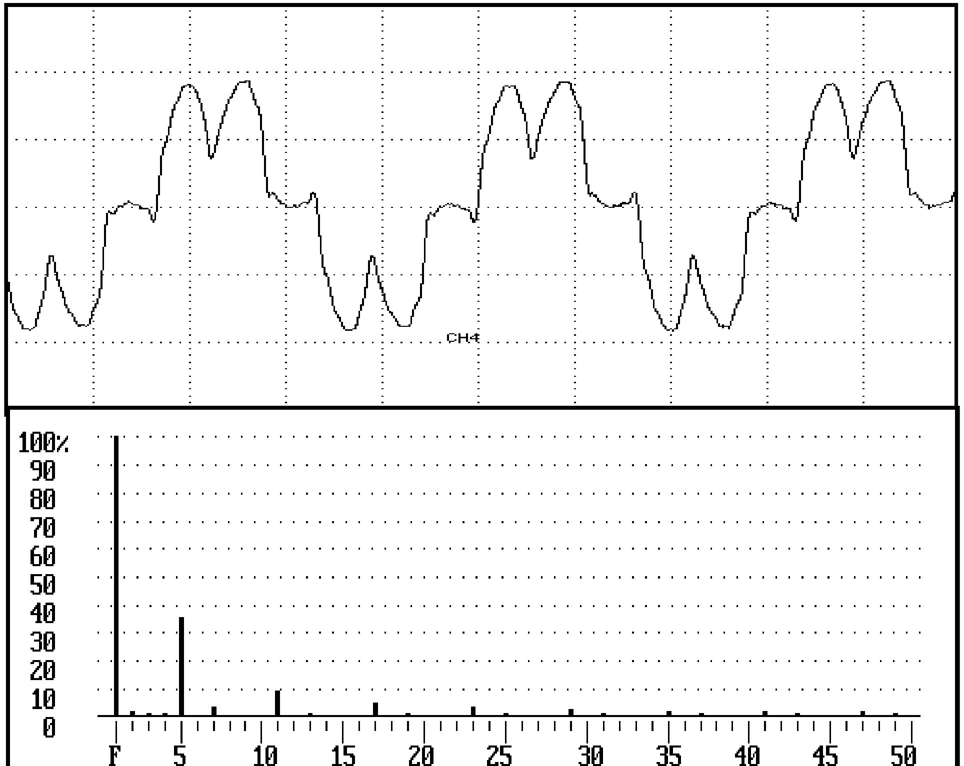
Source	Typical Harmonics*
6 Pulse Drive/Rectifier	5, 7, 11, 13, 17, 19…
12 Pulse Drive/Rectifier	11, 13, 23, 25…
18 Pulse Drive	17, 19, 35, 37…
Switch-Mode Power Supply	3, 5, 7, 9, 11, 13…
Fluorescent Lights	3, 5, 7, 9, 11, 13…
Arcing Devices	2, 3, 4, 5, 7...
Transformer Energization	2, 3, 4

* Generally, magnitude decreases as harmonic order increases

H = NP+/-1

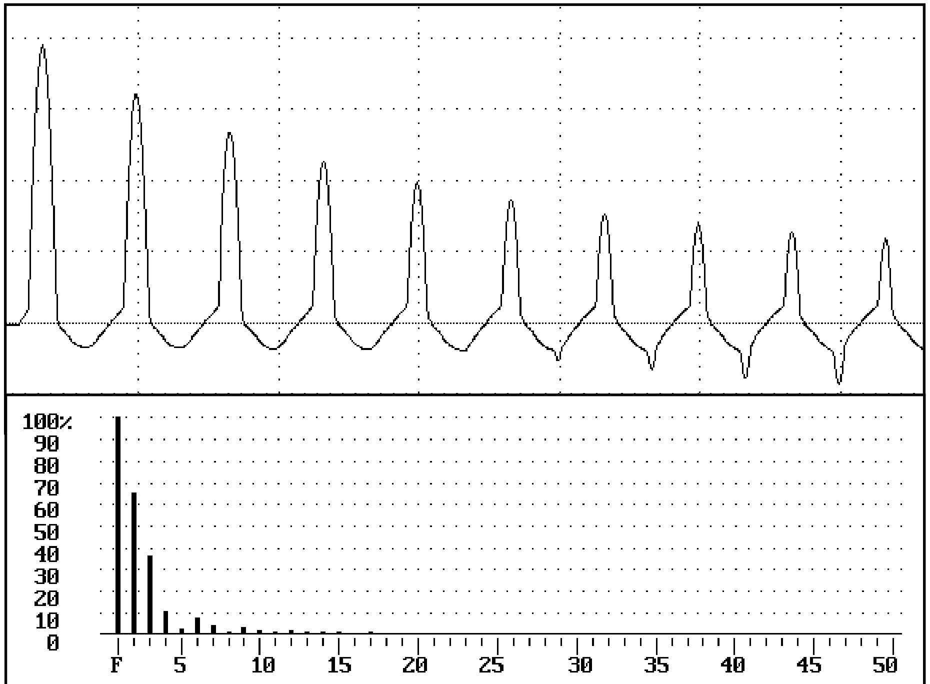
i.e. 6 Pulse Drive - 5, 7, 11, 13, 17, 19,…

Harmonic Sources – VFDs



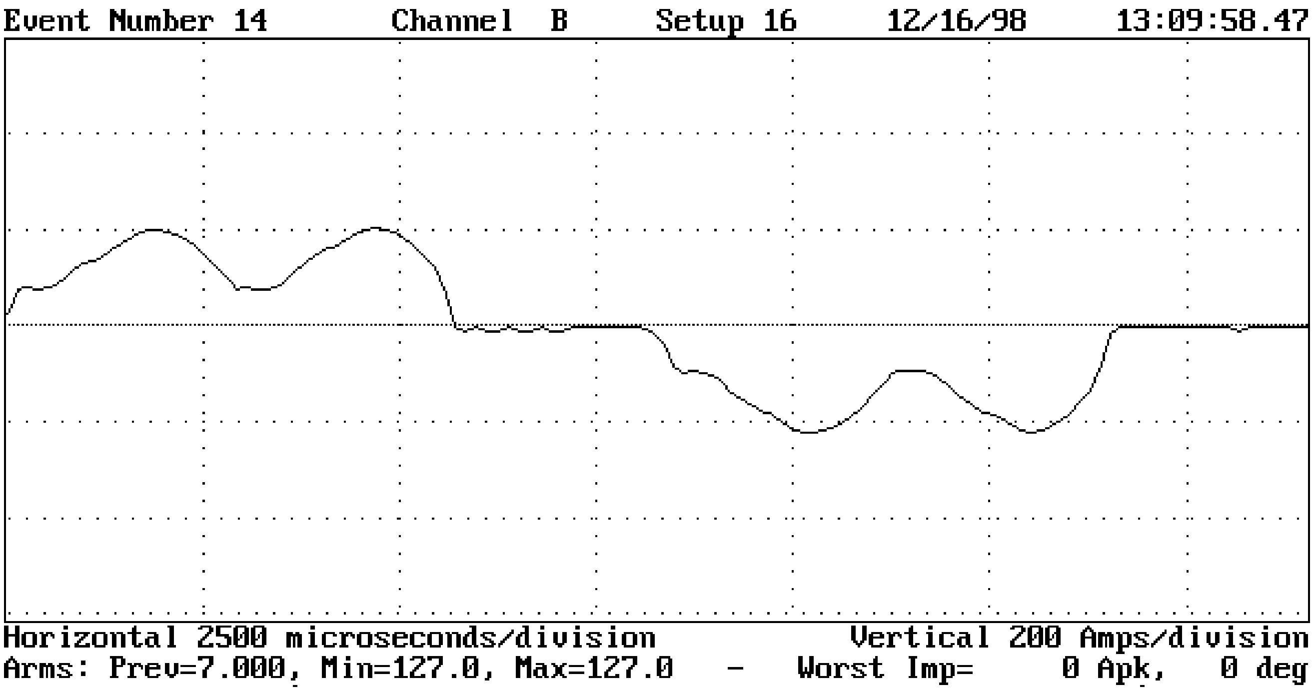
Fnd:	212.30A	291 deg	18th:	0.2%	298 deg	35th:	1.9%	75 deg
2nd:	2.1%	31 deg	19th:	1.2%	222 deg	36th:	0.2%	250 deg
3rd:	1.0%	73 deg	20th:	0.3%	327 deg	37th:	1.1%	137 deg
4th:	1.1%	118 deg	21st:	0.1%	8 deg	38th:	0.2%	266 deg
5th:	35.6%	208 deg	22nd:	0.1%	30 deg	39th:	0.2%	278 deg
6th:	0.4%	313 deg	23rd:	3.2%	129 deg	40th:	0.1%	270 deg
7th:	2.9%	64 deg	24th:	0.2%	278 deg	41st:	1.6%	47 deg
8th:	0.5%	11 deg	25th:	1.2%	192 deg	42nd:	0.2%	234 deg
9th:	0.2%	66 deg	26th:	0.2%	307 deg	43rd:	1.1%	110 deg
10th:	0.3%	94 deg	27th:	0.1%	337 deg	44th:	0.2%	239 deg
11th:	8.9%	184 deg	28th:	0.1%	336 deg	45th:	0.2%	244 deg
12th:	0.2%	310 deg	29th:	2.4%	102 deg	46th:	0.1%	228 deg
13th:	0.9%	258 deg	30th:	0.2%	267 deg	47th:	1.4%	20 deg
14th:	0.4%	348 deg	31st:	1.1%	164 deg	48th:	0.2%	218 deg
15th:	0.1%	43 deg	32nd:	0.2%	282 deg	49th:	1.2%	84 deg
16th:	0.2%	74 deg	33rd:	0.1%	306 deg	50th:	0.1%	223 deg
17th:	4.7%	156 deg	34th:	0.1%	305 deg			

Harmonic Sources – Transformer Inrush

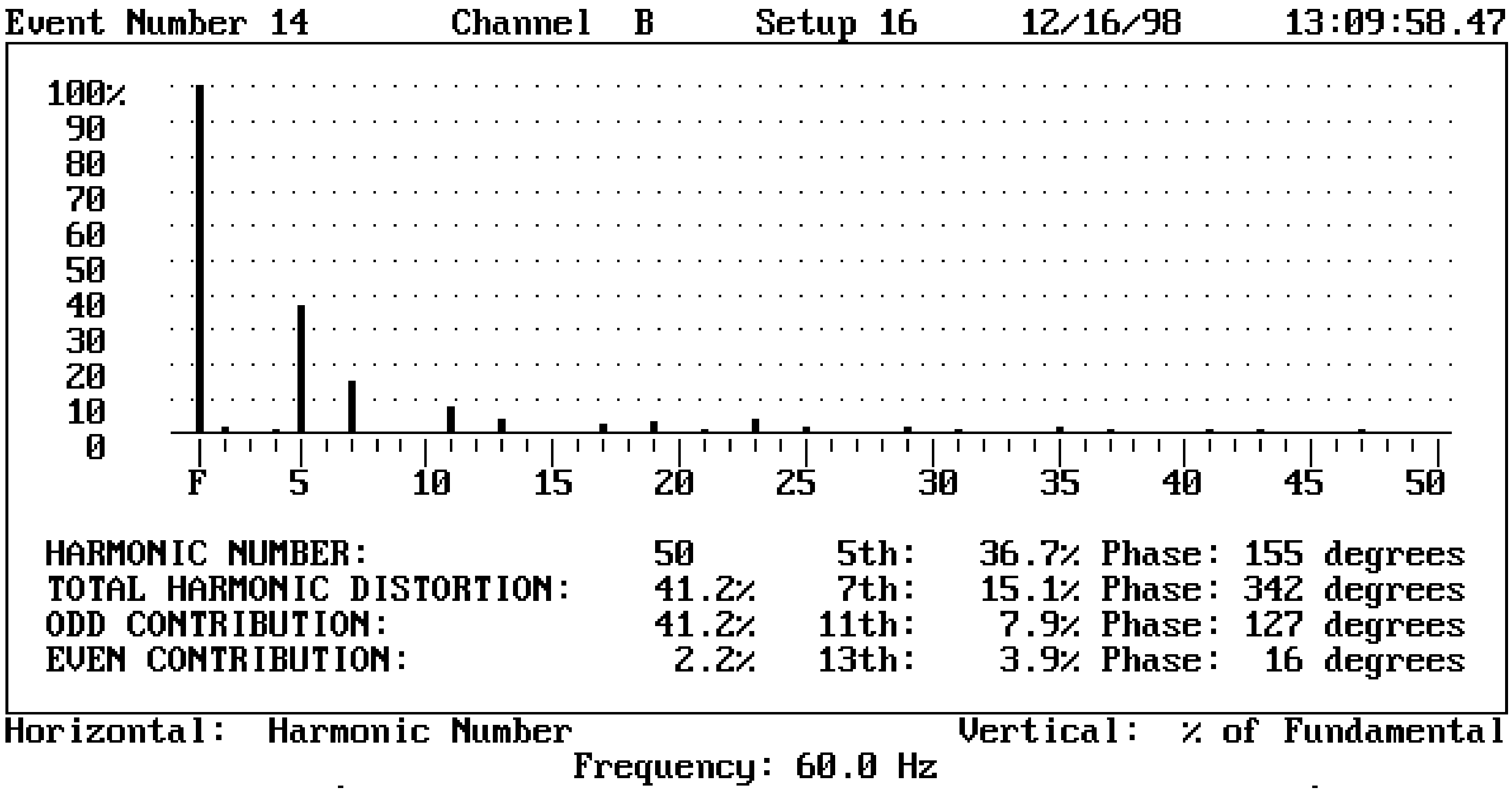


Fnd:	224.13A	165 deg	18th:	0.5%	39 deg	35th:	0.1%	66 deg
2nd:	65.4%	342 deg	19th:	0.6%	149 deg	36th:	0.3%	31 deg
3rd:	36.4%	144 deg	20th:	0.6%	9 deg	37th:	0.2%	37 deg
4th:	10.3%	325 deg	21st:	0.4%	48 deg	38th:	0.1%	53 deg
5th:	2.4%	330 deg	22nd:	0.5%	112 deg	39th:	0.2%	18 deg
6th:	7.9%	113 deg	23rd:	0.5%	346 deg	40th:	0.3%	51 deg
7th:	3.8%	292 deg	24th:	0.3%	62 deg	41st:	0.2%	35 deg
8th:	1.1%	54 deg	25th:	0.3%	85 deg	42nd:	0.2%	338 deg
9th:	3.2%	91 deg	26th:	0.3%	331 deg	43rd:	0.2%	28 deg
10th:	1.7%	263 deg	27th:	0.3%	58 deg	44th:	0.1%	77 deg
11th:	0.9%	65 deg	28th:	0.3%	82 deg	45th:	0.2%	27 deg
12th:	1.7%	67 deg	29th:	0.1%	326 deg	46th:	0.2%	22 deg
13th:	0.8%	227 deg	30th:	0.4%	39 deg	47th:	0.1%	40 deg
14th:	0.9%	51 deg	31st:	0.3%	55 deg	48th:	0.2%	12 deg
15th:	0.9%	52 deg	32nd:	0.1%	314 deg	49th:	0.3%	12 deg
16th:	0.6%	183 deg	33rd:	0.2%	42 deg	50th:	0.1%	33 deg
17th:	0.8%	27 deg	34th:	0.2%	48 deg			

Waveform Display



Harmonic Spectrum



Text and Phase Angle

Event Number 14 Channel B Setup 16 12/16/98 13:09:58.47

Fnd:	117.24A	64 deg	18th:	0.1%	256 deg	35th:	1.5%	166 deg
2nd:	1.7%	288 deg	19th:	3.4%	67 deg	36th:	0.2%	260 deg
3rd:	0.4%	92 deg	20th:	0.1%	0 deg	37th:	1.0%	70 deg
4th:	0.9%	320 deg	21st:	0.7%	20 deg	38th:	0.2%	87 deg
5th:	36.7%	155 deg	22nd:	0.4%	356 deg	39th:	0.3%	352 deg
6th:	0.2%	34 deg	23rd:	3.7%	134 deg	40th:	0.5%	109 deg
7th:	15.1%	342 deg	24th:	0.2%	72 deg	41st:	0.8%	188 deg
8th:	0.3%	297 deg	25th:	1.6%	64 deg	42nd:	0.2%	34 deg
9th:	0.4%	135 deg	26th:	0.2%	35 deg	43rd:	0.9%	90 deg
10th:	0.1%	320 deg	27th:	0.1%	140 deg	44th:	0.1%	27 deg
11th:	7.9%	127 deg	28th:	0.4%	85 deg	45th:	0.0%	93 deg
12th:	0.1%	176 deg	29th:	1.8%	155 deg	46th:	0.2%	270 deg
13th:	3.9%	16 deg	30th:	0.1%	207 deg	47th:	0.7%	192 deg
14th:	0.2%	215 deg	31st:	1.2%	76 deg	48th:	0.0%	324 deg
15th:	0.6%	207 deg	32nd:	0.2%	145 deg	49th:	0.4%	104 deg
16th:	0.1%	352 deg	33rd:	0.3%	230 deg	50th:	0.2%	6 deg
17th:	2.6%	113 deg	34th:	0.3%	27 deg			

T.H.D.: 41.2% ODD CONTRIB.: 41.2% EVEN CONTRIB.: 2.2%

Frequency: 60.0 Hz

WARNING: % alone (without reference to actual Amps or Volts) can be misleading – especially on the neutral conductor!

Sources of Harmonics

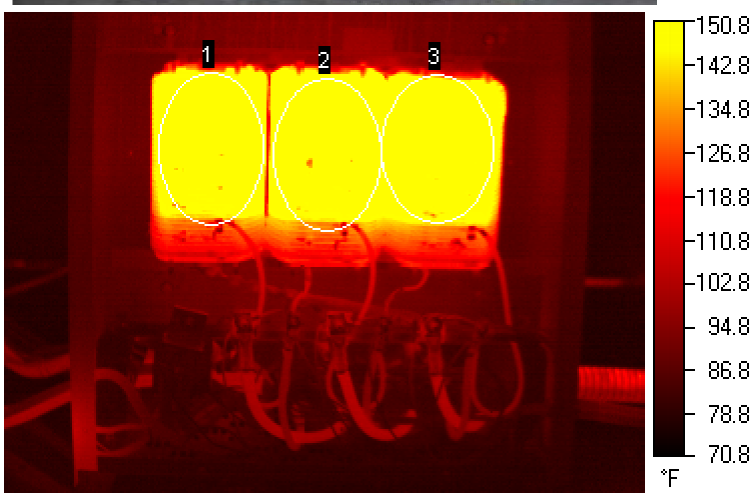
- General sources of harmonics
  - Power electronic equipment (drives, rectifiers, computers, etc.)
  - Arcing devices (welders, arc furnaces, florescent lights, etc.)
  - Iron saturating devices (transformers)
  - Rotating machines (generators)
- Most prevalent and growing harmonic sources:
  - Adjustable frequency drives (AFD)
  - Switch-mode power supplies (computers)
  - Fluorescent lightning
- Single loads or groups of loads

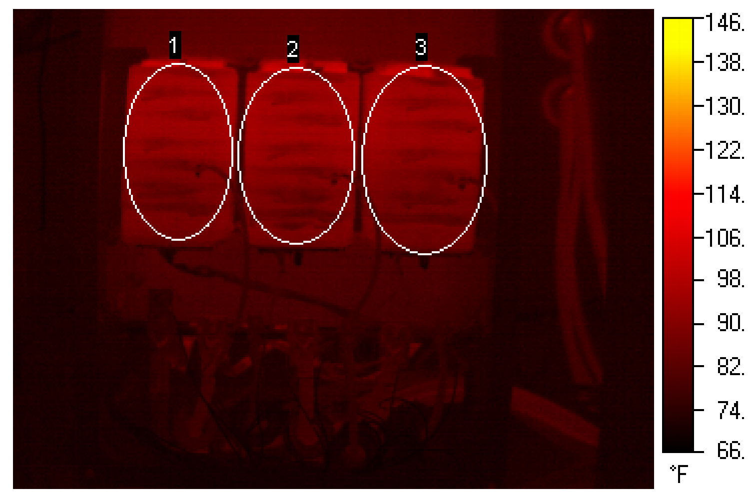
Harmonic Symptoms/Concerns

- Equipment Failure and Misoperation
  - Notching (electronic control malfunctioning, regulator misoperation)
  - Overheating/Failure (transformers, motors, cables/neutral)
  - Nuisance Operation (fuses, breakers)
  - Insulation deterioration
  - Audible noise in electrical equipment
- Economic Considerations
  - Oversizing (equipment is sized larger to accommodate harmonics)
  - Losses/Inefficiencies/PF Penalties
  - Inconsistent meter reading

Harmonics and Heating

Load 100% Harmonics

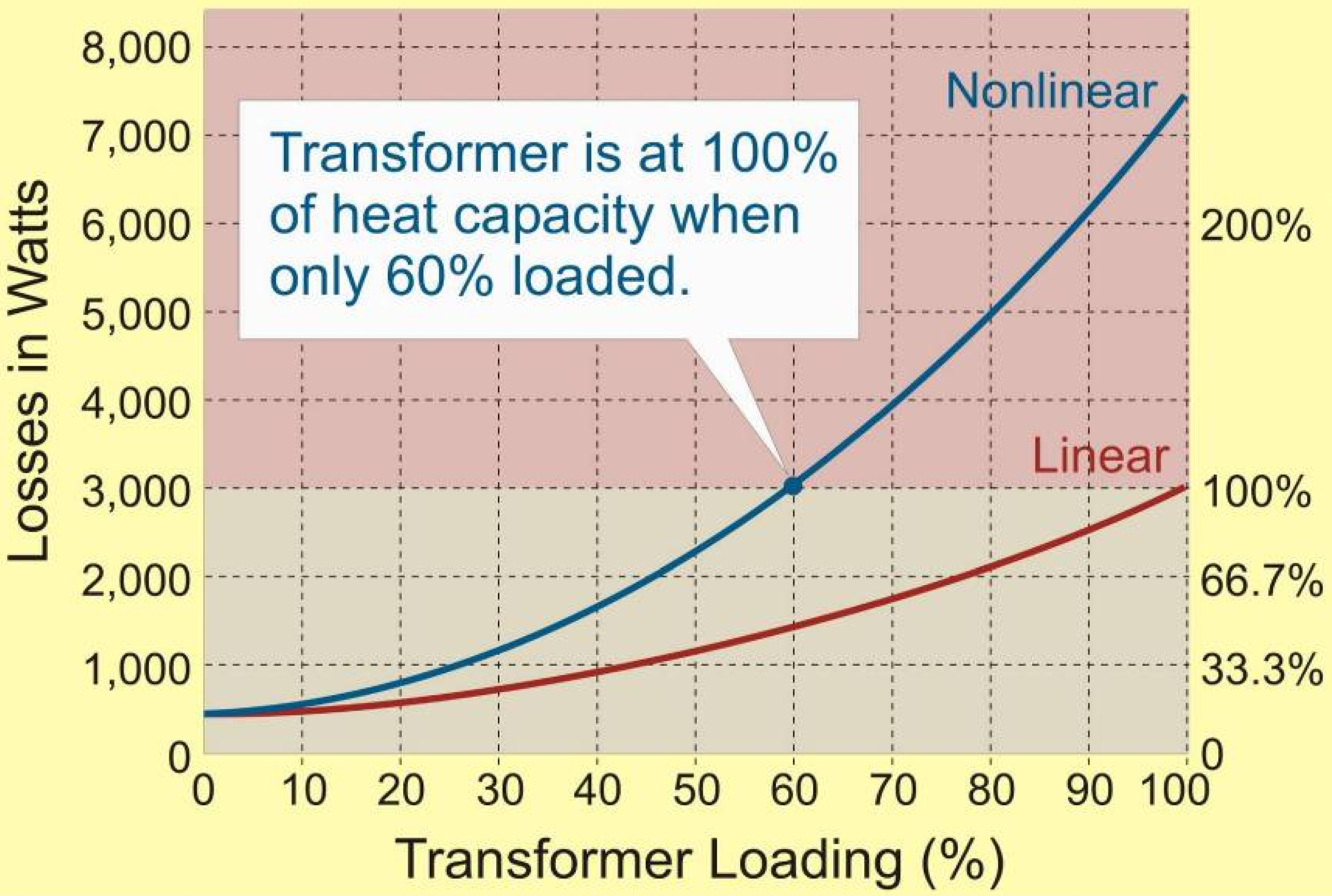




Std Transformer – Max Temp – 176 F

HMT – Max Temp – 105 F

Loss Comparison - Linear vs Nonlinear Load



Harmonics

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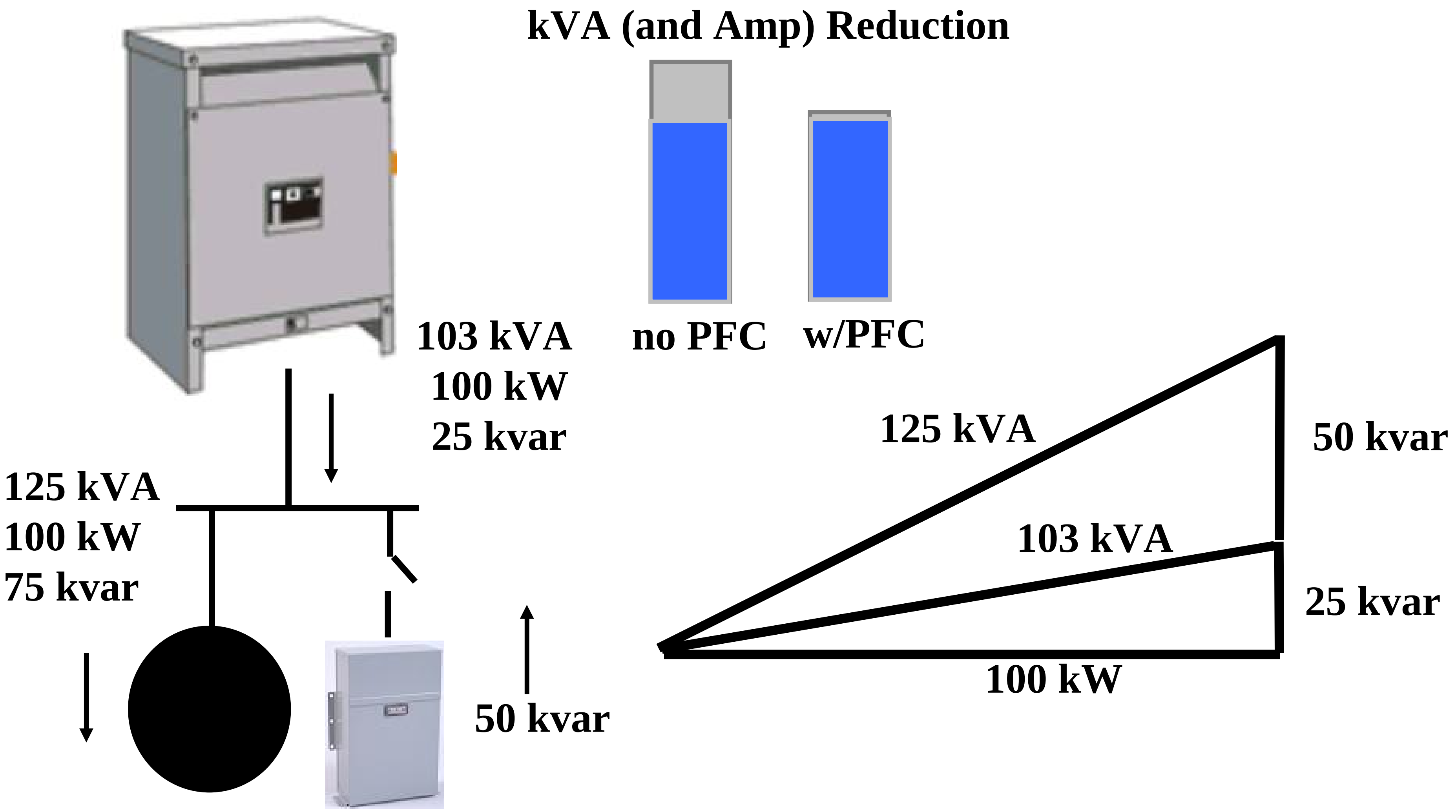
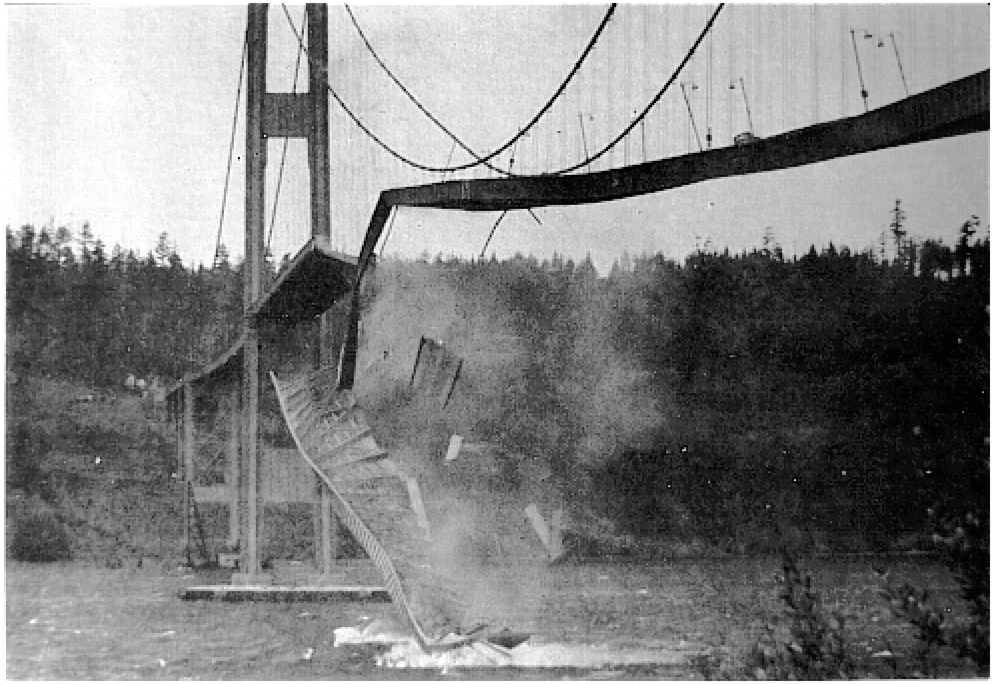
PF and Harmonics



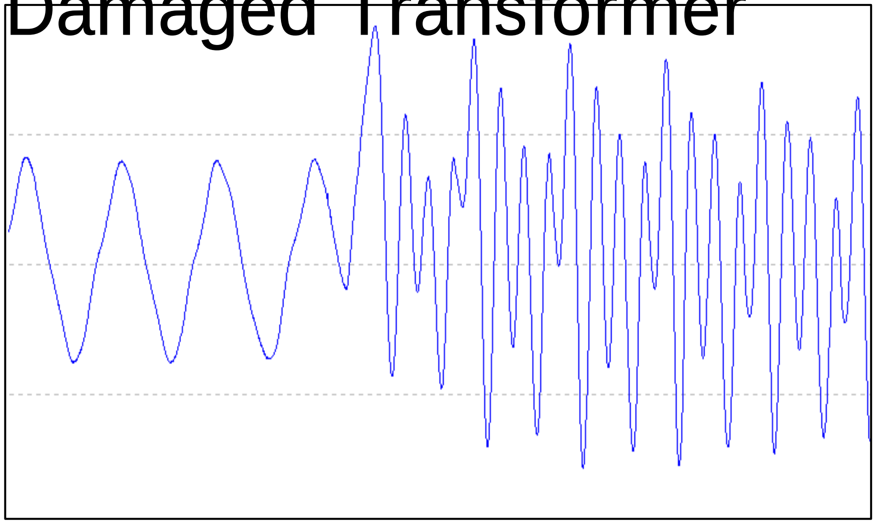
Harmonic Resonance



On November 7, 1940, at approximately 11:00 AM, the Tacoma Narrows suspension bridge collapsed due to **wind-induced vibrations**…the bridge had only been open for traffic **a few months**.

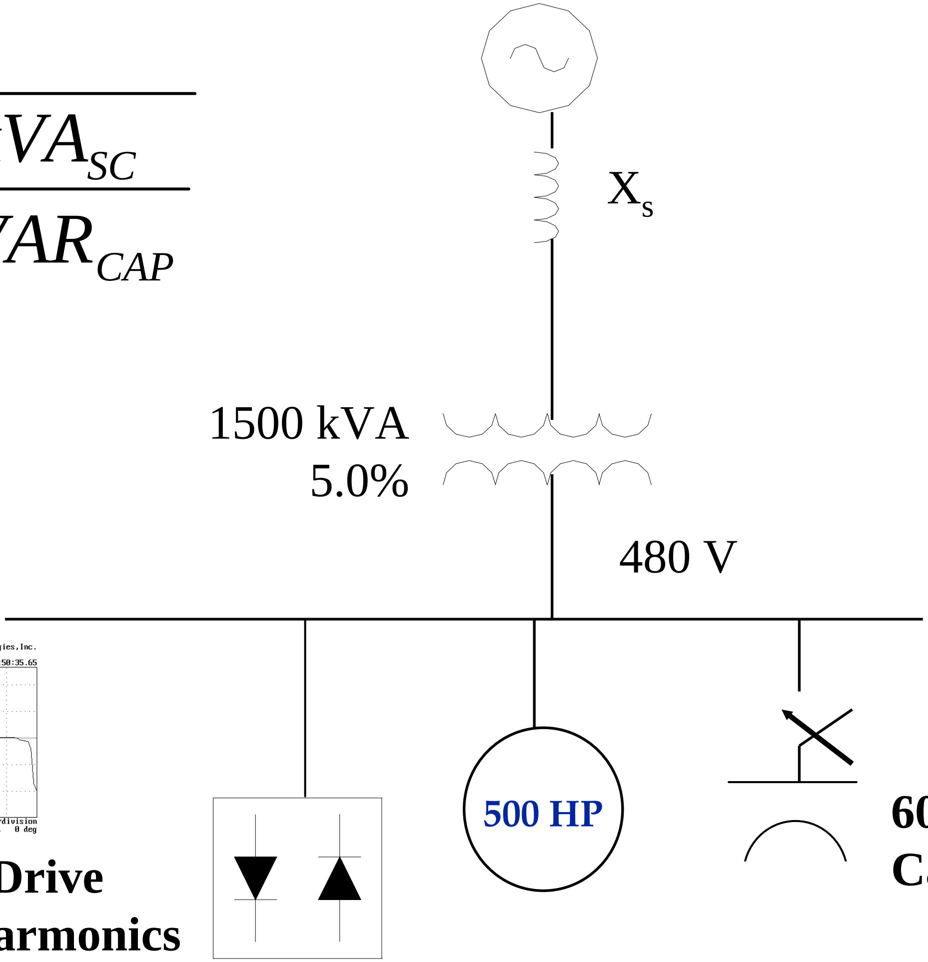
Harmonic Resonance

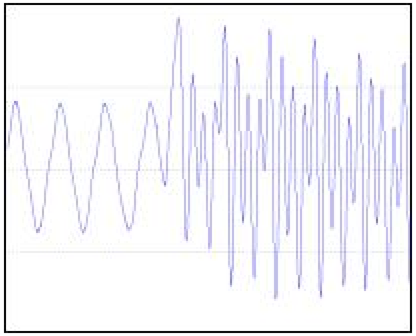
- The "Self Correcting" Problem
  - Blown Fuses
  - Failed Capacitors
  - Damaged Transformer

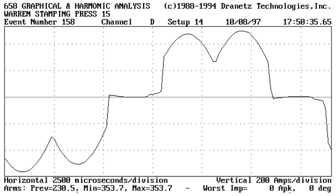


Harmonic Resonance

$$h_R = \sqrt{\frac{kVA_{SC}}{kVAR_{CAP}}}$$





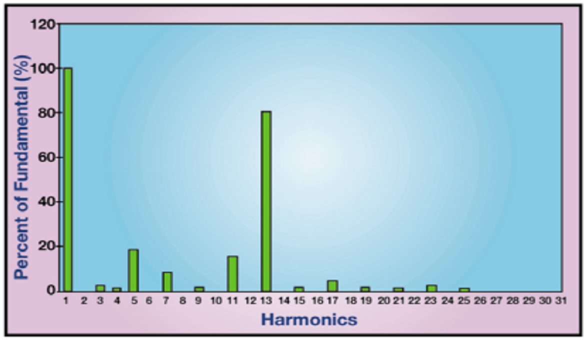


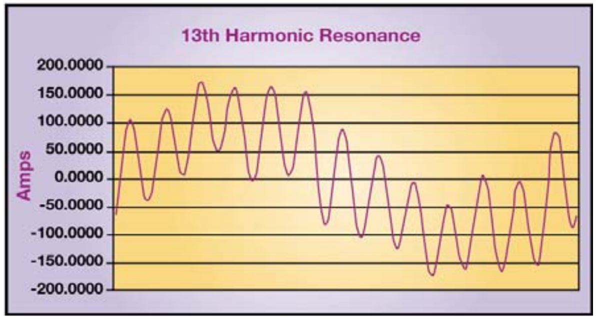
200 HP Drive
Source of Harmonics

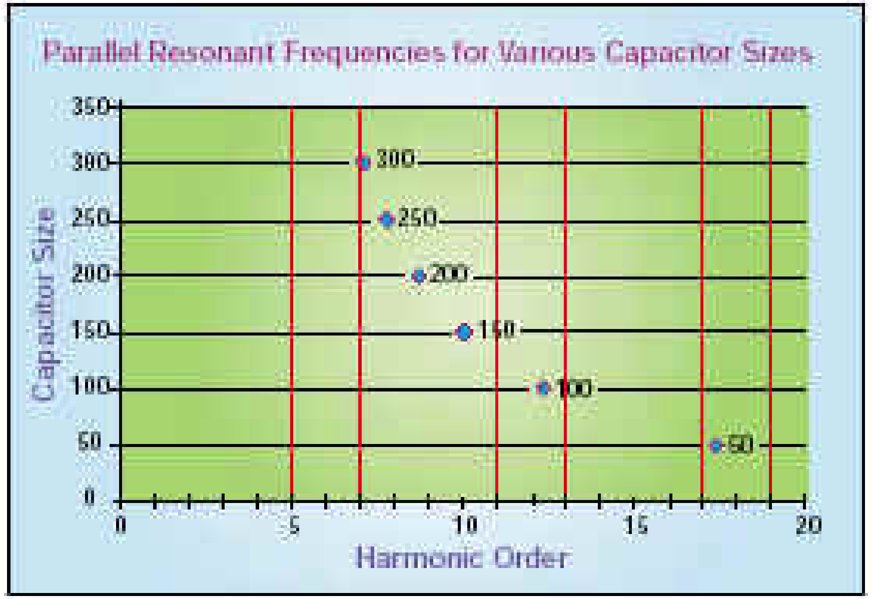
600 kvar
Capacitor

Harmonic Resonance - Solutions

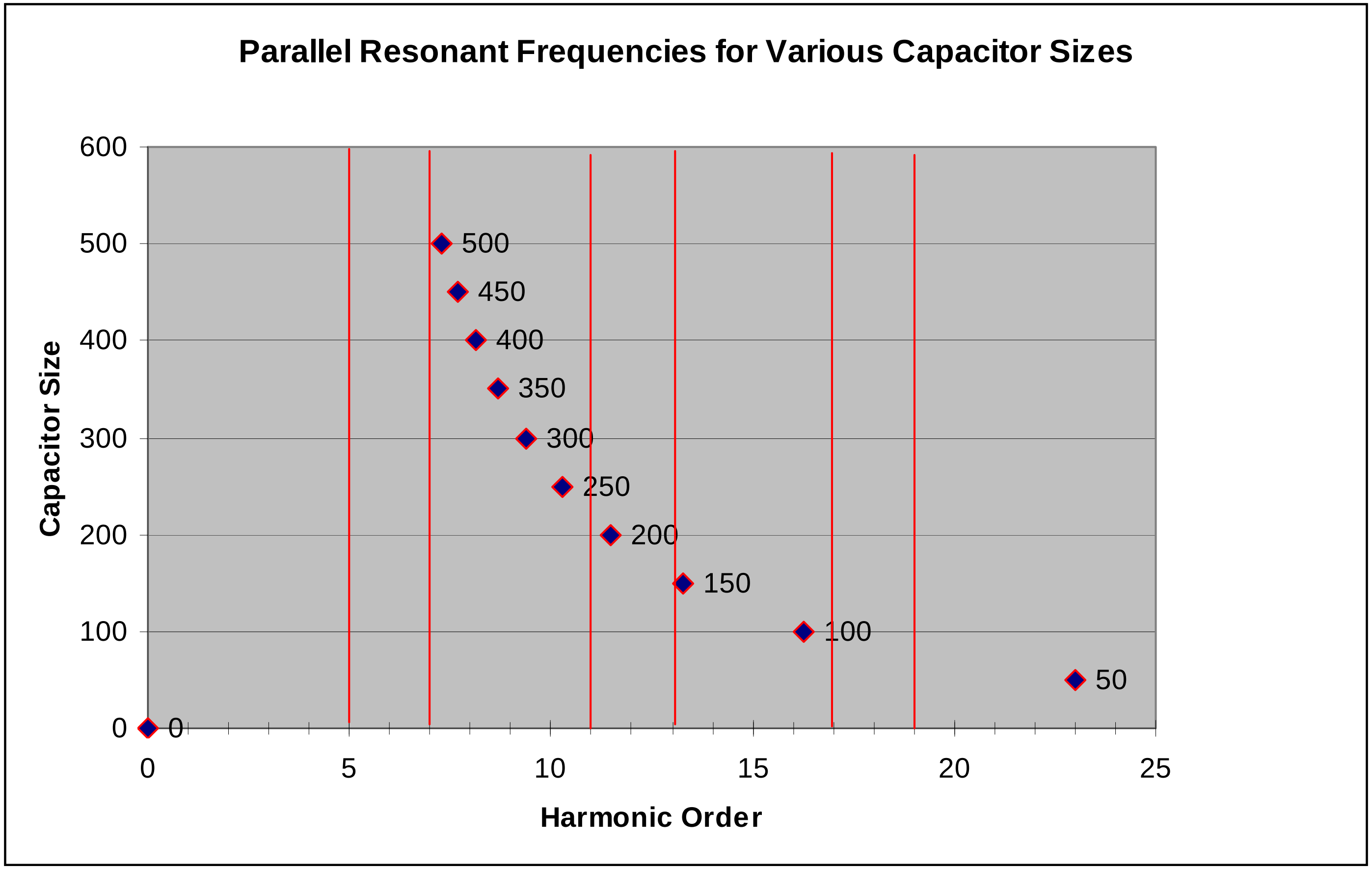
1. **Change the method** of kvar compensation (harmonic filter, active filter, etc.)
2. **Change the size** of the capacitor bank to over-compensate or under-compensate for the required kvar and live with the ramifications (i.e. overvoltage or PF penalty).



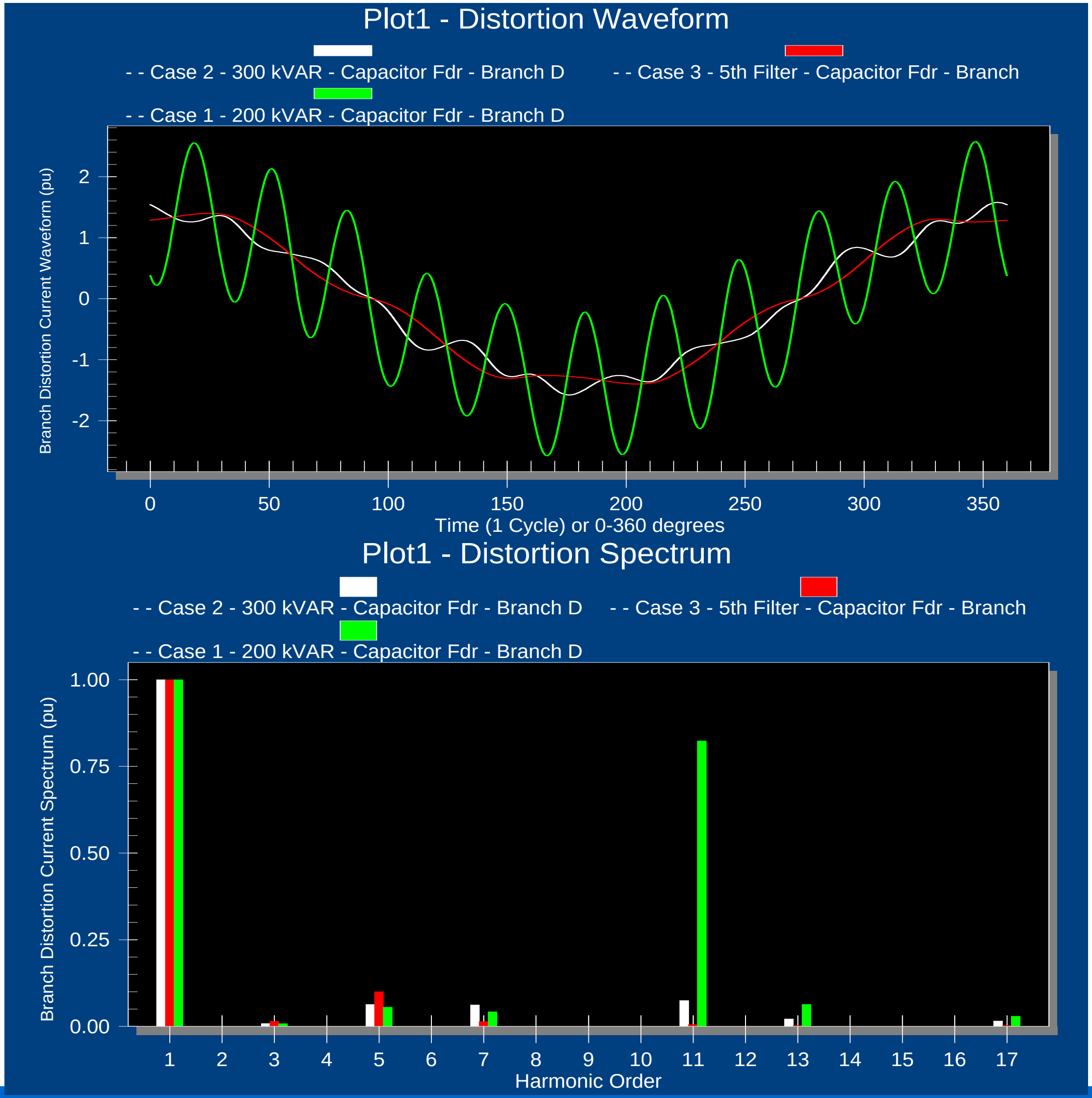




Harmonic Resonance – Switched Capacitor



Harmonic Resonance – SKM Output



Harmonics

- Introduction to Harmonics
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Harmonic Limits
IEEE Std. 519-1992

- Some harmonic sources are internal
  - VFDs, switch mode power supplies, etc.
- Other harmonic sources are external
  - Customers sharing the same line
- Is the voltage distortion caused by you or your neighbor?
  - Establish a baseline (your neighbor's load)
  - Determine the incremental change (your load)

Harmonic Limits
IEEE Std. 519-1992

- Utility is responsible for providing “clean” voltage
- Customer is responsible for not causing excessive current harmonics
- Utility can only be fairly judged if customer is within its current limits
- The Point of Common Coupling (PCC) is the location where the IEEE 519 limits should be applied
- Some customers choose to “voluntarily” select a PCC downstream near the loads

Harmonic Distortion Standards

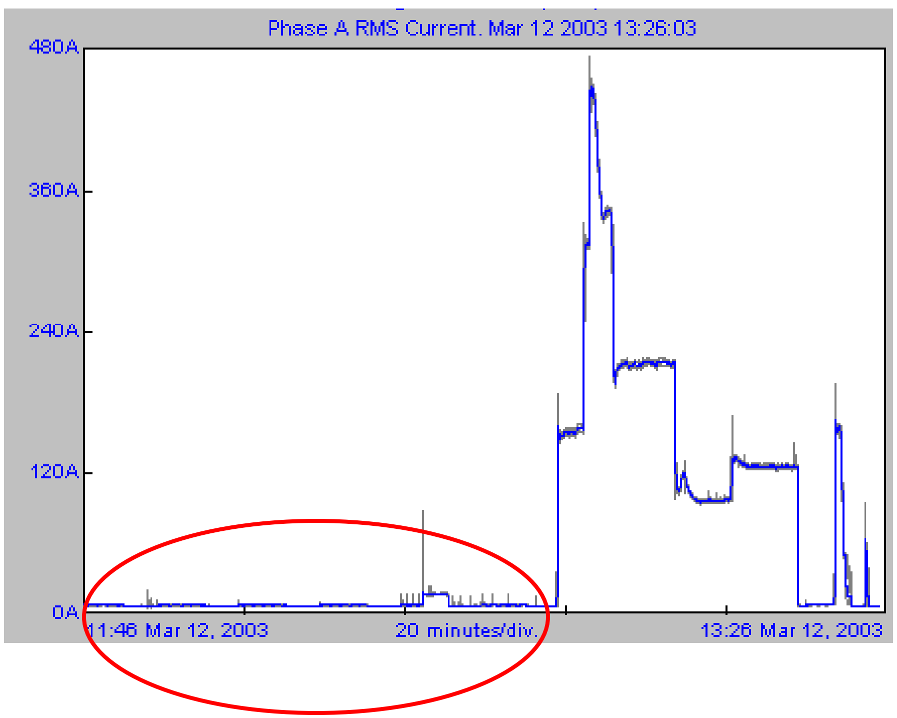
Harmonic Voltage Distortion Limits
IEEE Standard 519 – 1992

Maximum Voltage Distortion in % at PCC*

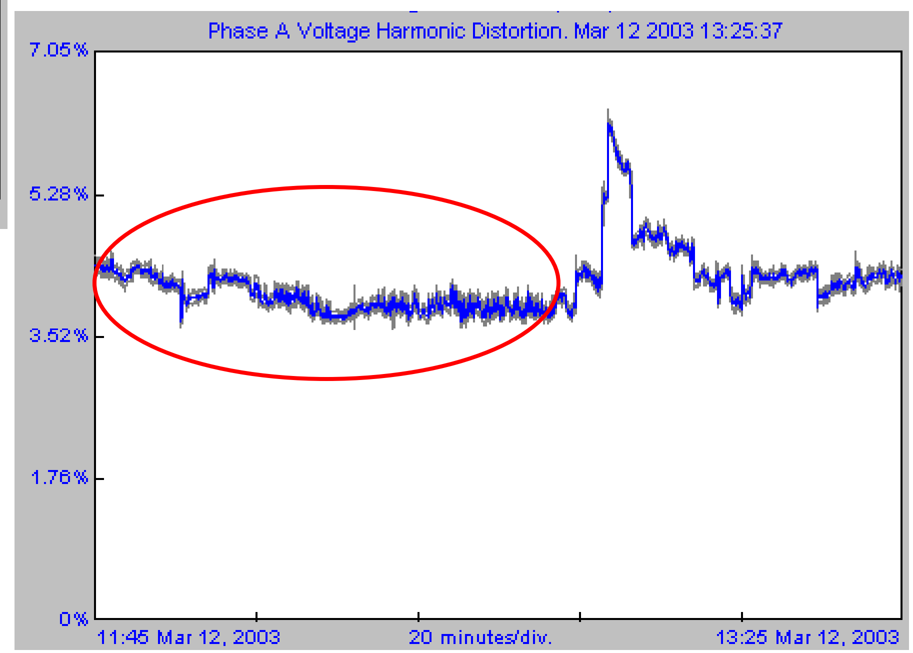
	Below 69kV	69-138kV	138kV
Maximum for Individual Harmonic	3.0	1.5	1.0
Total Harmonic Distortion (THD)	5.0	2.5	1.5

* % of Nominal Fundamental Frequency Voltage

Harmonic Limits - System Issues



Actual measurements at 480 V main breaker - system with large variable-frequency drives



Voltage distortion at no load is 4%!

Harmonic Limits

Current Distortion Limits for General Distribution Systems
(120 V Through 69000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	% 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

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

Where

I_{sc} = maximum short-circuit current at PCC.

I_L = maximum demand load current (fundamental frequency component) at PCC.

TDD = Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 min demand).

PCC = Point of common coupling.

Harmonic Limits

Update for IEEE 519

The Point of Common Coupling (PCC) with the consumer/utility interface is the closest point on the utility side of the customer's service where another utility customer is or could be supplied. The ownership of any apparatus such as a transformer that the utility might provide in the customers system is immaterial to the definition of the PCC.

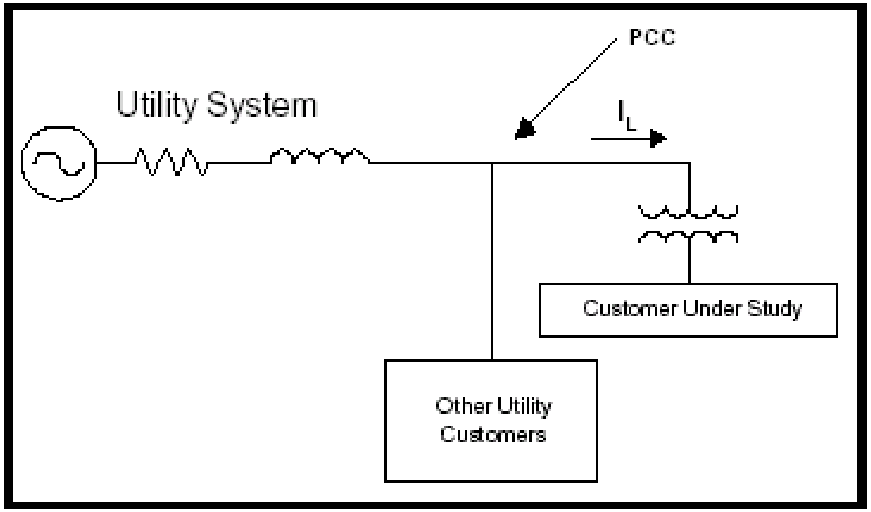
Note: This definition has been approved by the 519 Working Group.

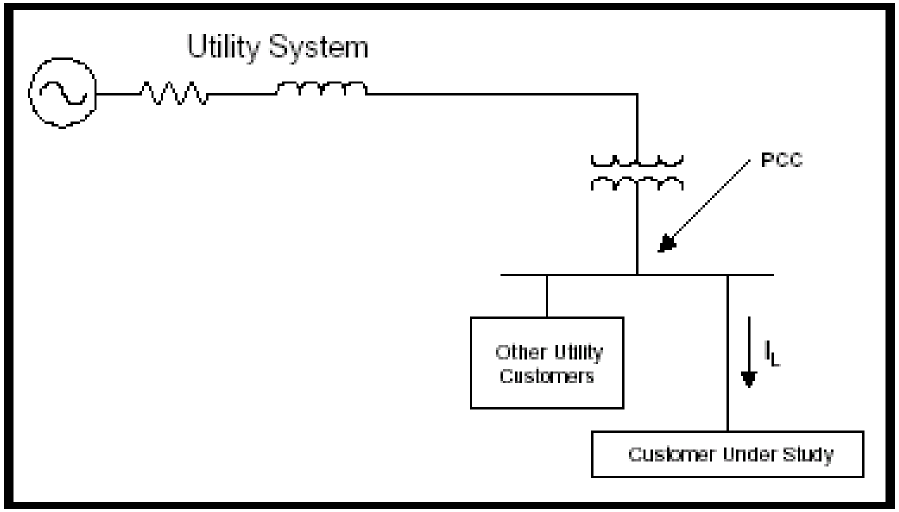
http://home.nas.net/~ludbrook/519error.html

From IEEE519A Draft

Harmonic Limits

•PCC (Point of Common Coupling) is defined as the point where another customer can be served





From IEEE519A Draft

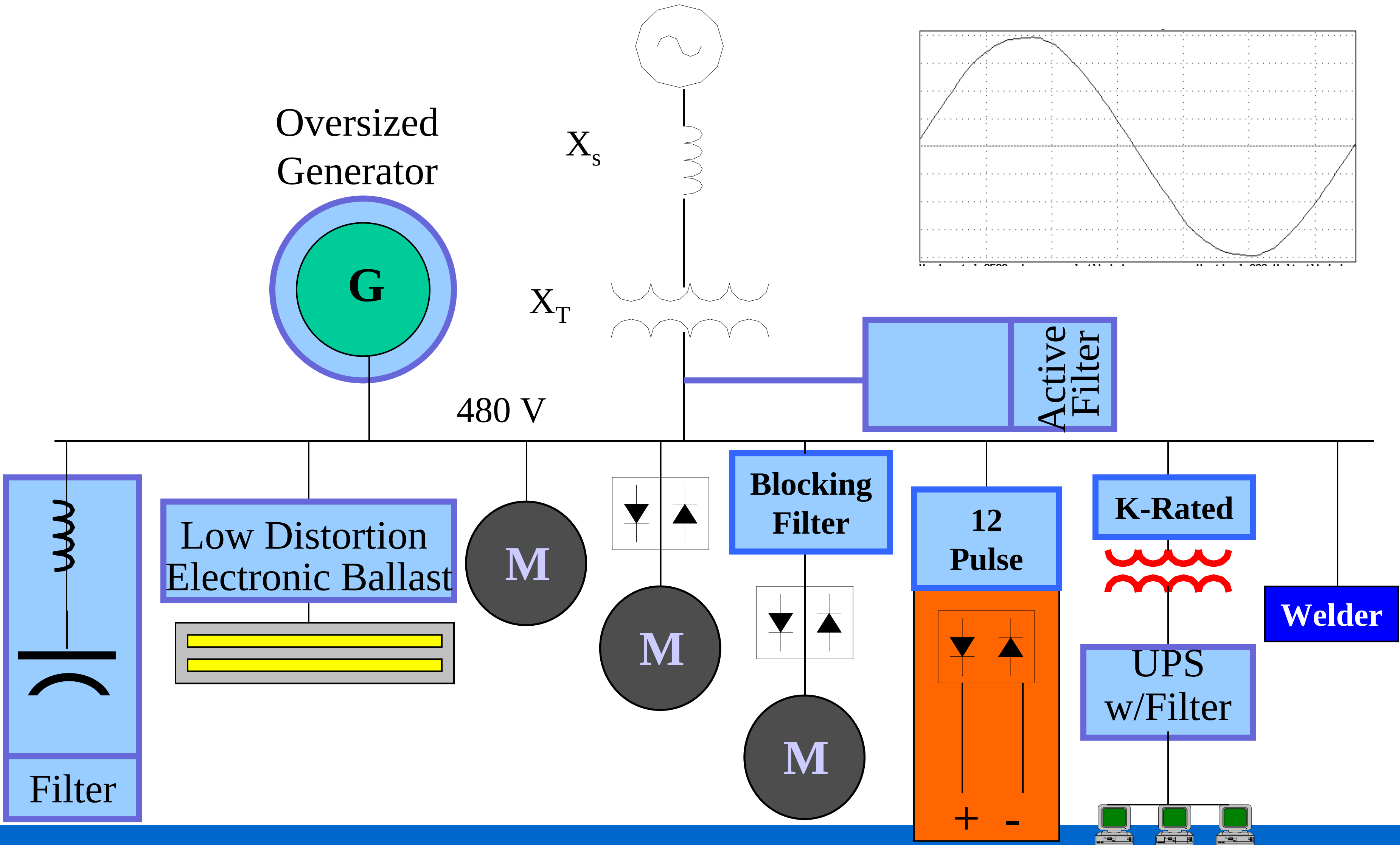
Future of IEEE 519 (2006+)

- More concise document
- PCC clarified
- New voltage range
  - 1.0 kV and below
    - 8% THD_V
    - 5% individual voltage harmonics

Harmonics

- Introduction to Harmonics
- Symptoms
- Characteristic Harmonics from non-linear loads
- Harmonic Resonance
- Understanding IEEE 519-1992
- **Harmonic Solutions**

Harmonic Solutions



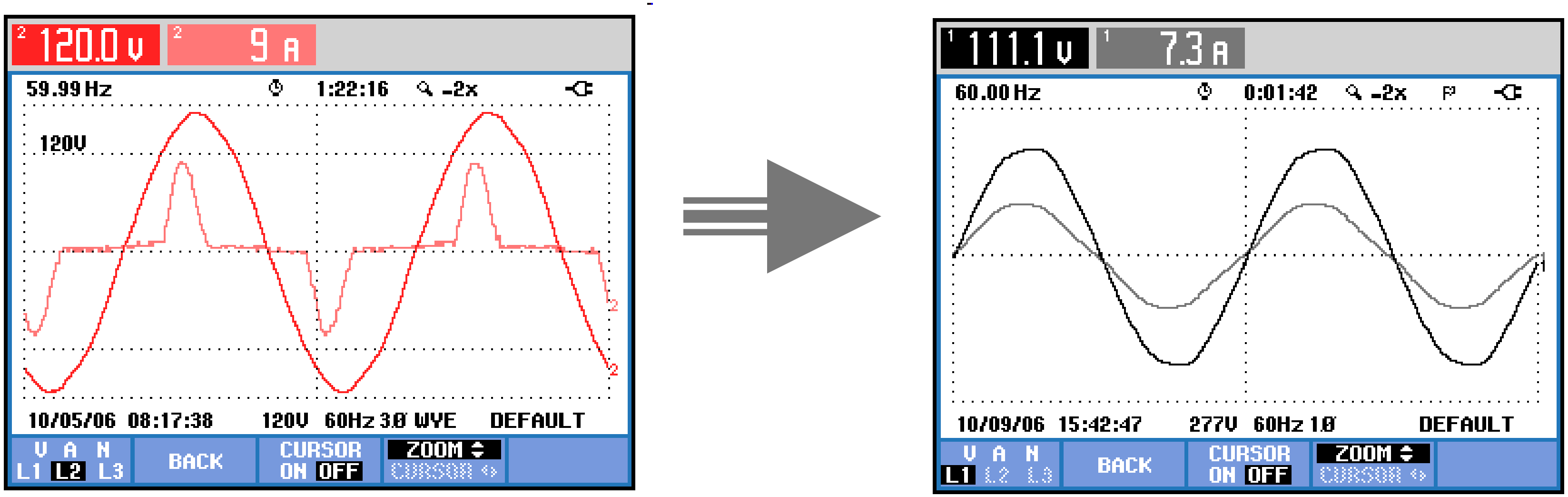
Harmonic Solutions - Commercial

Commercial / Data Center Systems

- UPS Filter
- UPS Active Front End (Rectifier)
- Harmonic Mitigating Transformers
- K-Rated Transformers
- 3rd Harmonic Blocking Filter
- Low Distortion Loads
  - Low Distortion Lighting Ballasts
  - PF Corrected Power Supplies

PF Corrected Power Supplies

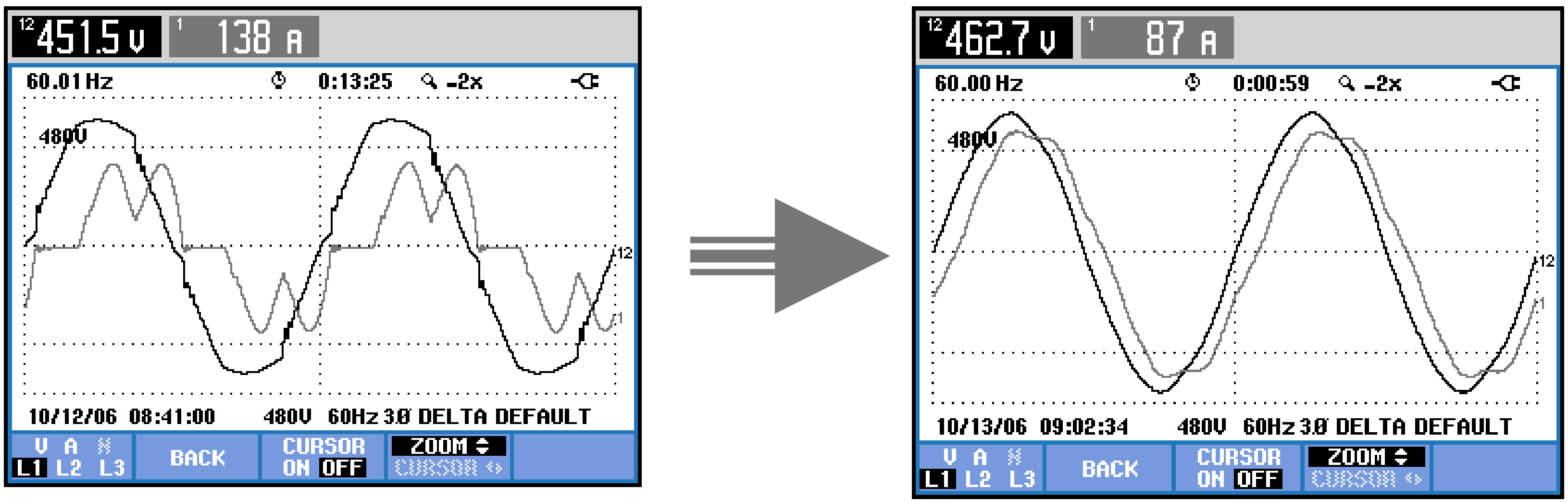
- Data Centers/Servers
  - Switch Mode Power Supplies (SMPS) have changed over to PF Corrected Power Supplies



Industry driven toward component (load) solutions

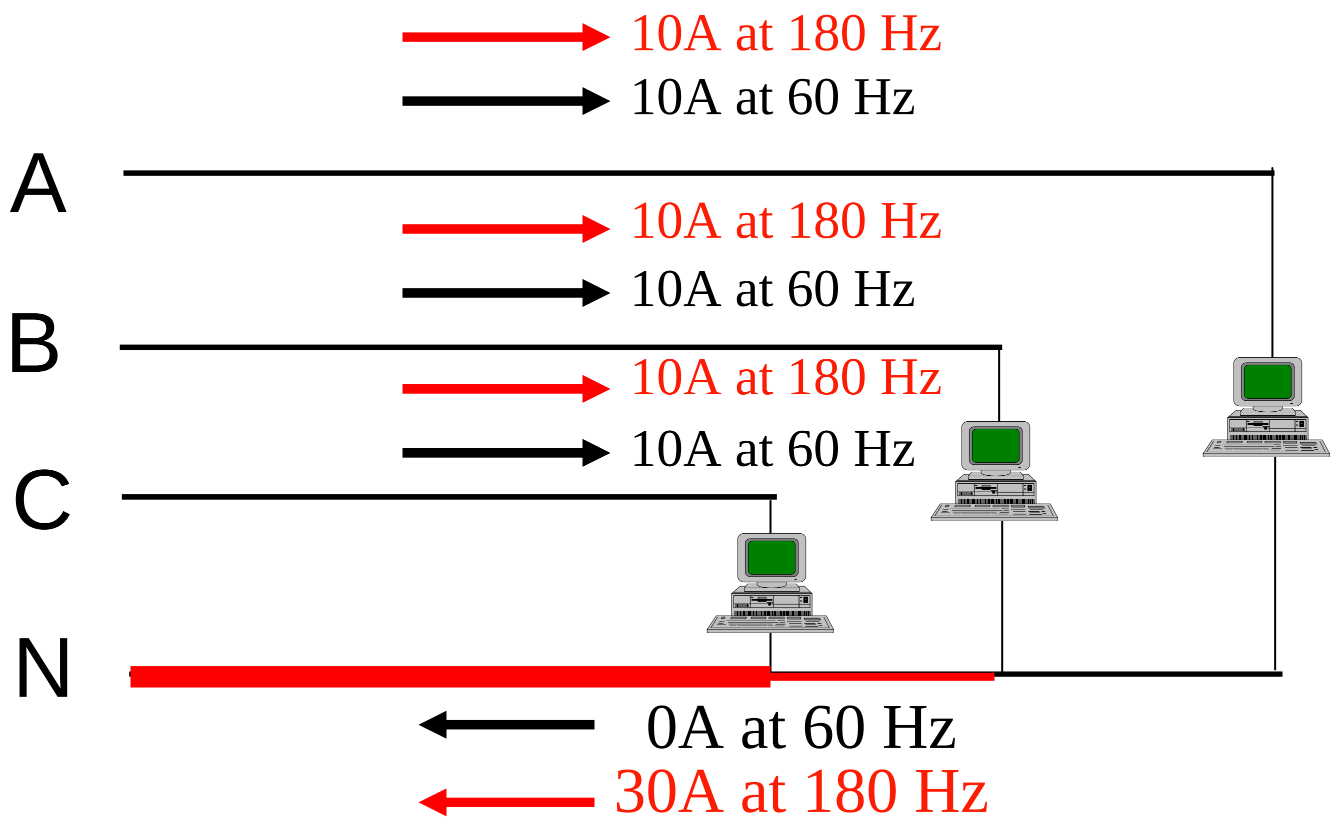
Rectifier Solutions

- Drives, UPS, Battery Chargers
  - Active front end on UPS and some drives



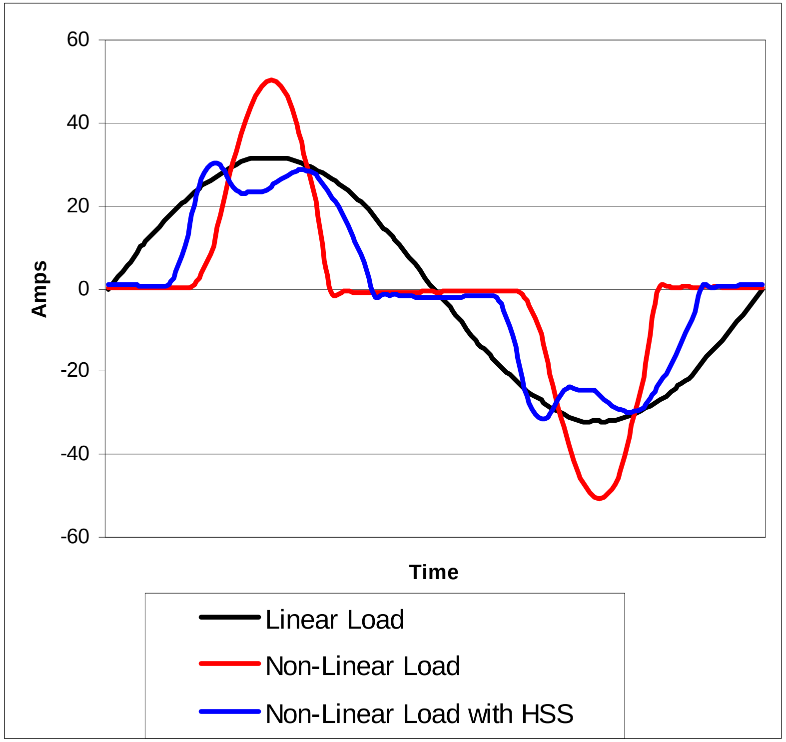
Industry driven toward component (load) solutions

Neutral Heating – Oversize Equipment

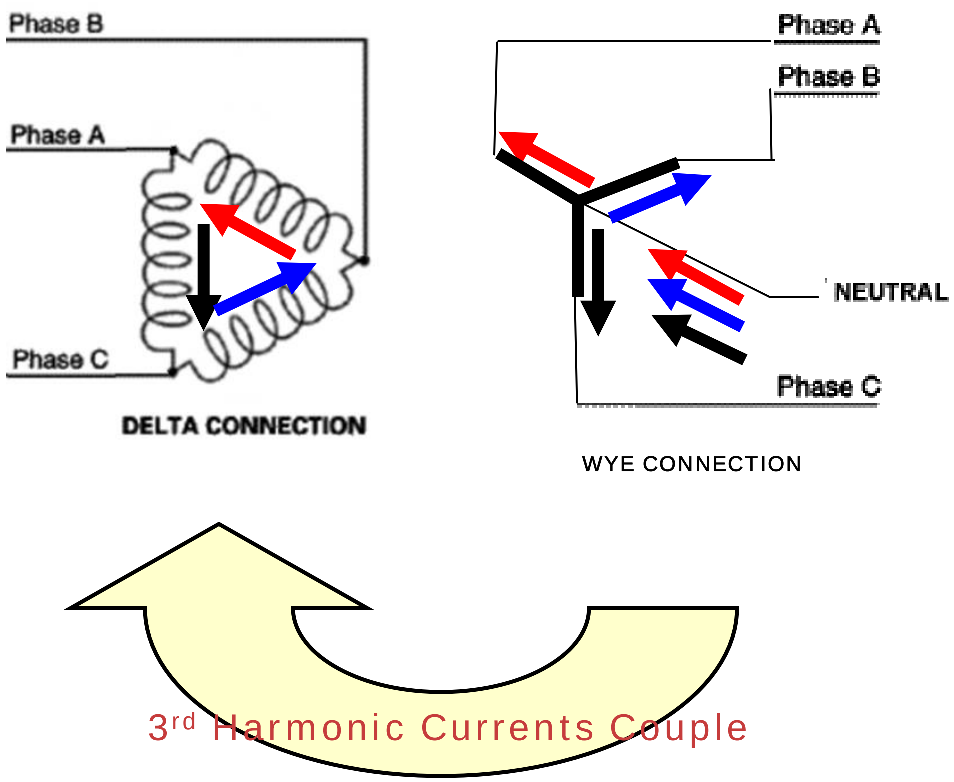


3rd Harmonic Blocking Filter

- *Application of 3rd Harmonic Blocking Filter addresses the most dominant harmonic in the distribution system.*
- *Makes the current waveshape significantly more linear*
- *K-rating the transformer is no longer necessary.*
- *Most appropriate for retrofit*

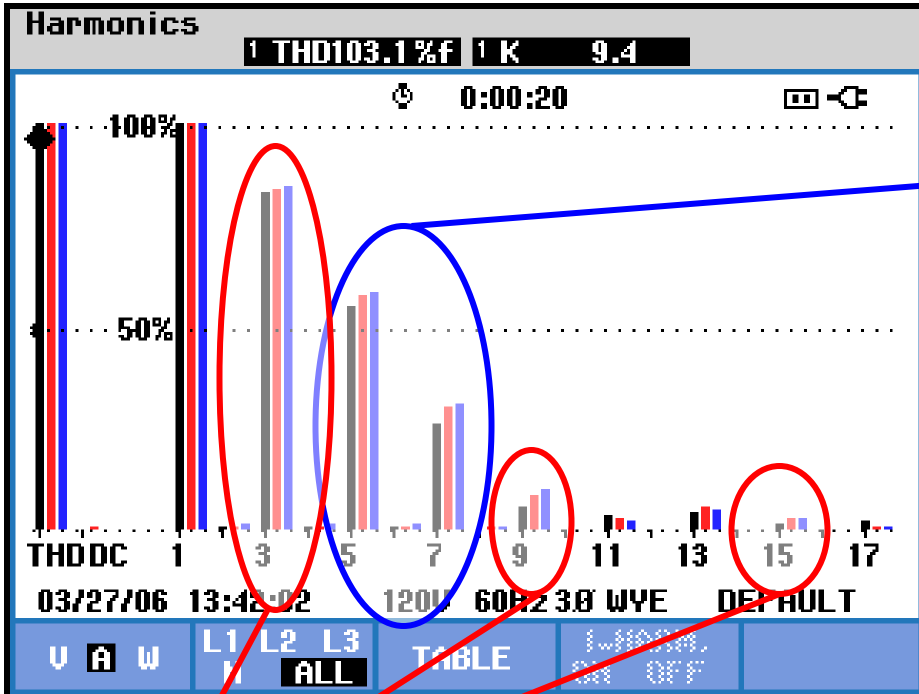


3rd Harmonics and Delta/Wye Transformers



- Third harmonic current flowing in the phases adds up in the neutral.
- On the primary, the third harmonic current is trapped in the delta if it is balanced. Otherwise, the difference flows in the phases.
- Balanced third harmonic currents are called "triplen" harmonic currents (3^{rd}, 9^{th}, etc.).
- Delta-wye transformers are said to "trap" triplen harmonic current in the delta. They do not eliminate other harmonics.

Transformers and Harmonics (HMT's)



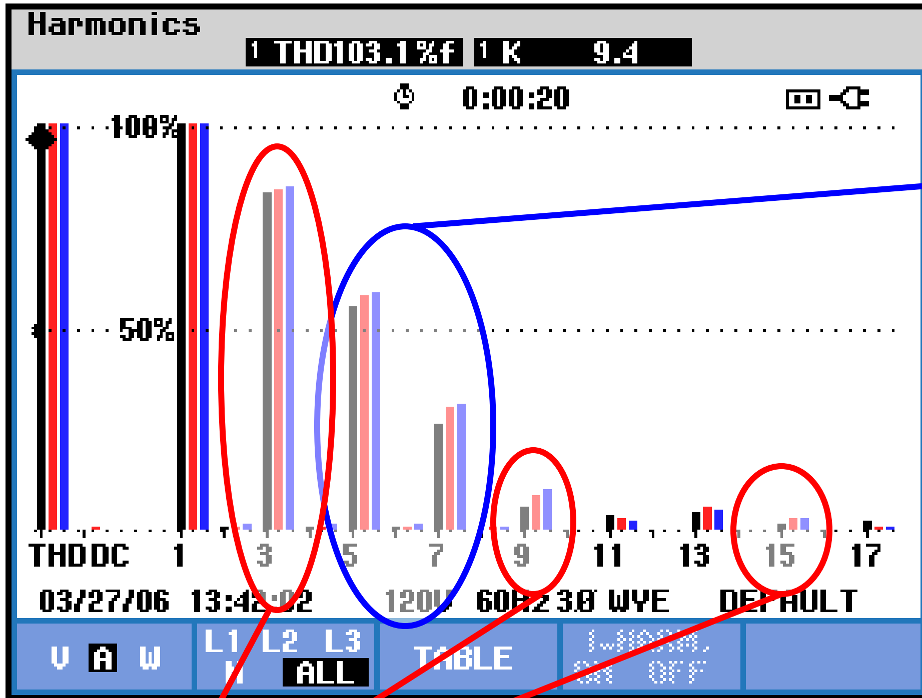
5th & 7th harmonics

Use ***Phase-Shifting*** to treat these

Use ***different secondary*** winding to treat these

Triplen Harmonics

Transformers and Harmonics (HMT's)



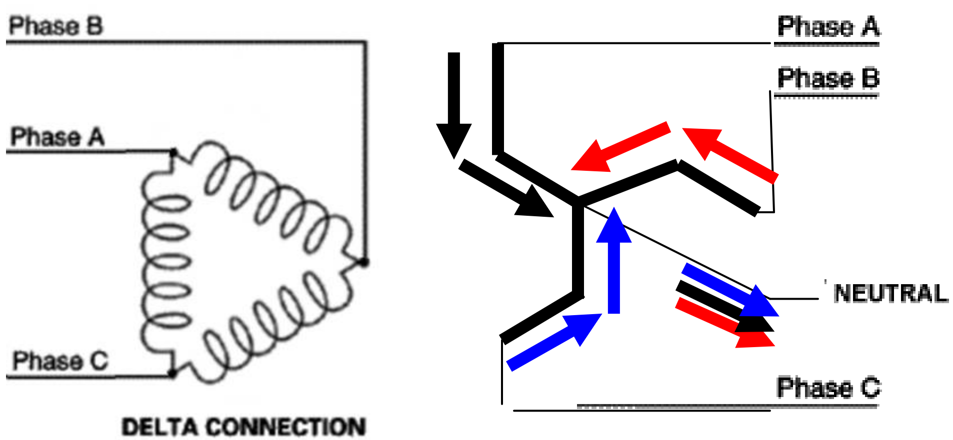
5th & 7th harmonics

Use ***Phase-Shifting*** to treat these

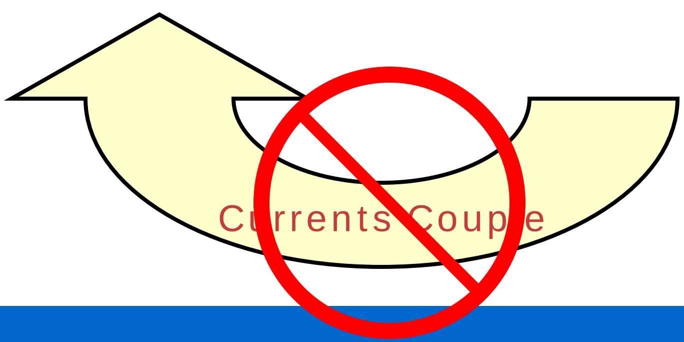
Use ***different secondary*** winding to treat these

Triplen Harmonics

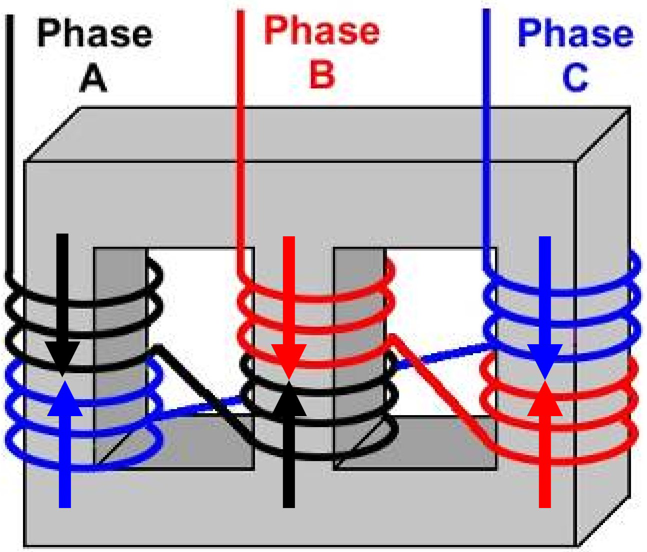
Secondary Treatment of Triplens (HMT's)



ZIG-ZAG CONNECTION

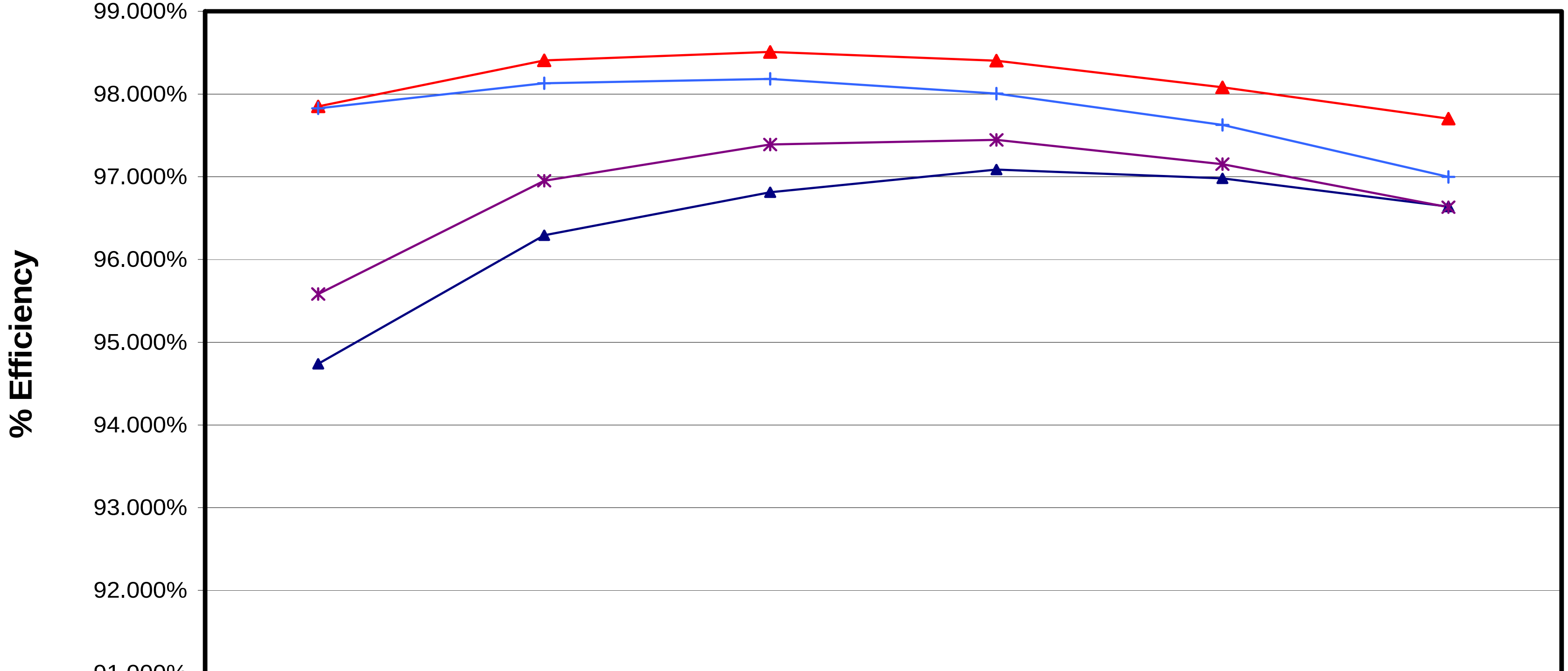


HMT Secondary



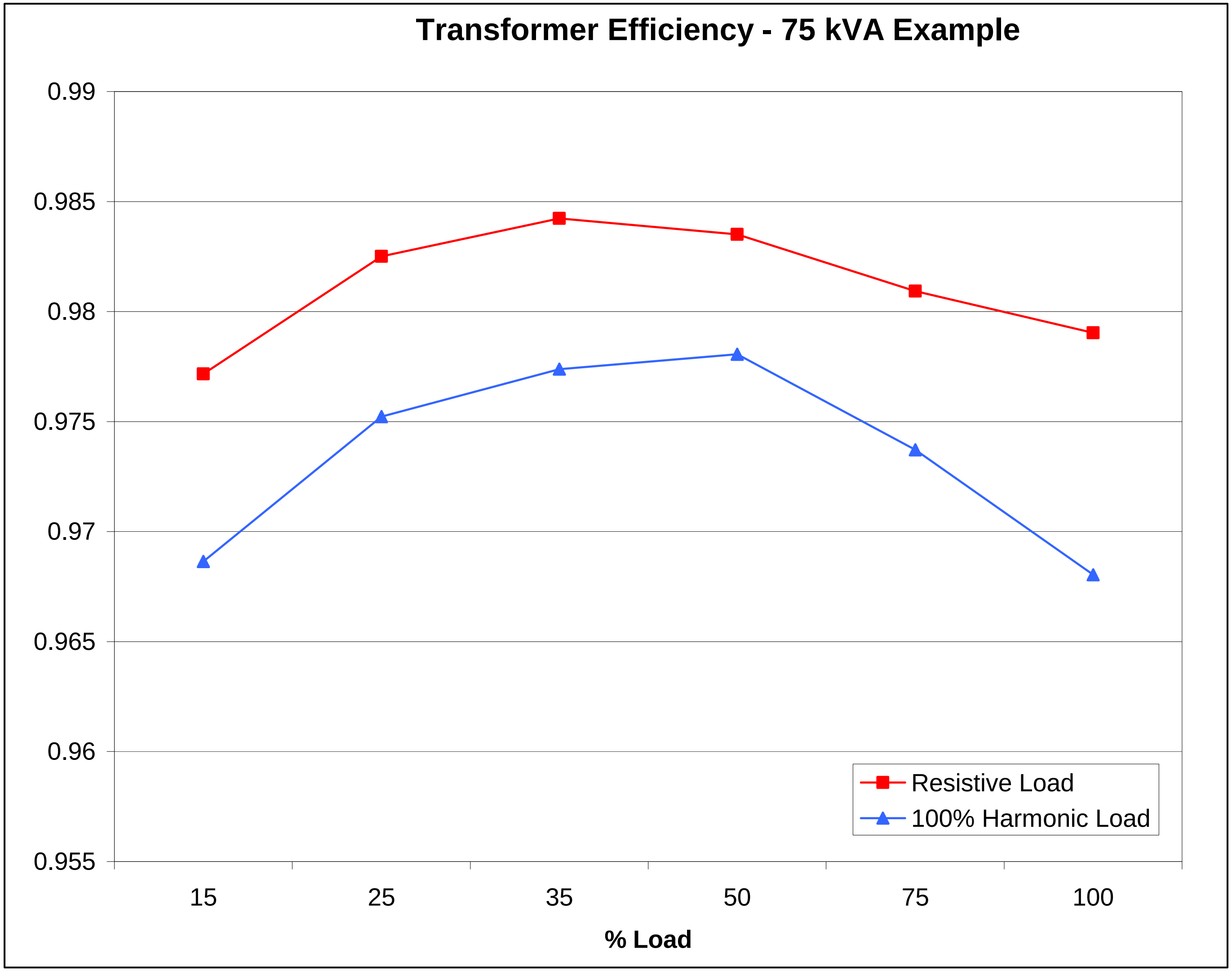
- Opposing magnetic fields – triplens aren't magnetically coupled to primary
- Loads continue to operate as designed
- Minimizing impact on electrical infrastructure

Affect of Harmonic Load on Efficiency



	15	25	35	50	75	100
K-13	94.74%	96.29%	96.81%	97.09%	96.98%	96.64%
HMT	97.85%	98.41%	98.51%	98.40%	98.08%	97.70%
Standard	95.58%	96.95%	97.39%	97.45%	97.15%	96.63%
TP-1	97.83%	98.13%	98.18%	98.01%	97.63%	97.00%

Affect of Harmonic Load vs. Resistive Load



Transformer Technology 'Rule of Thumb' Comparison Chart

Transformer Type	Approx. Cost	Energy Usage	Power Quality Attributes
Standard Delta-Wye TP-1, Copper, 115C	1X	say 100W	None
K-Factor K13 Copper, 115C	1.5X - 2X	130W 30% more	Designed to Withstand Heating Effects
HMT TP-1, Copper, 115C	1.5X - 4X	40W 250% ***less***	Corrects Root Cause

- YES, The INITIAL cost of an HMT is greater than the other transformers, however the Energy Savings you receive over the life of the HMT (20-30 years) pays back that difference multiple times!
- Same mentality as using a Compact Fluorescent vs. Incandescent Lamp

Harmonic Solutions – Industrial

Industrial System (Drives and Rectifiers)

- Line Reactors
- Drive Isolation/Harmonic Mitigating Transformers
- Tuned Filters – LV/MV – Fixed/Switched
- De-Tuned Filters
- Static Switched (Transient Free) Filters
- Harmonically Hardened Capacitors
- Active Filters
- Clean Power (18 Pulse) Drives
- Broadband Drive Filters
- Active Rectifier Drives

MCC Solutions for Harmonics

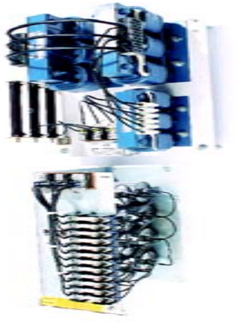
18 Pulse Drives

5%*

Clean Control Center with Active Harmonic Correction

5-20%

Drive with Passive Filter



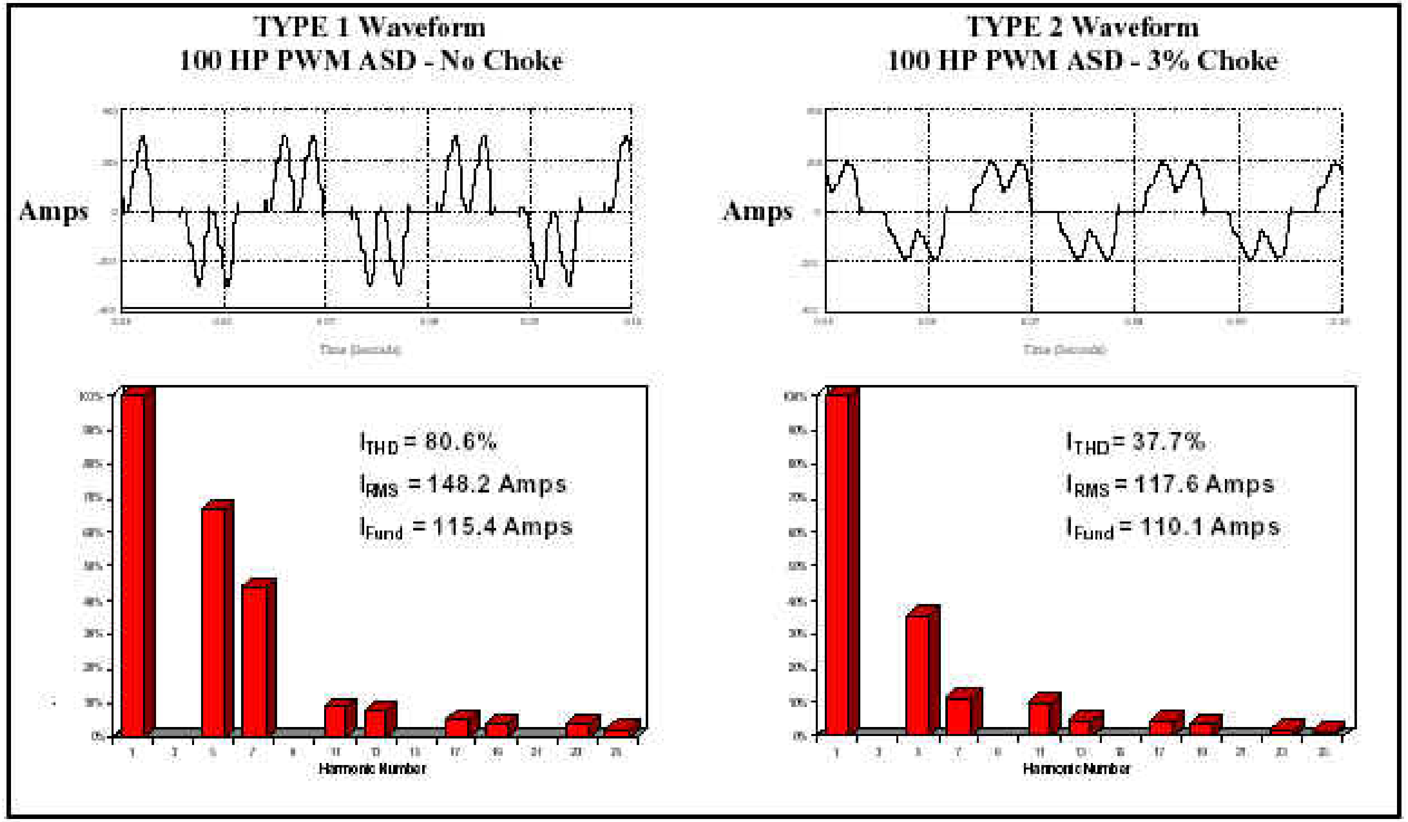
8-15%

Drive with 3% Input Reactor

43%*

Harmonic Distortion

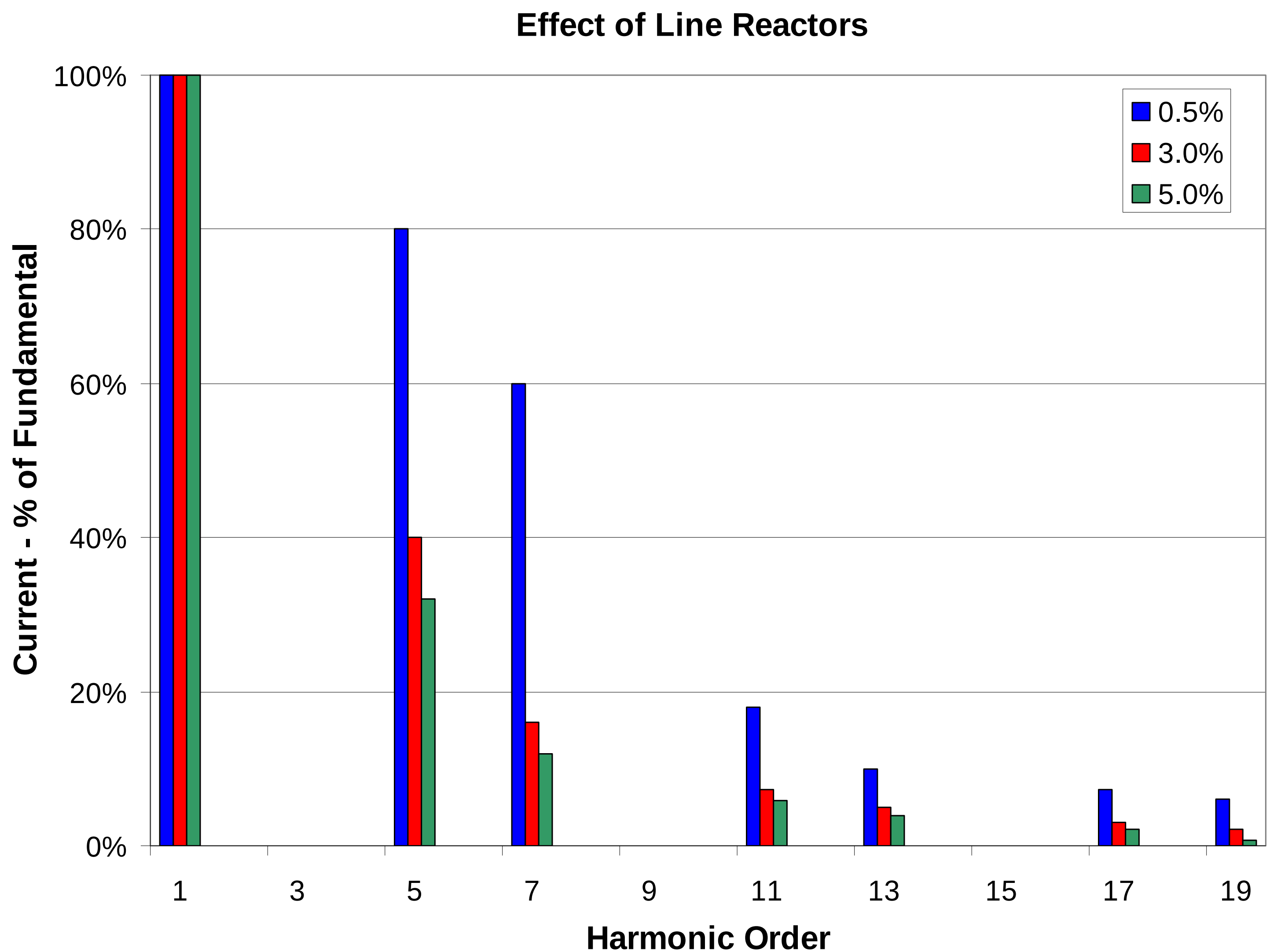
Drive and Rectifier Solutions



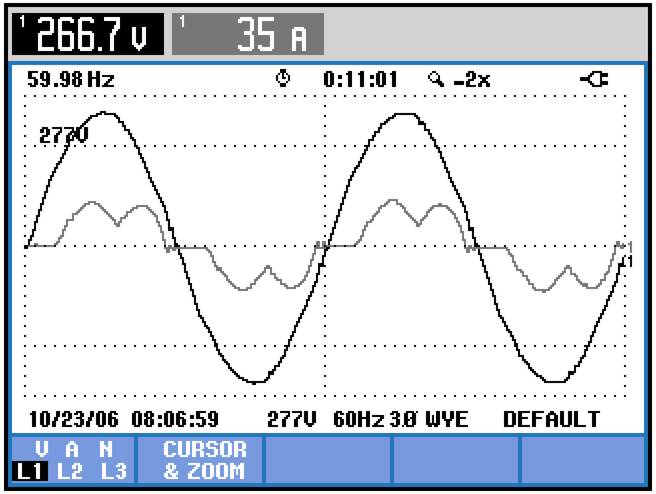
Drive without line reactor

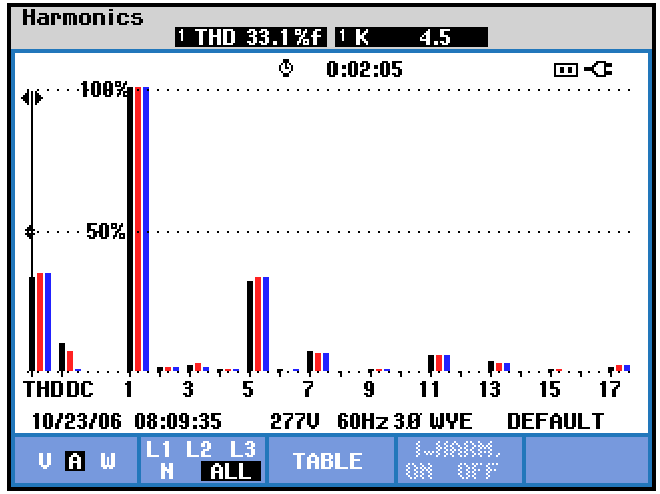
Drive with line reactor

Effect of Drive Line Reactors



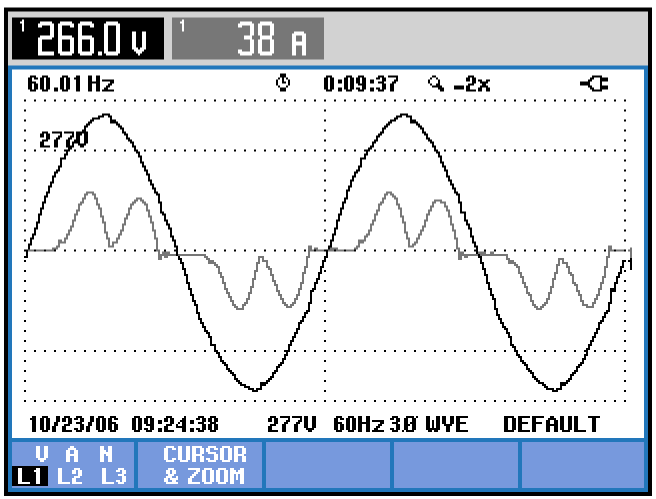
Reactor/Isolation Transformer

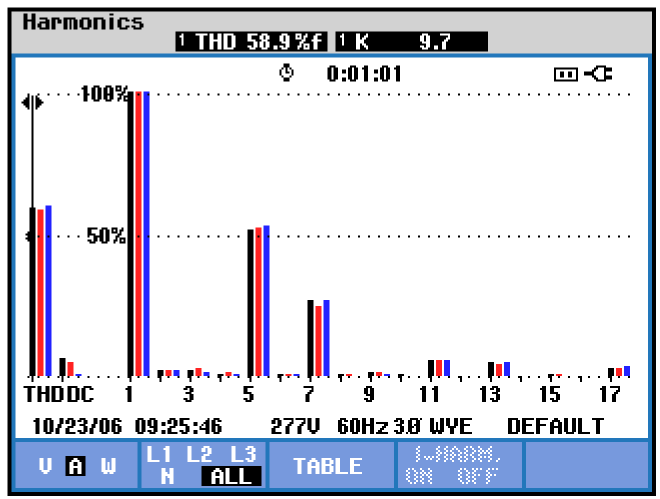




w/ isola trans

Order	Magnitude	Angle
1	33.41	-16
3	0.90	-186
5	9.92	101
7	2.00	-182
11	1.87	-154
13	1.10	-127
17	0.67	-70
19	0.67	-50



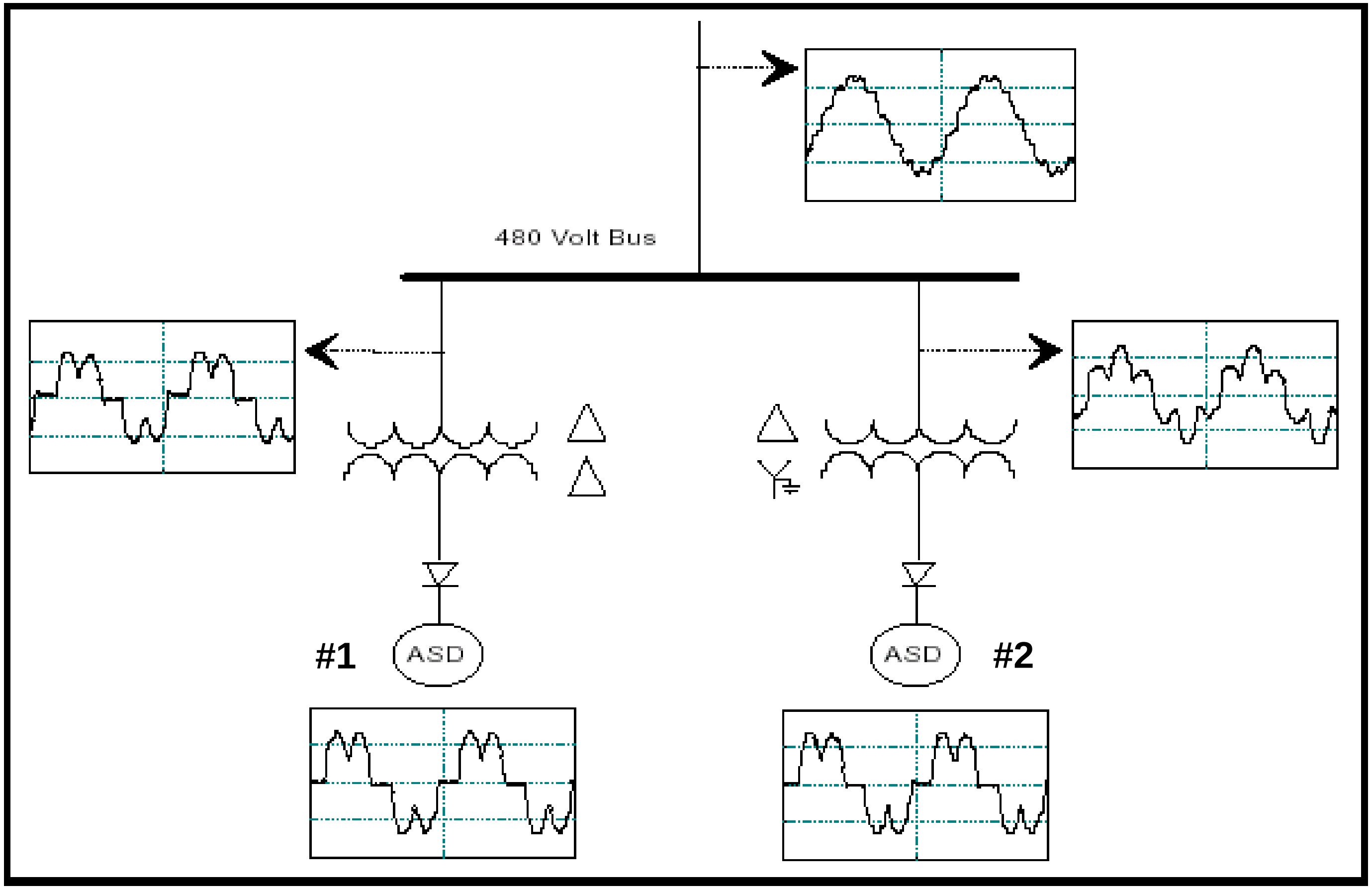


w/o isola trans

Order	Magnitude	Angle
1	33.41	-14
3	0.60	-160
5	15.97	114
7	7.48	-110
11	1.77	-89
13	1.40	-1
17	0.87	60
19	0.57	122

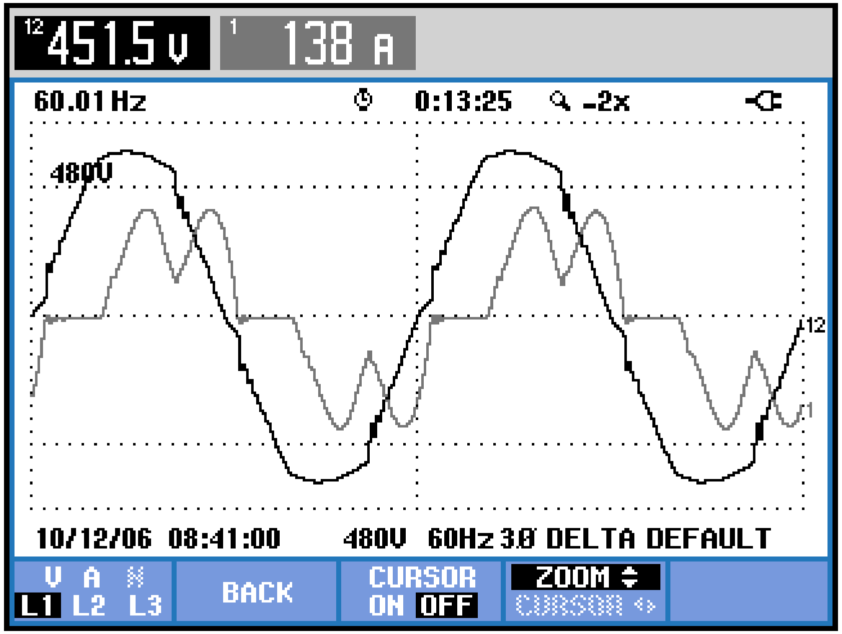
Phase Shifting/Cancellation

12 Pulse, 18 Pulse or 24 Pulse Cancellation by Design

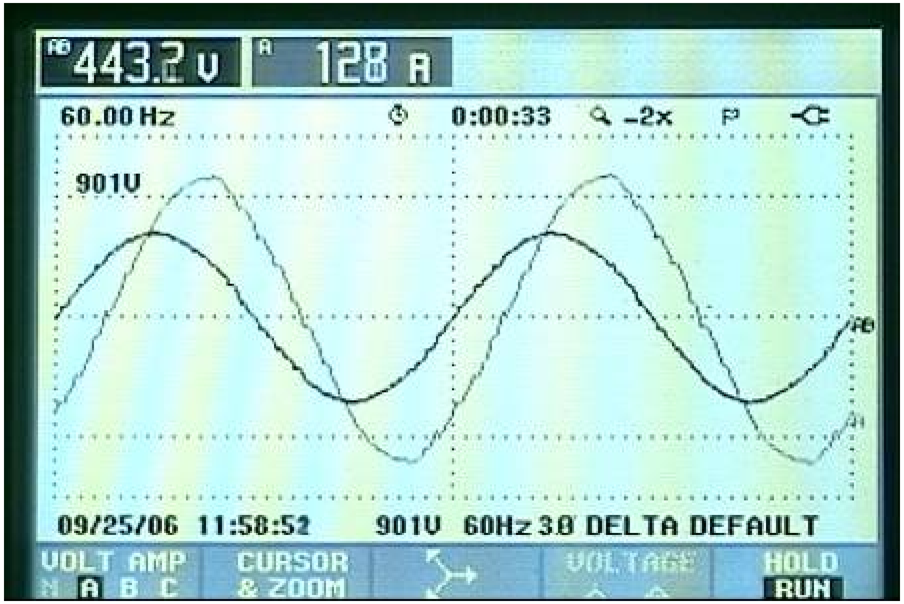


Phase Shifting/Cancellation

Without Cancellation

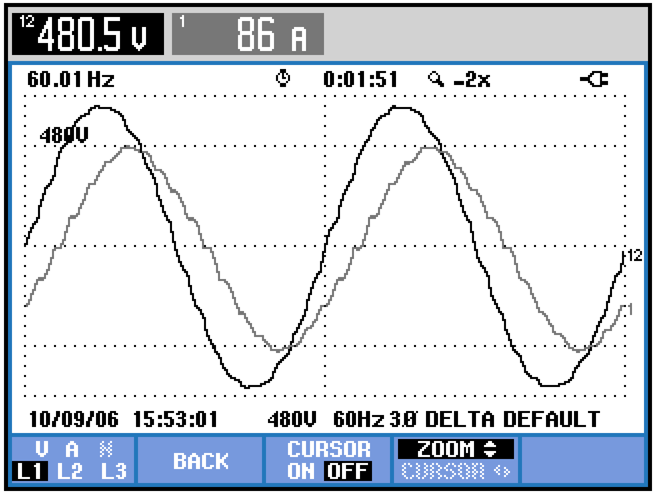


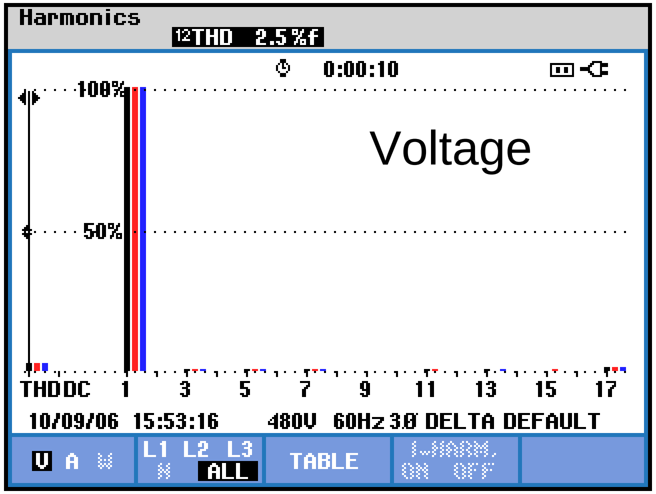
With Cancellation

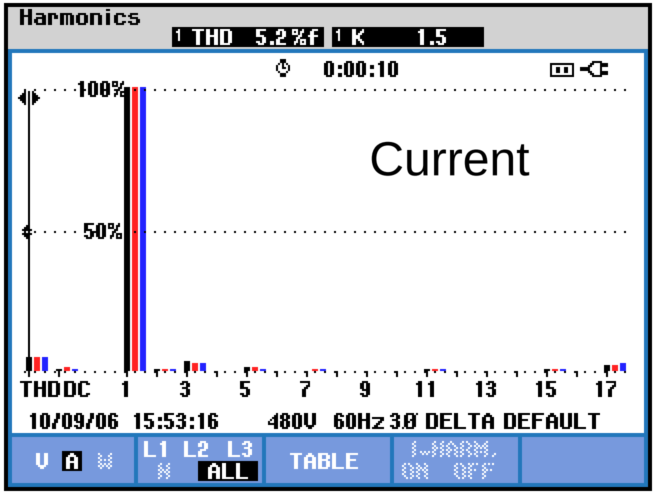


18 Pulse Rectifier

18 Pulse Design

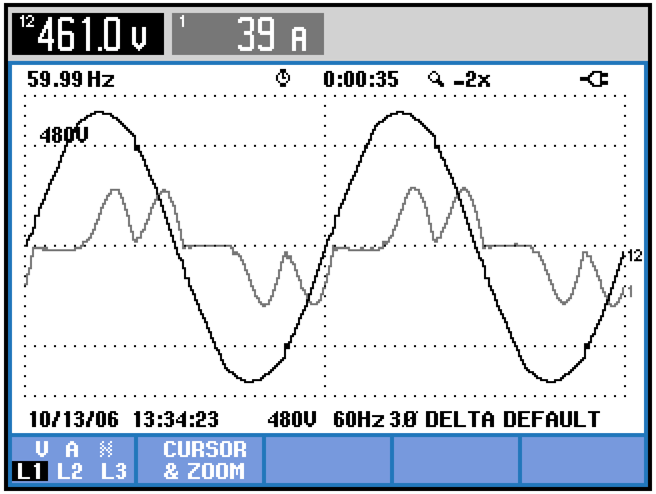


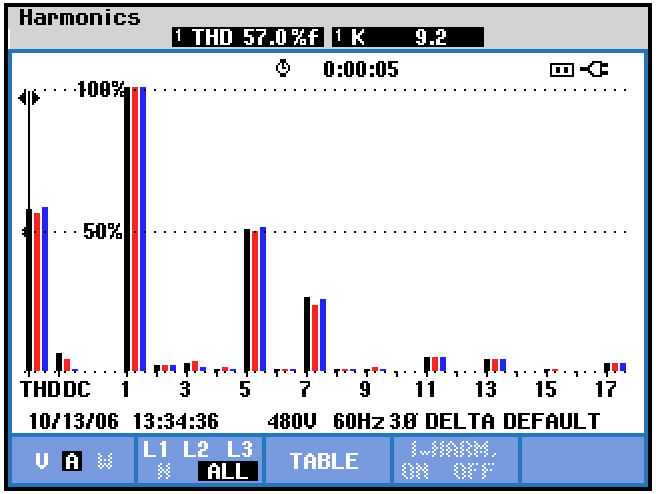




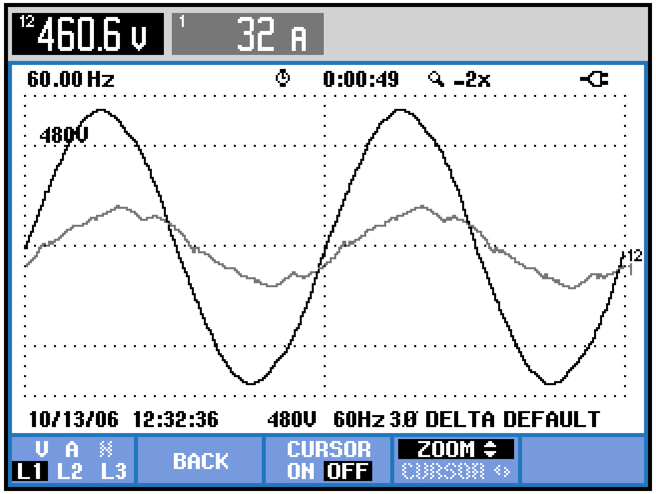
Drive/UPS Dedicated Filter

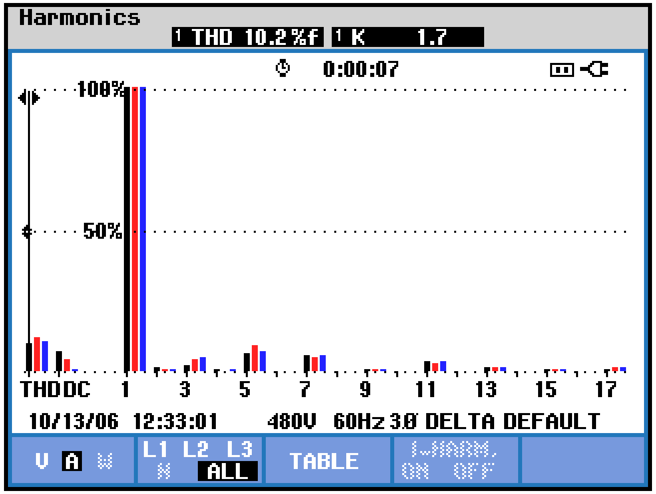
Standard Drive





Drive with Dedicated Filter



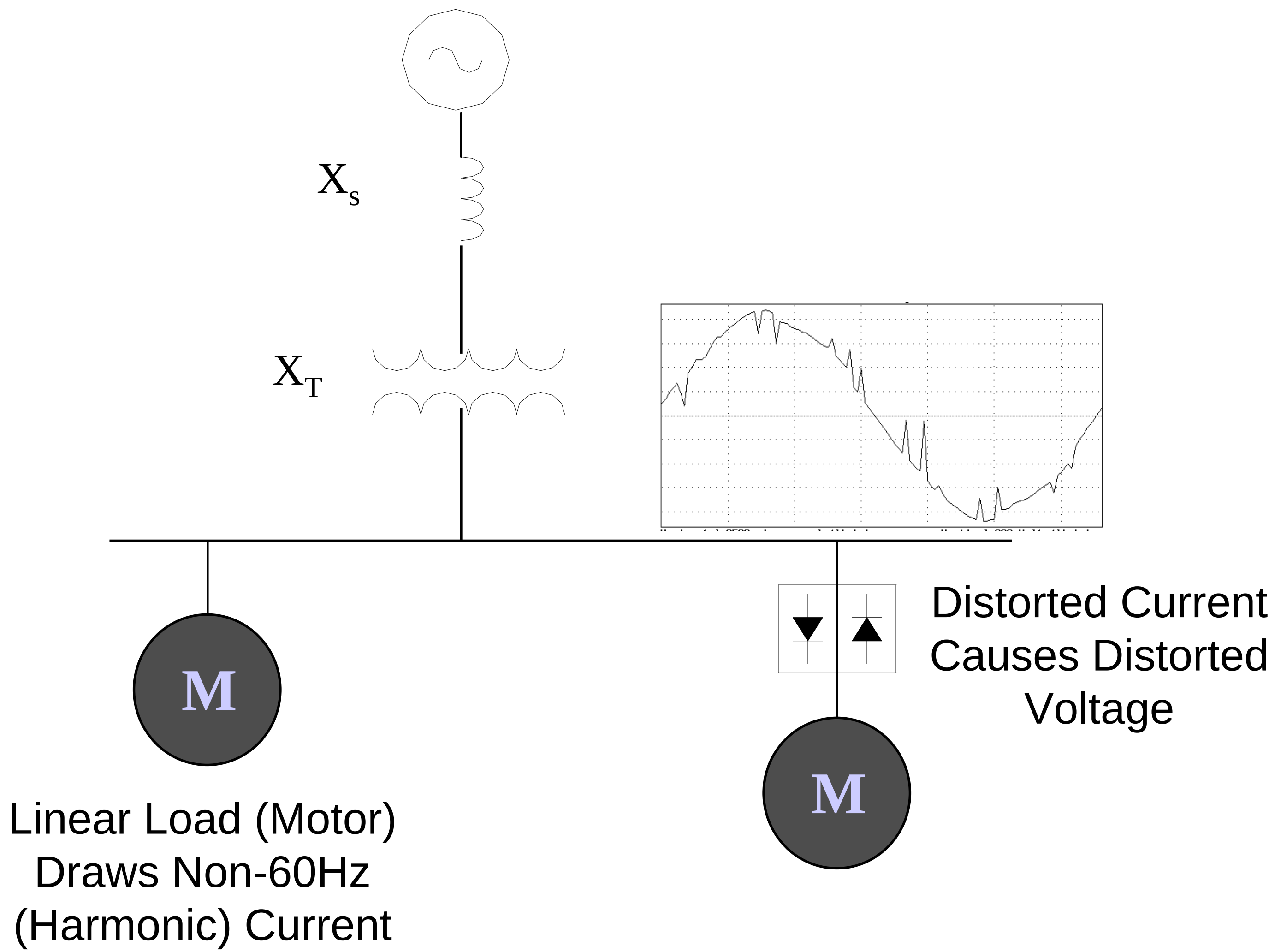


Video Demonstrations

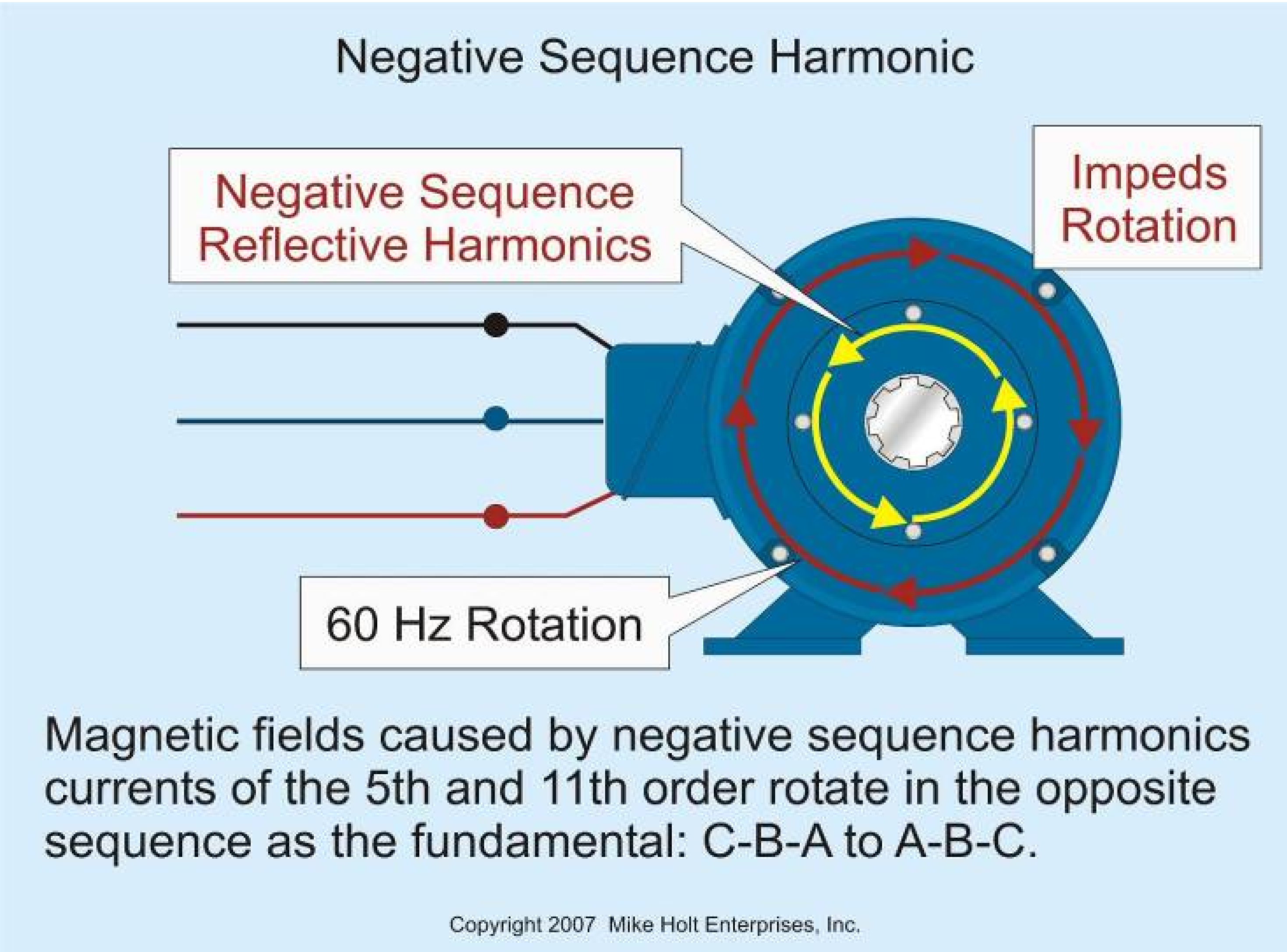
http://www1.eatonelectrical.com/pqlab/pqvideos

- 4 drives without phase shifting
- 4 drives with phase shifting (24 pulse system)
- Active Fitler
- 18 pulse (clean power) drive
- Tacoma Narrows Bridge

Harmonics and Motor Heating

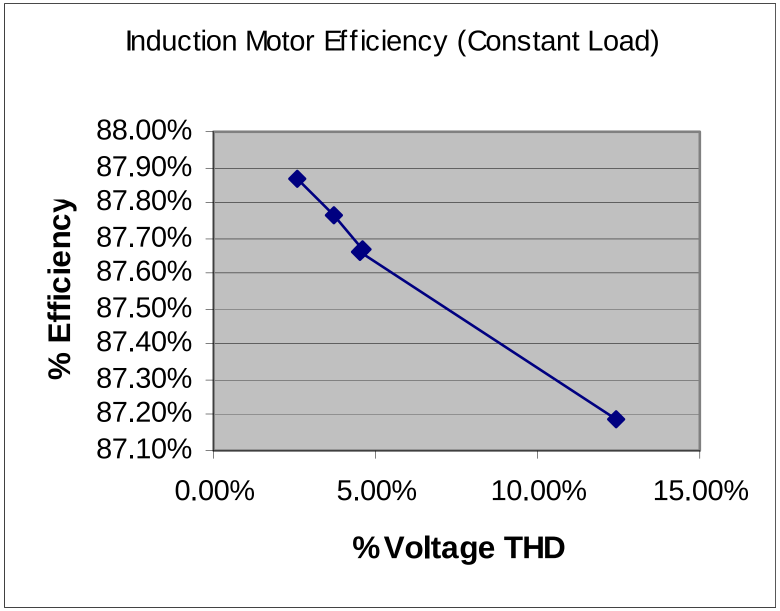


Motor Heating and Vibrations



- Motor Heating
- Vibrations
- System Losses

V_{THD} and Motors – Results



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^{O}C increase decreases component life by 50%"
- More Testing Required

Cost of Harmonic Correction

Description	Cost $/kVA	Cost p.u.
Reactor	3	1
Capacitors (LV)	12	4
Filter (MV)	12	4
Filter (MV) Switched	15	5
K-Rated Transformer	20	7
Capacitors (LV) Switched	25	8
Filter (LV)	35	12
Filter (LV) Switched	45	15
Harmonic Mitigating Transformer	50	17
Blocking Filter (3rd's)	100	33
Broadband Filter (Drives)	100	33
Active Filter	150	50
Per unit costs compared to reactor pricing		
Note that prices are generalized for comparison only		
Some equipment must be fully rated for loads - others can be partially rated		
Capacitors are shown for reference only		

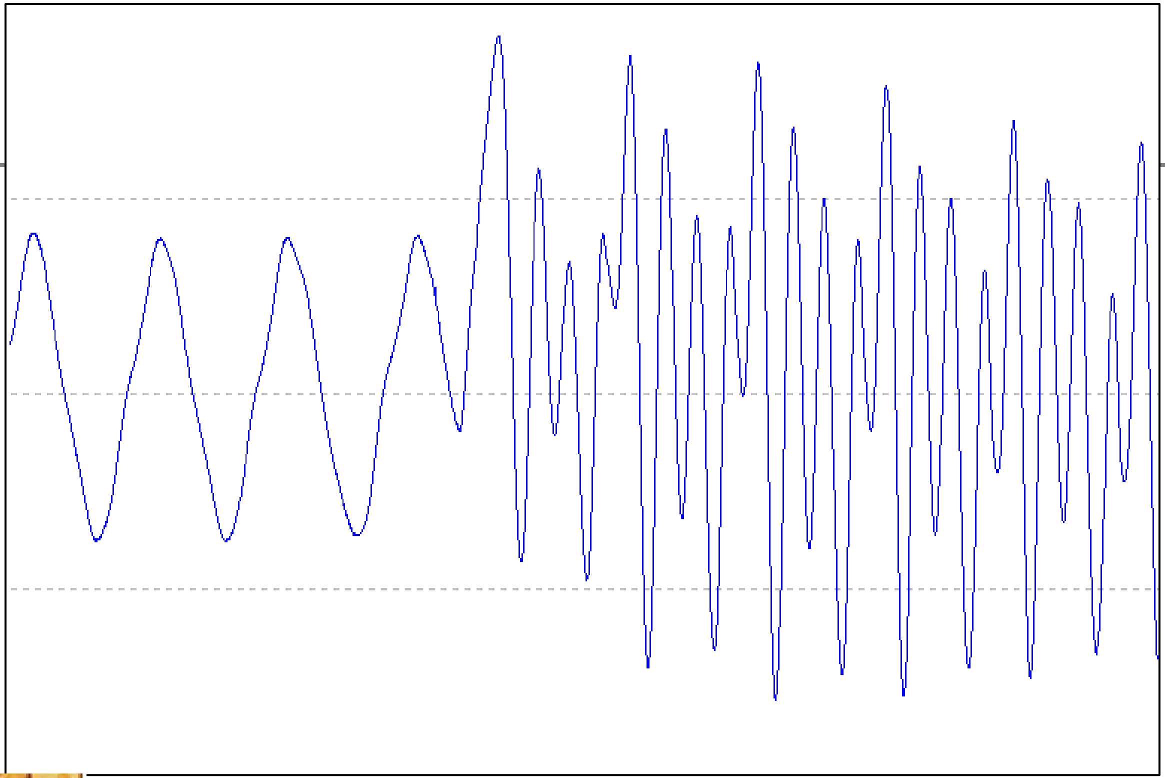
Harmonics and Energy Efficiency

- EPRI Presentation – “You can only save energy that is wasted”
  – Infrastructure (system) losses are generally 1-4%
    - Saving 25% of your “losses” is not equal to saving 25% of your energy bill (ex: 25% X 2% = 0.5% of your bill)
  – UPS losses may be 2-10% or more
  – PQ solutions are often sold as ”energy-saving”

Reducing Harmonics – Saving Money

How can reducing harmonics save you money?

- Physical damage from overheating and misoperation
- Energy savings
- HVAC savings
- Oversizing equipment / Release Capacity
- Motor failure or overheating
- Low PF



Thank You!

Questions?