Harmonics
Advanced Application Training

Eaton Application Engineering Meeting

April 2011

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Introduction - Harmonics

Utility is responsible for providing “clean” voltage

Customer is responsible for not causing excessive current harmonics

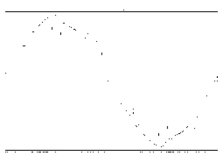
Utility can only be fairly judged if customer is within its current limits

Harmonics cause voltage and current problems in power systems

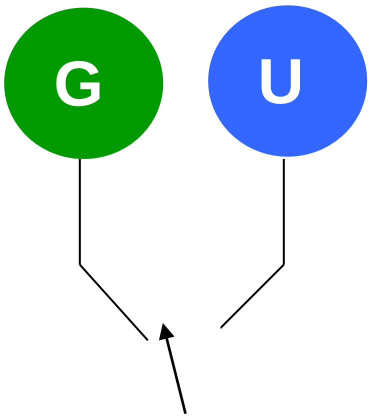
IEEE Std 519-1992 provides a basis for limiting harmonics

Multiple methods exist for mitigating harmonics and “one size does not fit all”

Harmonics – it's not that complicated….



$$V_d = I_d Z_h$$



Misoperation Problems

Heating Problems (Load Related)

Source Impedance

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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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What's YOUR (Harmonic) Problem?

- Voltage Problem
- Current Problem
- Impedance Problem

Solutions exist for every problem but you have to understand the problem first!

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

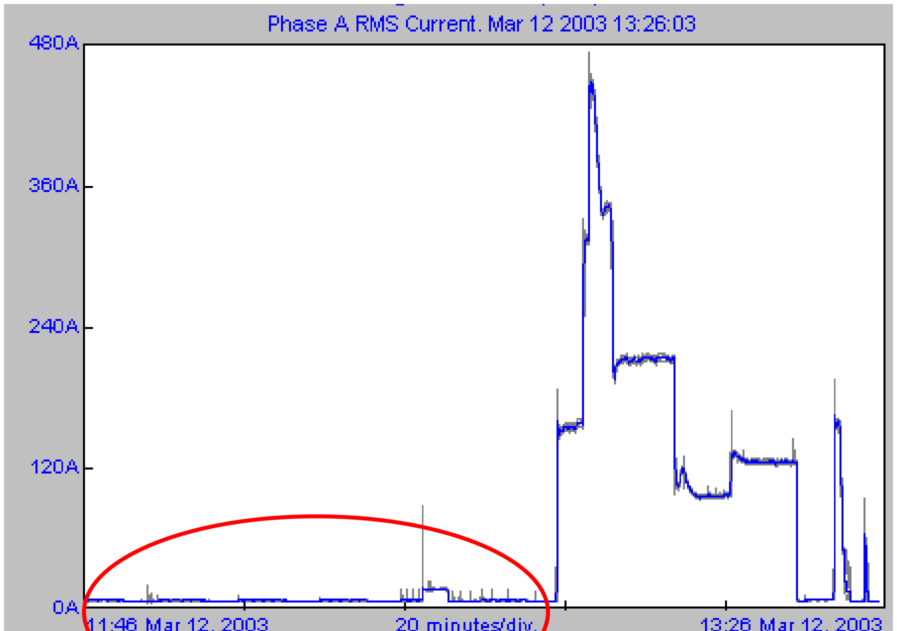
Internal vs. External Sources

Some harmonic sources are internal
- VFDs, switch mode power supplies, etc.

Other harmonic sources are external
- Customers sharing the same line

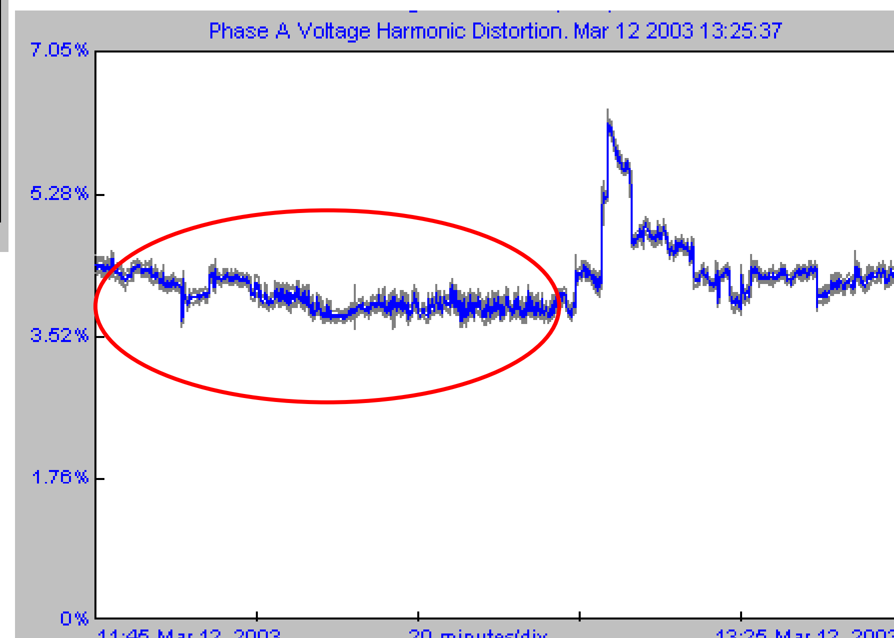
Is the voltage distortion caused by you or your neighbor?
- Establish a baseline (your neighbor's load)
- Determine the incremental change (your load)

Harmonic Limits System Issues



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

Voltage distortion at no load is 4%!



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Expected Harmonics

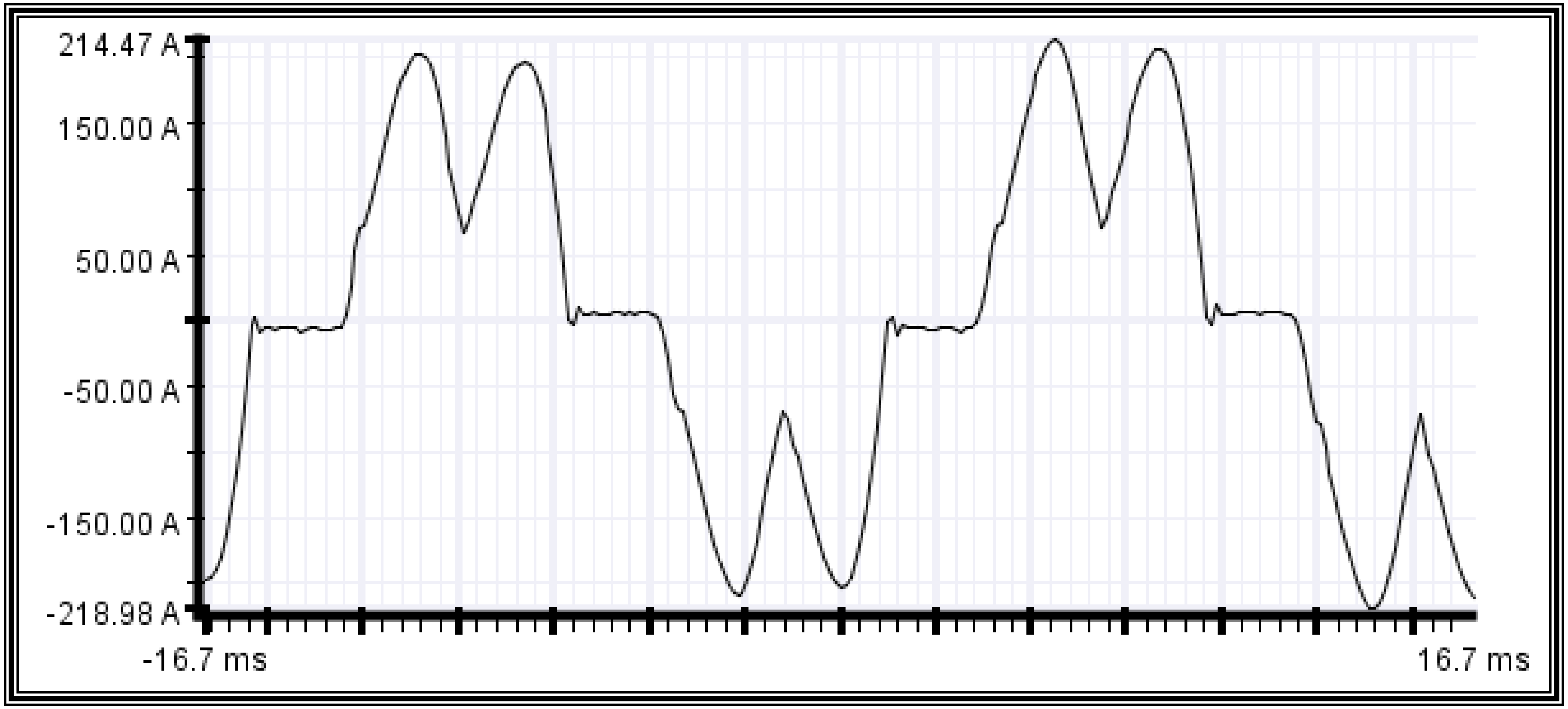
Source	Typical Harmonics*
6 Pulse Drive/Rectifier	5, 7, 11, 13, 17, 19…
12 Pulse Drive/Rectifier	11, 13, 23, 25…
18 Pulse Drive	17, 19, 35, 37…
Switch-Mode Power Supply	3, 5, 7, 9, 11, 13…
Fluorescent Lights	3, 5, 7, 9, 11, 13…
Arcing Devices	2, 3, 4, 5, 7...
Transformer Energization	2, 3, 4

* Generally, magnitude decreases as harmonic order increases

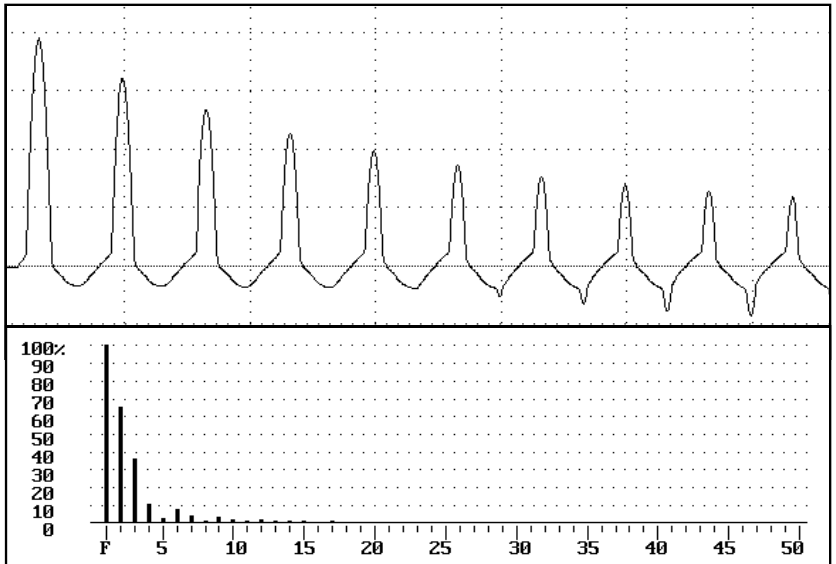
H = NP+/-1

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

Harmonic Sources – Continuous Current



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			

Harmonic sources don't have to be continuous…

Think…

- Soft starters
- Transformers
- Welding

Harmonics can "kick" your $@(()!!#$ (system)

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

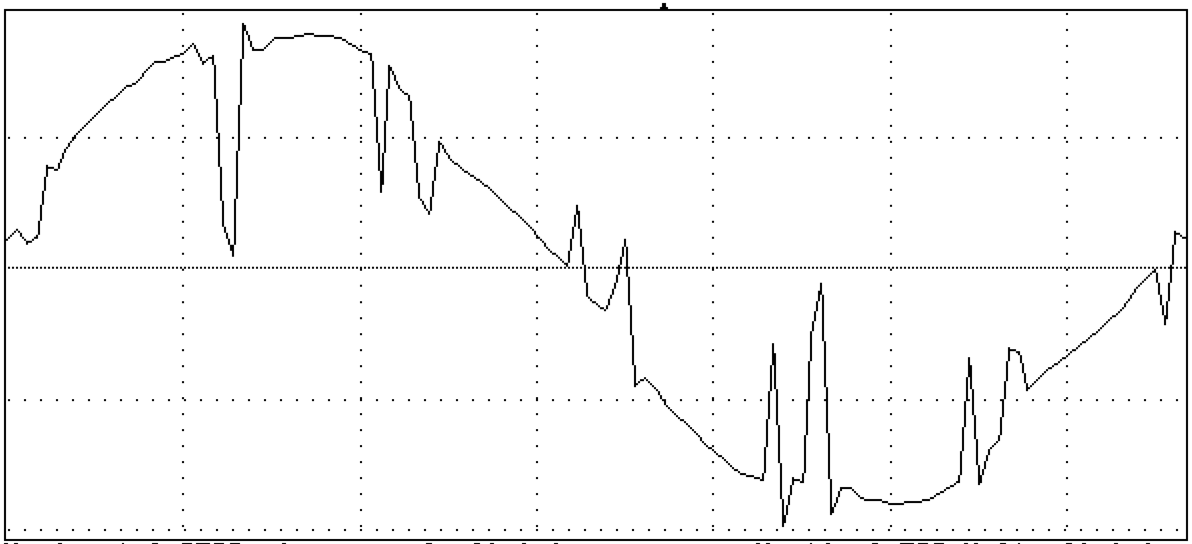
Economic Considerations

- Oversizing (equipment is sized larger to accommodate harmonics)
- Losses/Inefficiencies/PF Penalties
- Inconsistent meter reading

Harmonic Resonance with Power Factor Correction Capacitors

… But Remember

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



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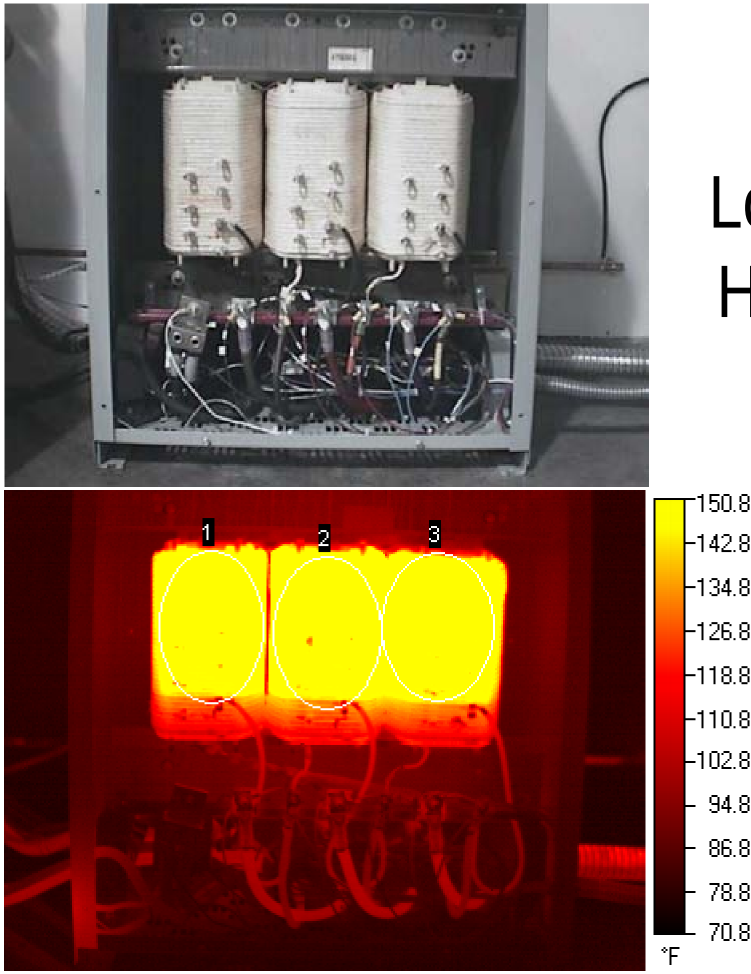
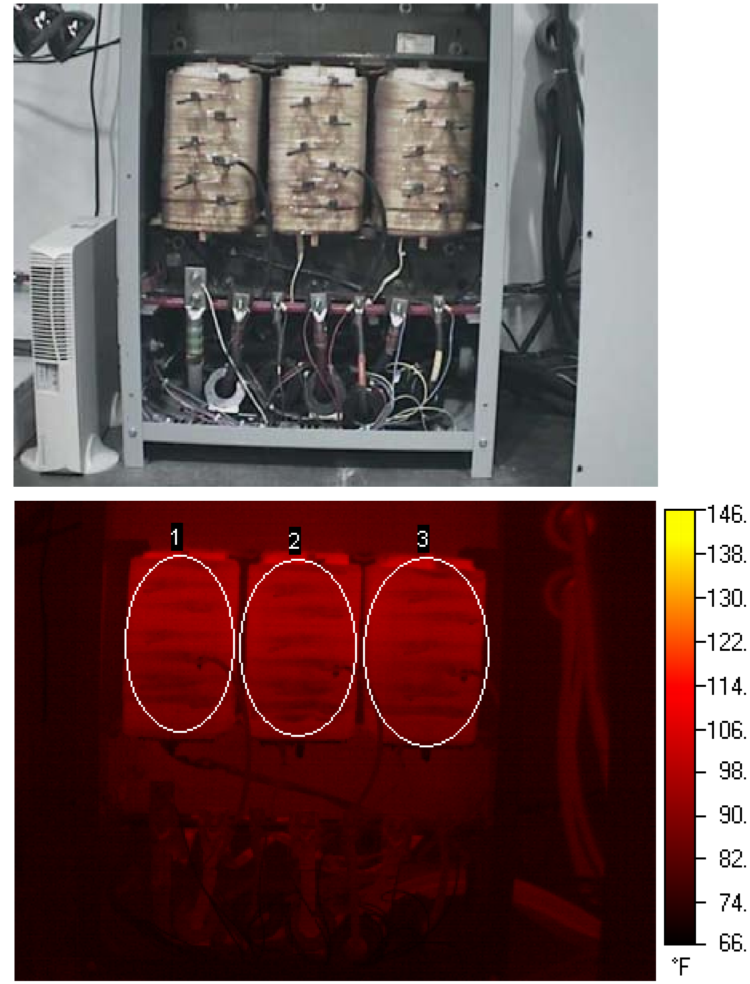
Harmonics and Heating

Load 100%
Harmonics



Std Transformer – Max Temp – 176 F



HMT – Max Temp – 105 F

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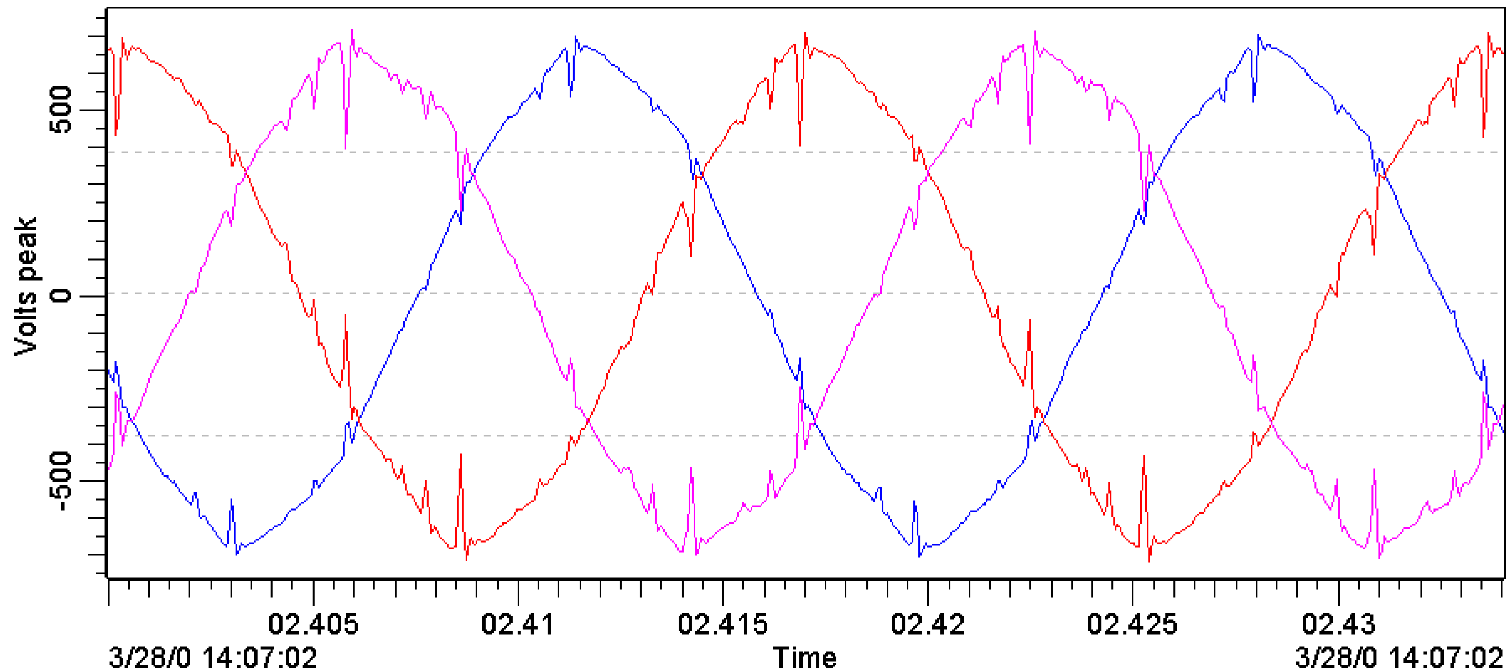
Voltage Notching



Measurement	Minimum	Maximum
Time	March 28, 2000 14:07:02.399	March 28, 2000 14:07:02.434
Voltage Waveform L1L2 Inst.	-702.2Vpk	707.1Vpk
Voltage Waveform L2L3 Inst.	-715.8Vpk	711.9Vpk
Voltage Waveform L3L1 Inst.	-703.6Vpk	719.8Vpk

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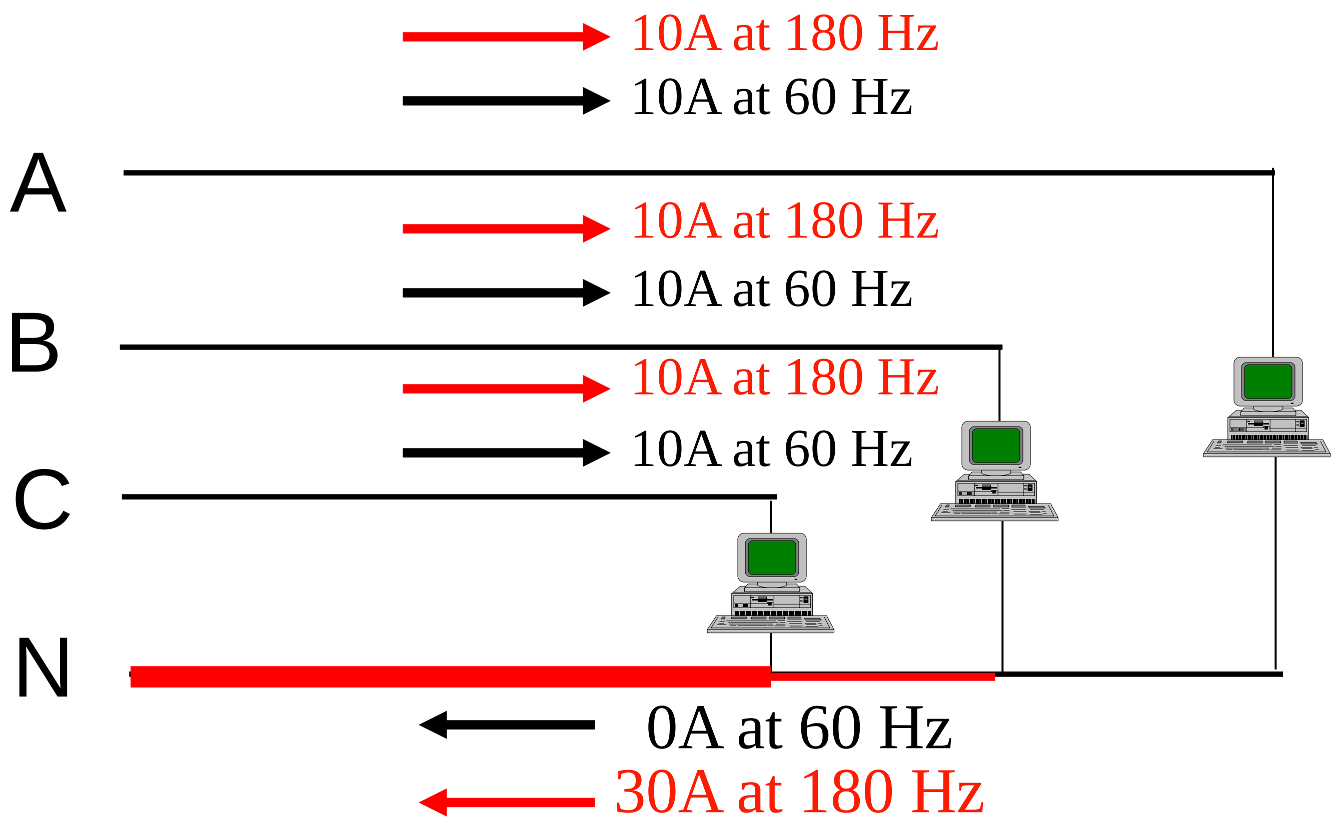
Neutral Heating – Oversize Equipment



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3rd Harmonic Summation in Neutral

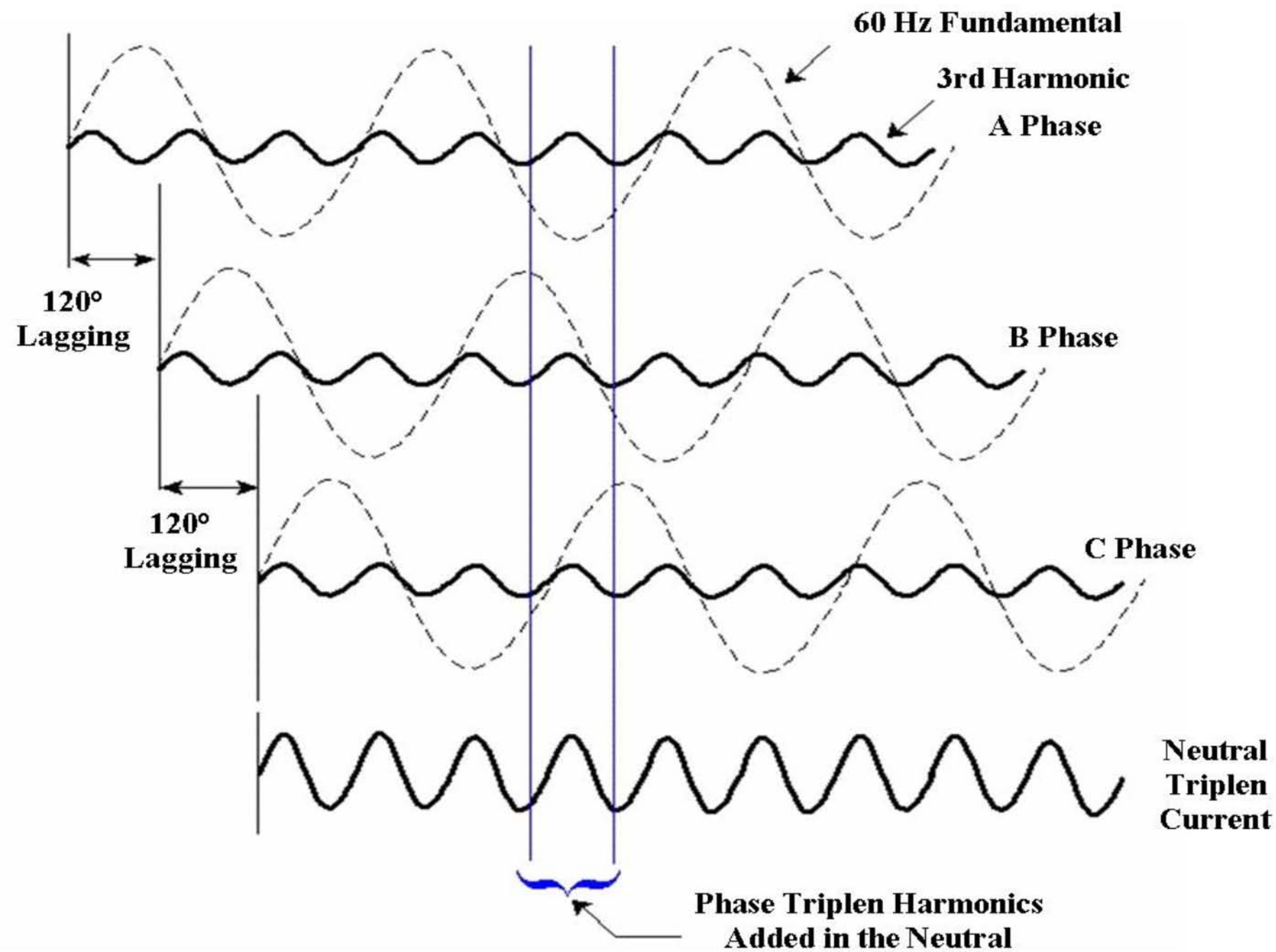
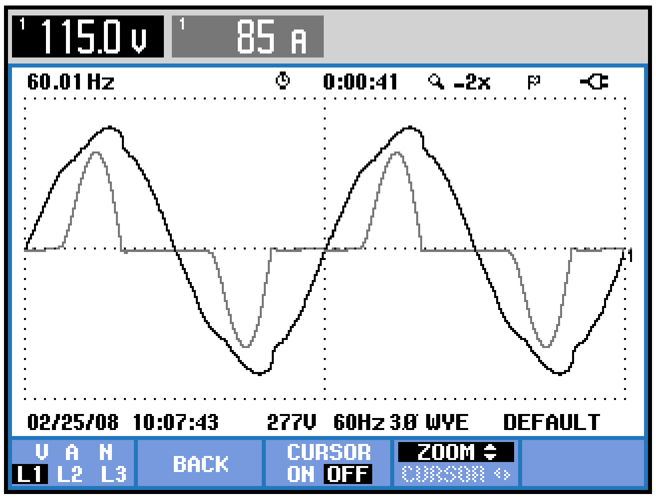
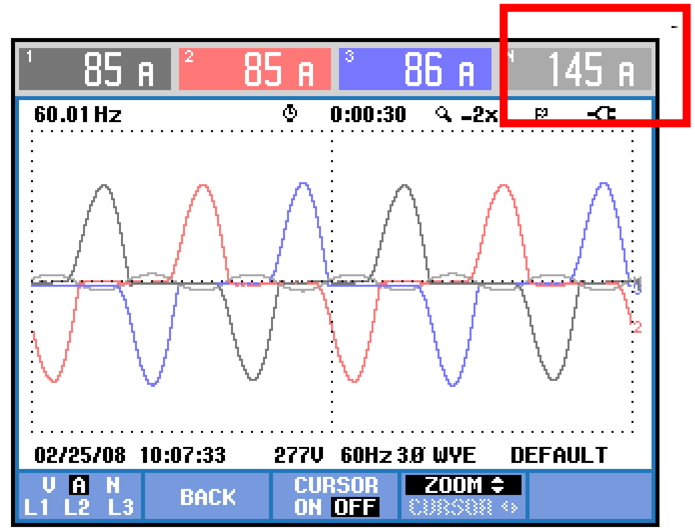
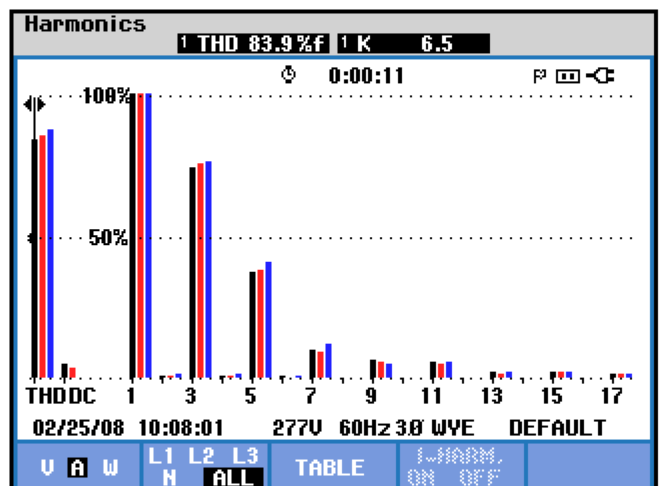


FIGURE 2 - Unbalanced Single Phase Loads with Triplen Harmonics

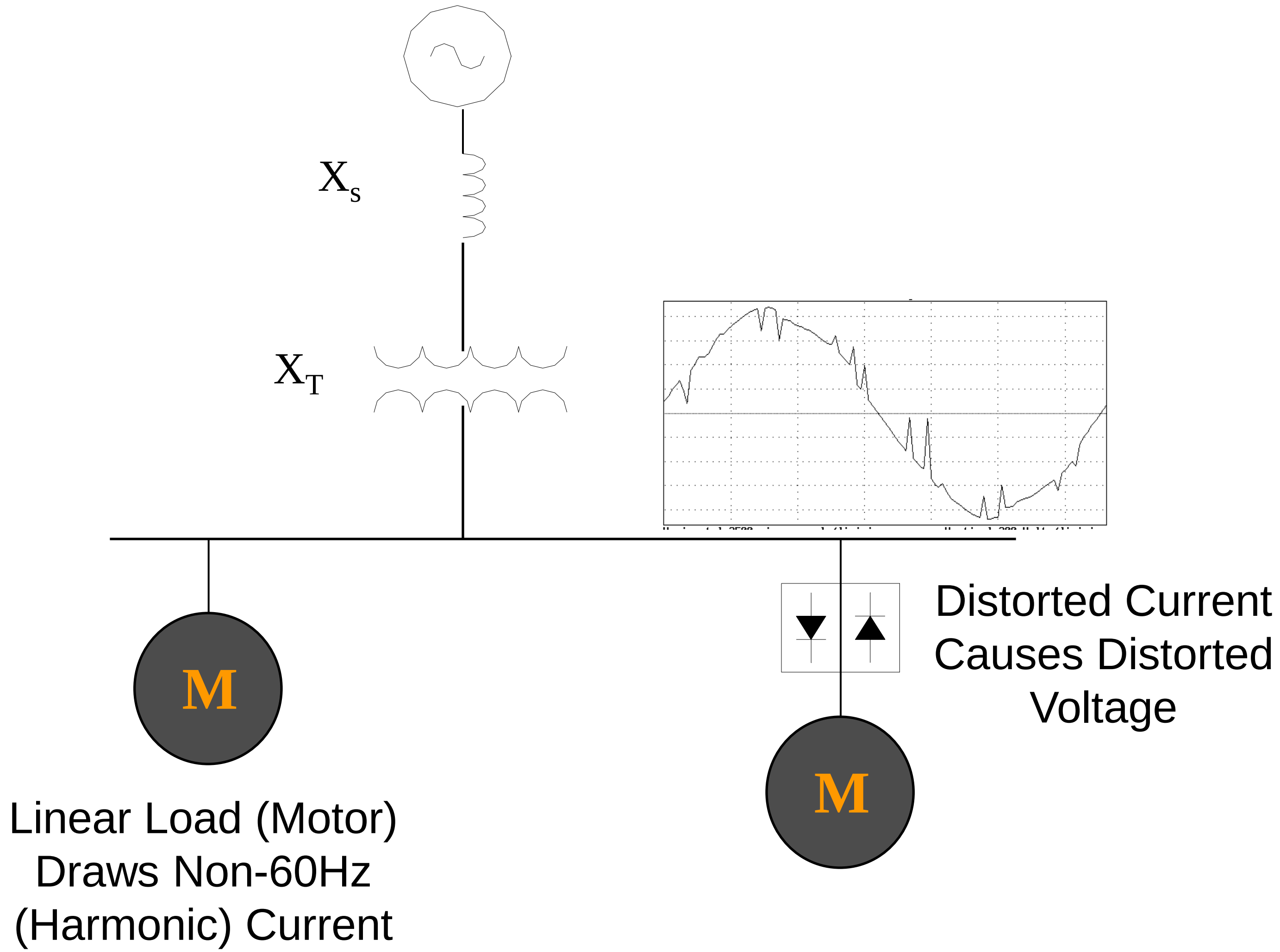
3rd Harmonic Summation in Neutral



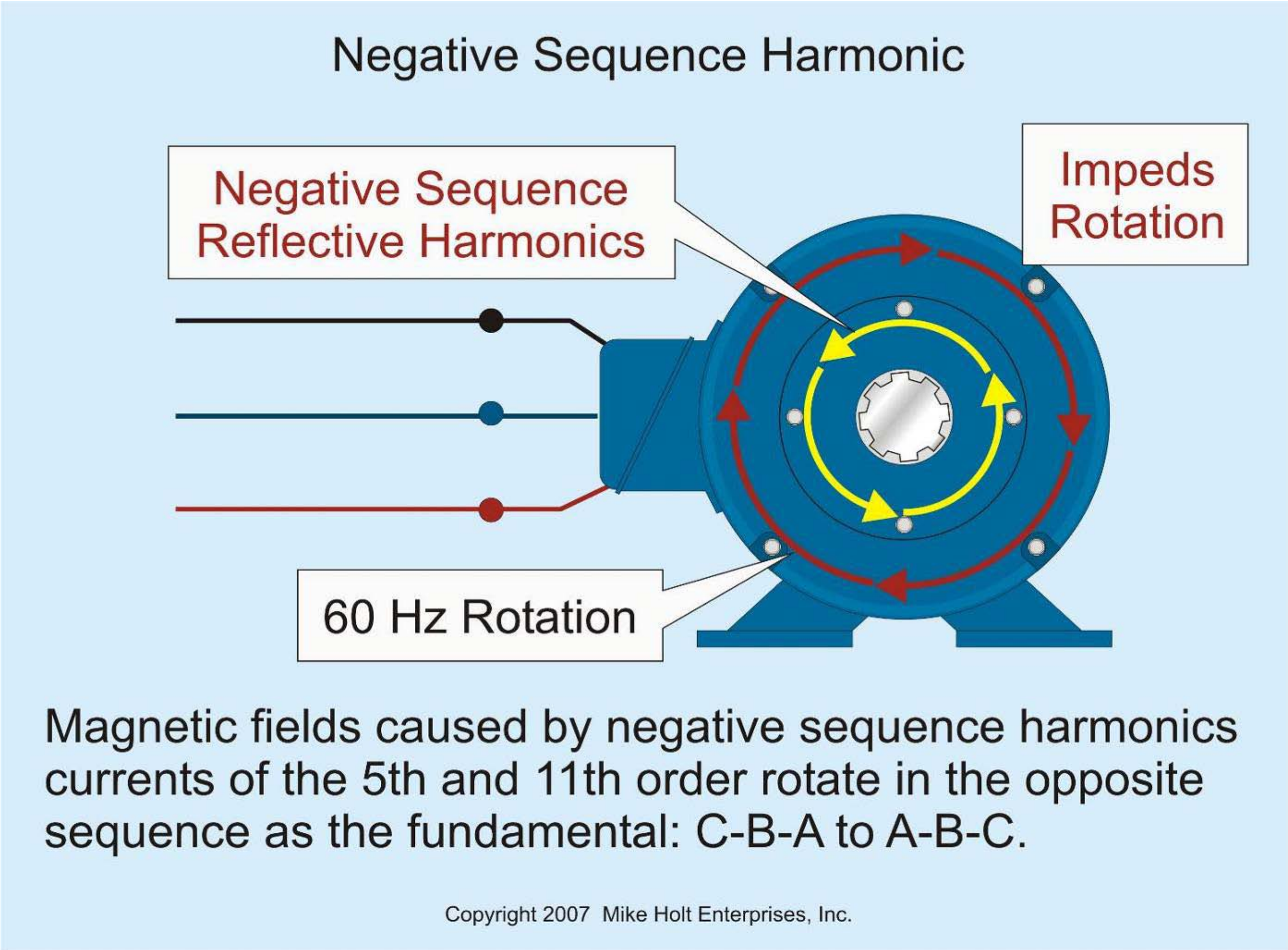




Harmonics and Motor Heating



Motor Heating and Vibrations



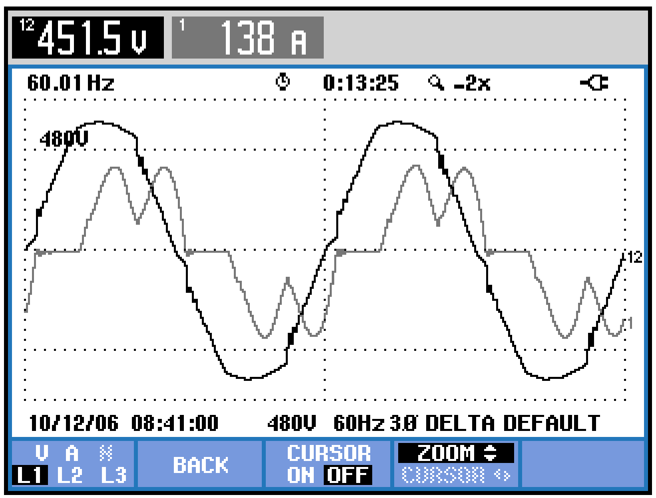
- Motor Heating
- Vibrations
- System Losses

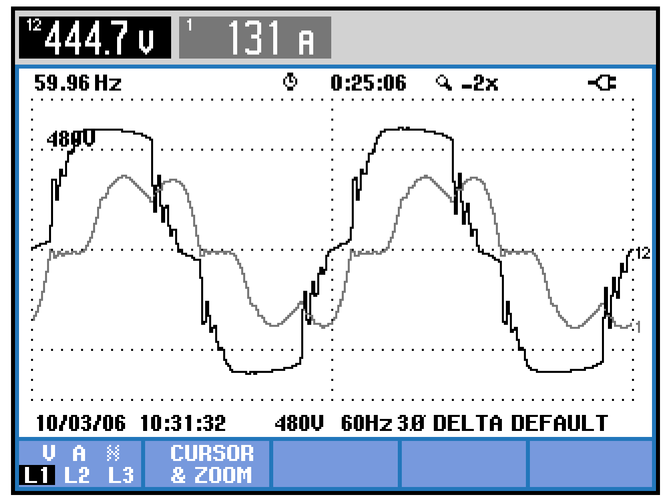
Like driving with one foot on the gas and one on the brake …

Harmonics and Generators

Generator Concerns

Generator impedance (16-18%) is generally 3-4 times the equivalent source transformer (5-6%)





Utility Source

4.4% Vthd

Generator Source

13% Vthd

Same Load

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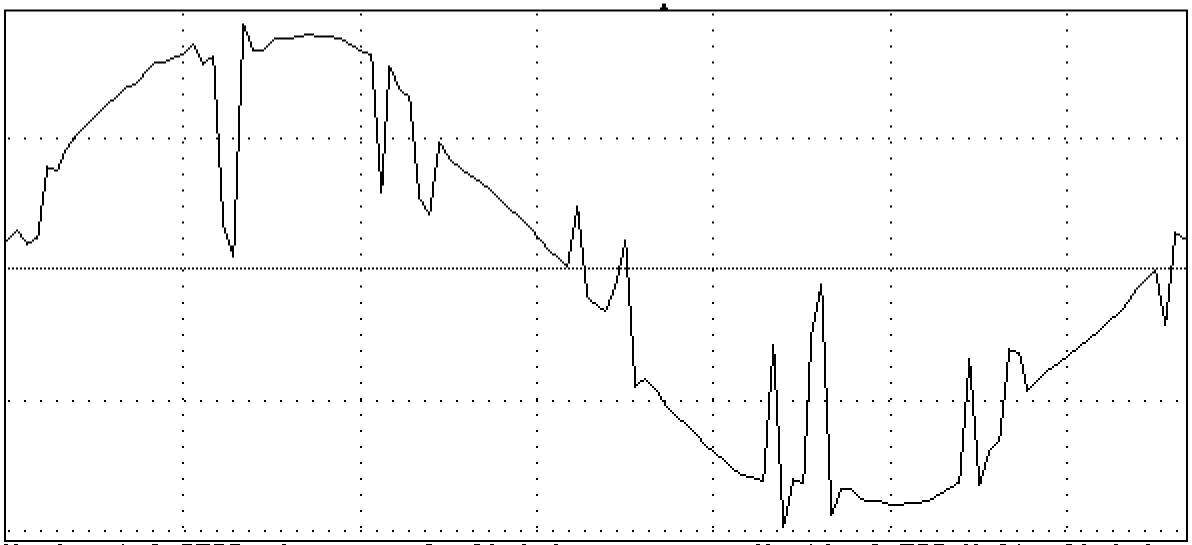
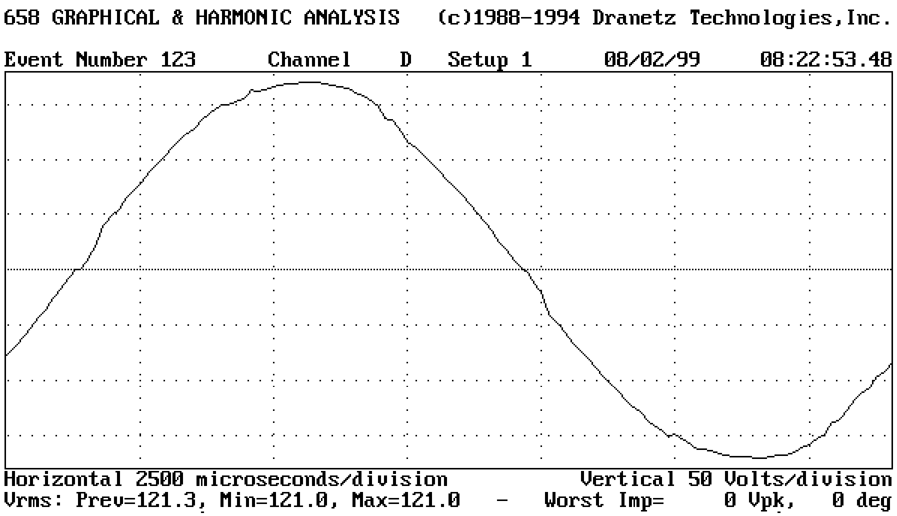
Notching and Generators

Generator Source may result in larger commutation notches and transients

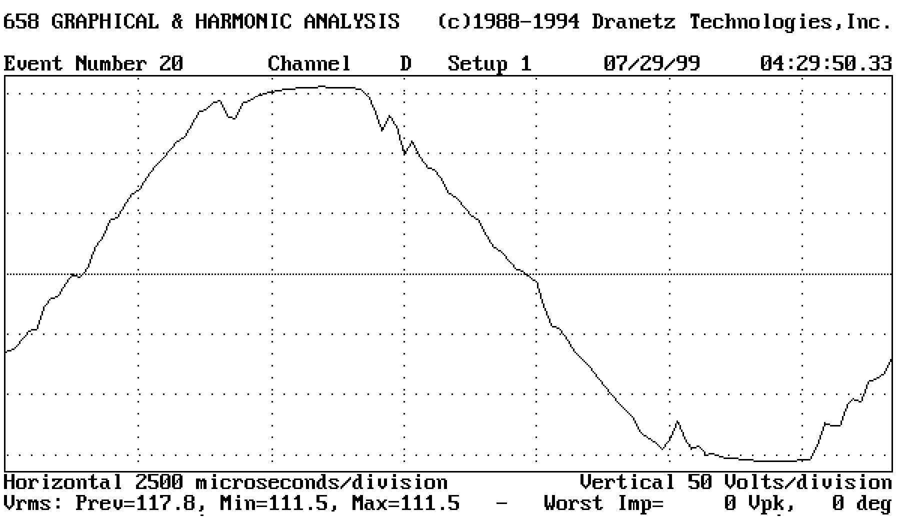


Horizontal 2500 microseconds/division Vertical 500 Volts/division
Vrms: Prev=610.7, Min=605.5, Max=605.5 - Worst Imp= 0 Vpk, 0 deg

Harmonics and Generators



Utility Source
2.3% THD

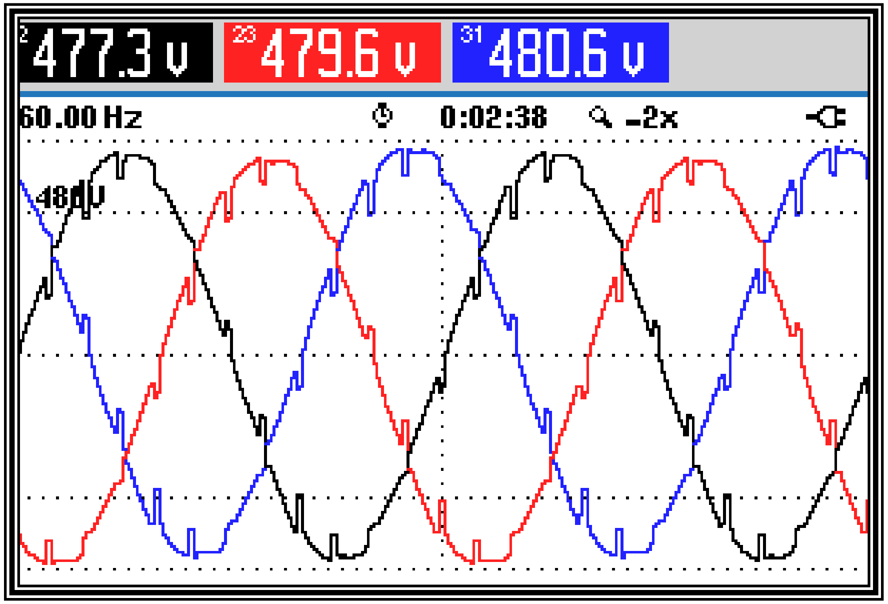


Generator Source
5.7% THD

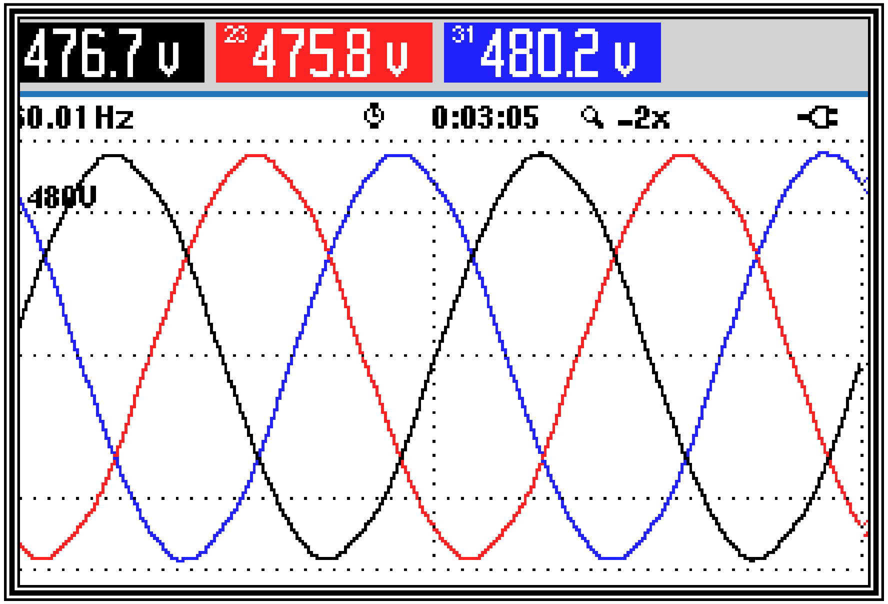
Harmonics and Generators

Example – Generator Sync Failure

Generator 1 (Loaded)

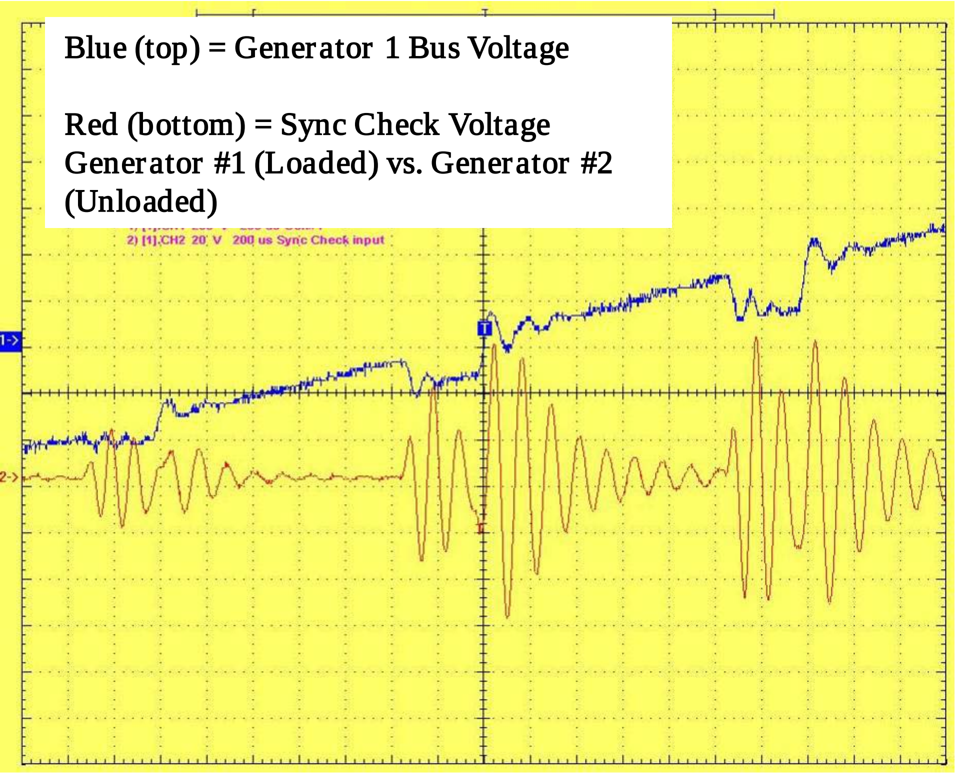


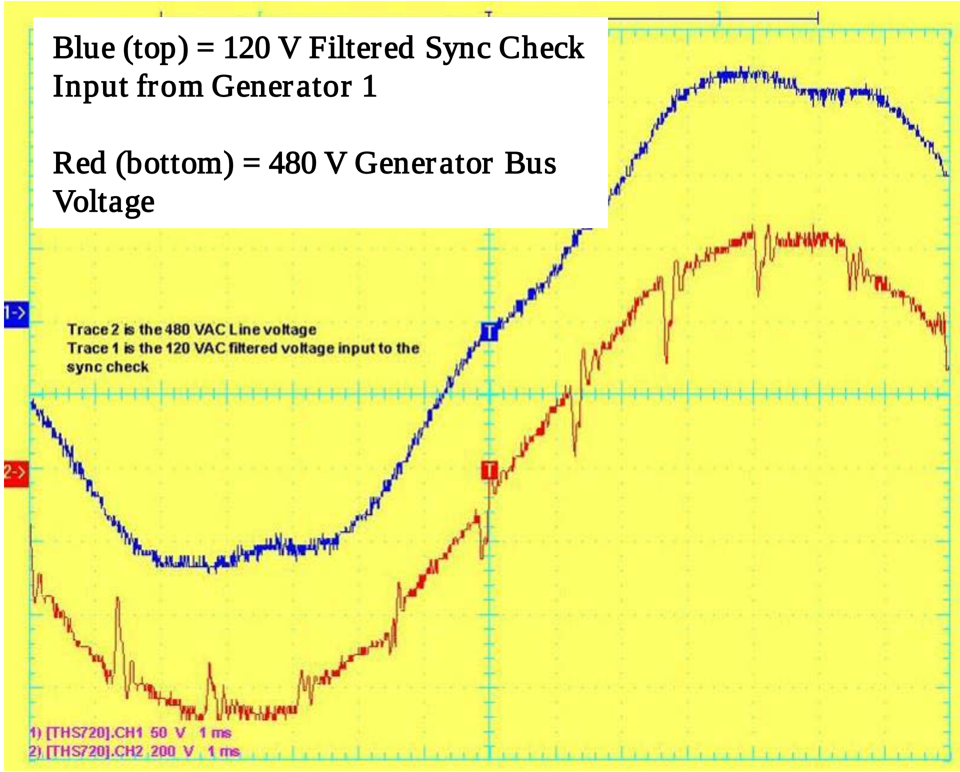
Generator 2 (Unloaded)



Harmonics and Generators

Example – Generator Sync Failure





Solution: Series-rated surge protector/ring-wave filter

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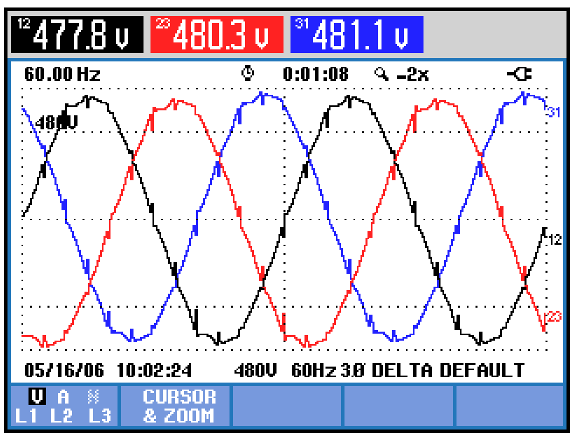
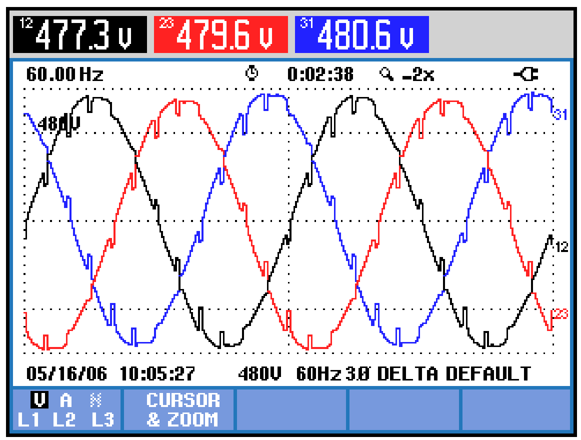
Harmonics and Generators

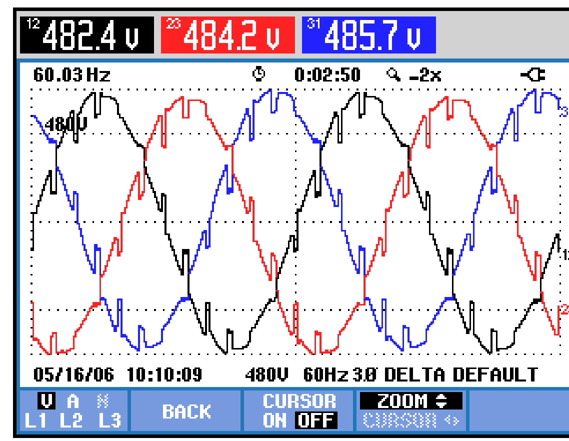
Generator Filter – UPS Filter On/Off

Utility Source | **Generator Source**

Harmonic Filter ON | Harmonic Filter ON | Harmonic Filter OFF







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Power Systems Experience Center

Purpose: to demonstrate and test PQ problems and solutions

- Full-scale power system
- Demystify solutions
- “Seeing is Believing”
- Technical vs. Economic Solutions

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Equipment (PF/Harmonic Related)

- Fixed capacitors
- Switched capacitors
- Static switched capacitor
- Broadband Filters
- Passive (Fixed) Filters
- Passive (Switched) Filters
- Active Filters
- Reactors
- 3rd Harmonic Filter
- HMT Transformers
- K-Rated Transformers
- Phase shifting transformers

Power Systems Experience Center – Live Tour

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Specifications

- What are some of the specs that you see???
  - Must comply with IEEE519 Standard
  - Must maintain less than 5% THD
  - Must use active harmonic cancellation
  - Customer must not exceed 8% TDD
- What do these all mean???

Terminology

- Total Harmonic Distortion - THD
  - Harmonic current distortion in % of fundamental load current (instantaneous)
- Total Demand Distortion - TDD
  - Harmonic current distortion in % of max demand load current (15 - 30min)
- Harmonic Current – I_h
  - Harmonic current distortion for individual harmonic orders (h)
- Fundamental Current - I_1
  - Current at fundamental frequency (60hz) excluding harmonics

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Terminology

- Short Circuit Current – I_{SC}
  - Maximum three phase short circuit current available at the point of common coupling
- Demand Load Current – I_L
  - Sum of max load and harmonic currents
  - 15 or 30 minute demand, not momentary peak current
  - Common to use transformer full load current if planning for new load
- Point of Common Coupling – PCC
  - Closest point where another customer may interface with the utility

IEEE 519-1992 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:

Application Class	Example	THD (Voltage)
Special System	Hospital	3%
General System	WWTP	5%
Dedicated System	AFD's Only	10%

IEEE 519-1992 Recommendations

IEEE 519-1992 recommends different limits on Individual Harmonics (I_h) and Total Demand Distortion (TDD), depending on the I_{SC} / I_L ratio. I_{SC} is the short circuit current at the PCC, and I_L is the maximum demand load current (fundamental) at the PCC. More current distortion is allowed at higher I_{SC} / I_L ratios, since voltage distortion decreases as the ratio increases.

Harmonic current distortion limits (I_h and TDD in % of I_L($\leq$ 69KV):

I_{SC} / I_L	$I_h < 11$	$11 \leq I_h \leq 17$	$17 \leq I_h \leq 23$	$23 \leq I_h \leq 35$	**TDD**
< 20	4.0	2.0	1.5	0.6	5.0
20 – 50	7.0	3.5	2.5	1.0	8.0
50 – 100	10.0	4.5	4.0	1.5	12.0
100 – 1000	12.0	5.5	5.0	2.0	15.0
> 1000	15.0	7.0	6.0	2.5	20.0

Current Harmonic Limits Vary

- I_{SC}/I_L ratio shows relative size of the load compared to the utility system
  - Larger loads have greater ability to cause voltage distortion on the utility system
- System short circuit vs. load size (I_{SC}/I_L)
  - Larger load: stricter limits
  - Weaker system: stricter limits
- Higher order current harmonics
  - Stricter limits for higher order harmonics

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Harmonic Limits

- Where to assess the limits?
  - Point of Common Coupling (PCC)
- Which row of current limits applies?
  - Determine I_{SC}/I_L ratio
- How to calculate current harmonics for limit assessment?
  - Total Demand Distortion (TDD) versus Total Harmonic Distortion (THD)

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
- Some customers "voluntarily" comply to IEEE limits within their own systems

Point of Common Coupling

I_{SC}/I_L ratio

- Also proportional to kVA_{SC}/kVA_L
- kVA_{SC} is approximately = kVA_{Transf}/Z_{Transf}
- Example:
  - Transformer kVA = 1000, Z = 5%
  - kVA_{SC} = 1000/0.05 = 20,000
  - Peak Demand = 500 kVA
  - Ratio = 20,000/500 = 40
- If the transformer was smaller or the load was larger, the ratio would be smaller and visa versa

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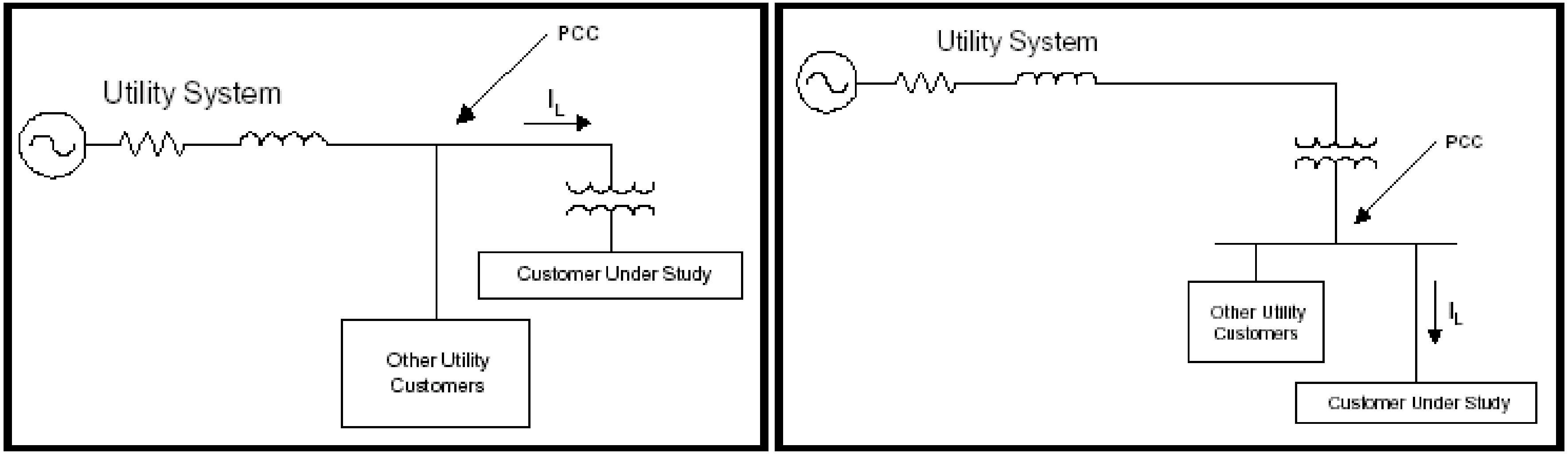
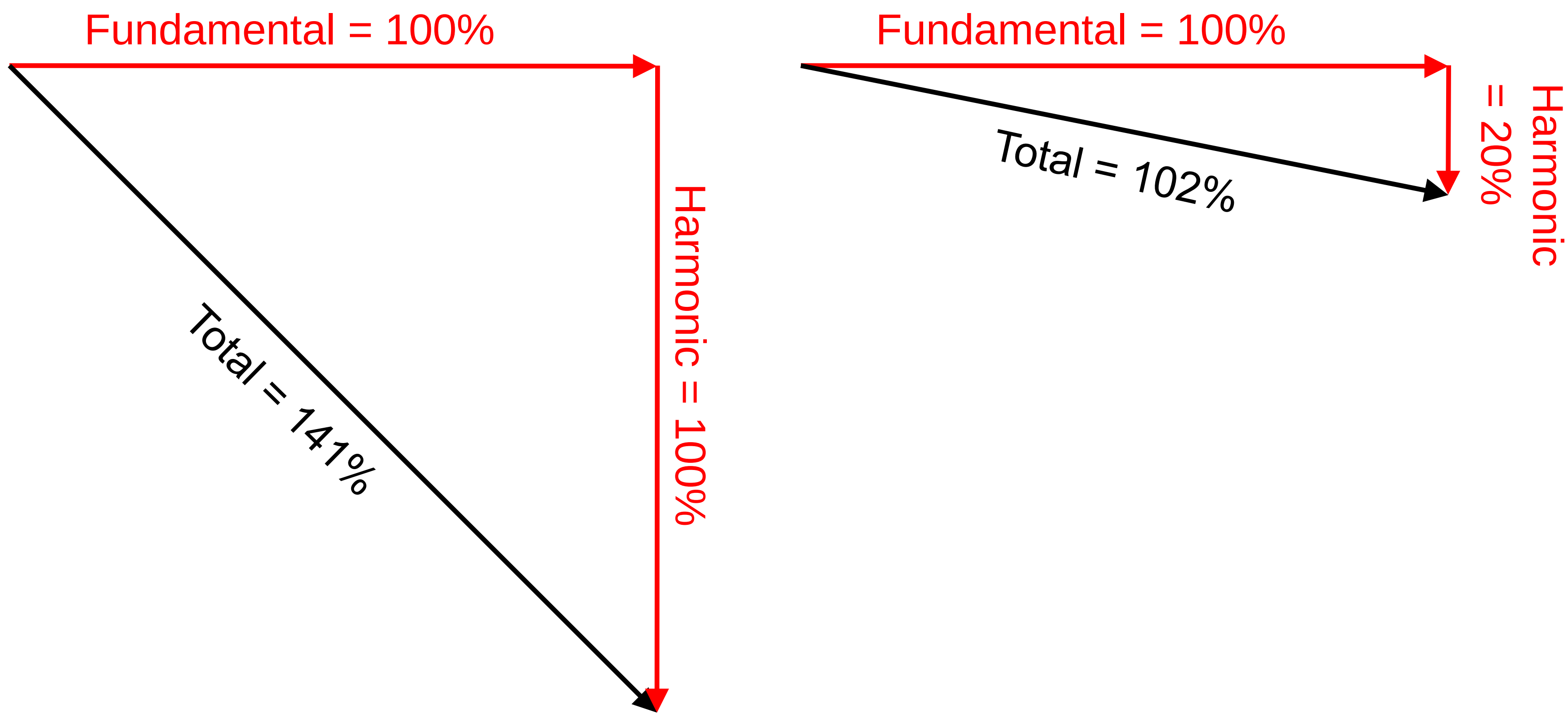
Point of Common Coupling

- PCC is where another customer can be served by the utility



Total Current – Why is this Important?



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 you pass on the secondary, you will pass on primary**
- If dispute between utility and customer, it may be necessary to measure or calculate harmonics at the MV transformer primary

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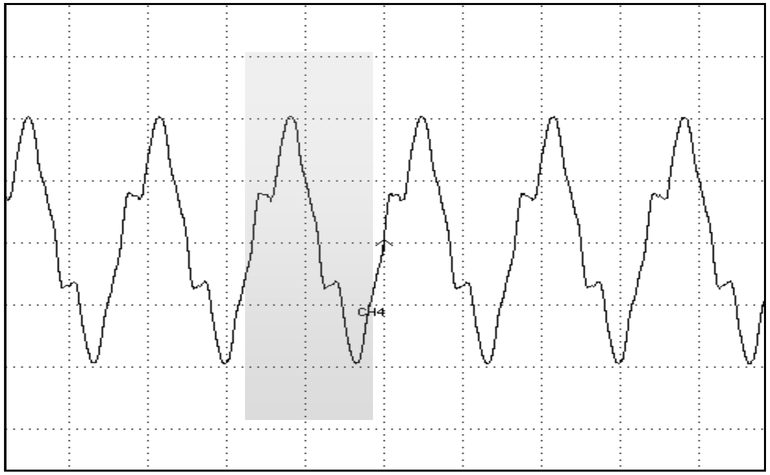
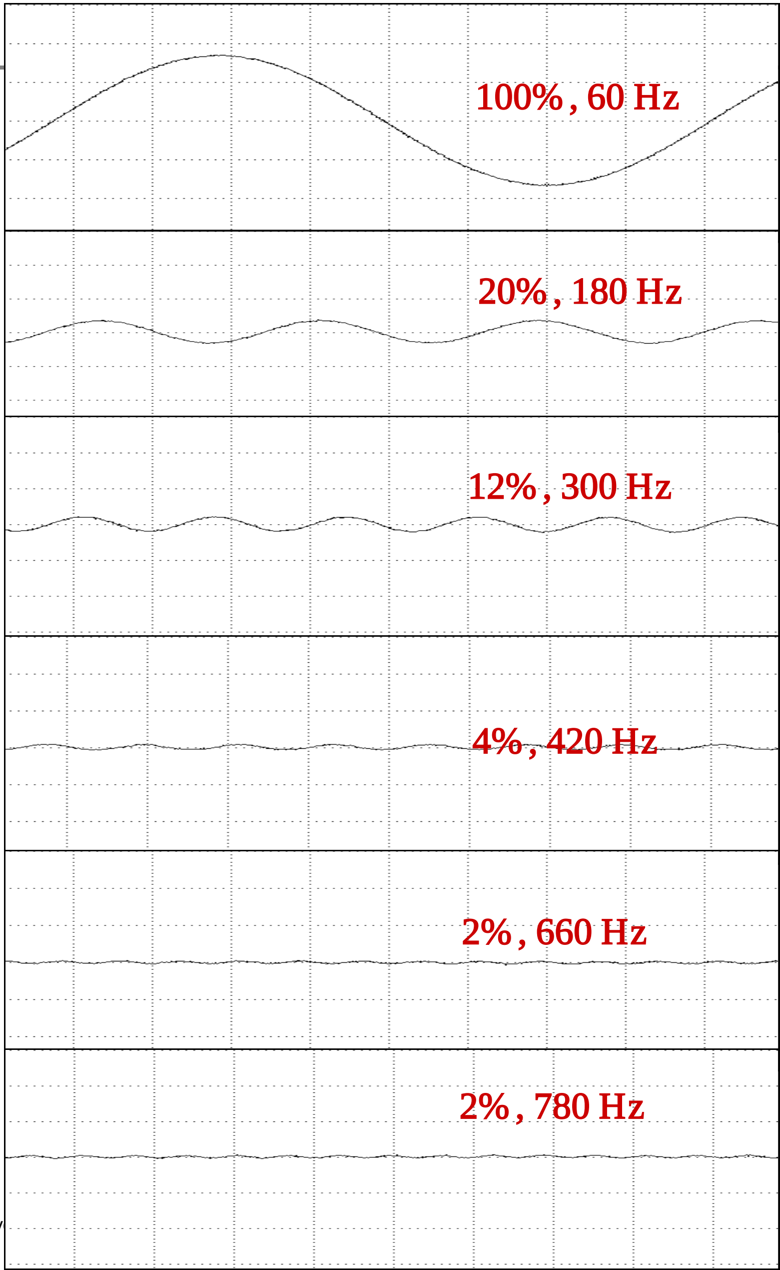
Total Demand Distortion

- Harmonic meters measure THD
  - Individual harmonics in % of I_1 (fundamental)
- IEEE-519 current harmonic limits use TDD
  - Individual harmonics in % of I_L (load)
- PX Meters measure TDD (…sort of)

Harmonics





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

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TDD and THD definitions are similar

- Only difference is the denominator

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots}}{I_1}$$

$$TDD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots}}{I_L}$$

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Total Demand Distortion

- Important to distinguish between TDD and THD (and % of I_L and % of I_1)
- Prevents user from being unfairly penalized during periods of light load
  - Harmonics could appear higher as a percent of a smaller I_1 value

Total Demand Distortion

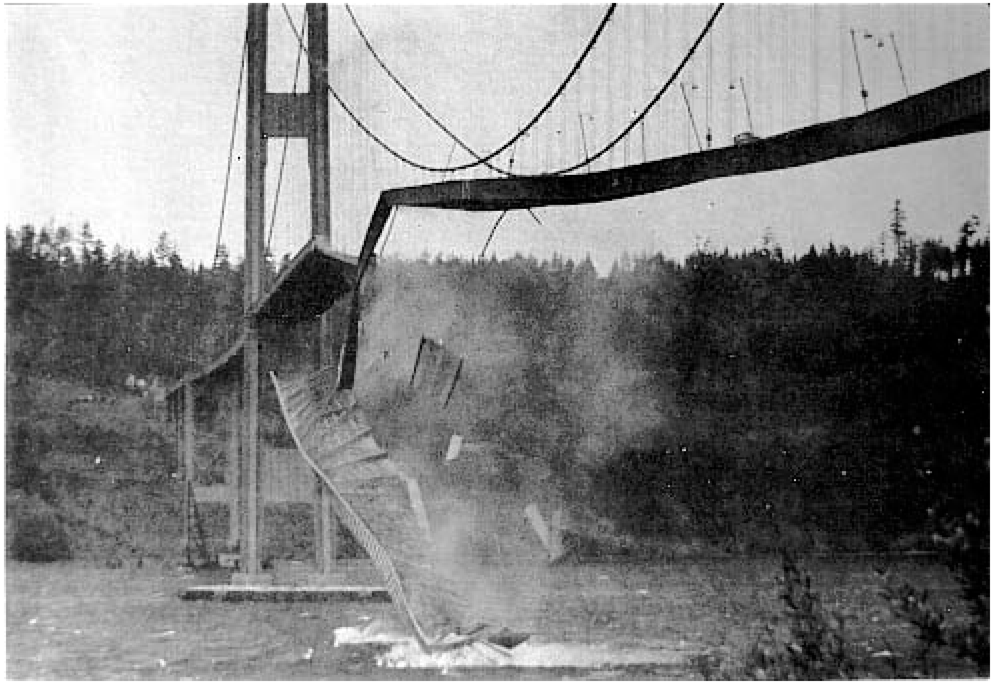
- Some specifications call for verification measurements at different load levels
  - Worry that THD increases at lower load
- Lower loading
  - THD increases, as suspected
  - TDD decreases
  - Amps of harmonics decrease
- Full load current is the worst case TDD
  - No need for measurements at partial load

Total Demand Distortion – CPX 9000 Example

Harmonic	30 Hz	40 Hz	50 Hz	60 Hz
THD (% of I_1)	26.7 %	14.1 %	9.1 %	5.9 %
TDD (% of I_L)	3.6 %	4.1 %	4.5 %	4.8 %
All Harmonics	8.2	9.2	10.1	10.8
RMS	31.9	65.8	110.7	183.1
1 (fundamental)	30.8	65.2	110.3	182.3
2	0.1	0.4	1.2	0.9
3	3.1	3.8	3.9	3.9
5	5.4	6.1	6.8	8.3
7	5.1	5.1	4.9	4.3
11	0.2	0.2	0.5	1.2
13	0.4	0.8	1.0	1.2
17	1.5	2.0	2.1	2.1
19	0.8	1.7	2.5	2.5
23	0.3	0.4	0.4	0.3
25	0.3	0.4	0.7	0.7
29	0.0	0.1	0.1	0.3
31	0.2	0.1	0.2	0.3
35	0.1	0.2	0.3	0.4
37	0.2	0.3	0.4	0.5

225 A Demand Load

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.

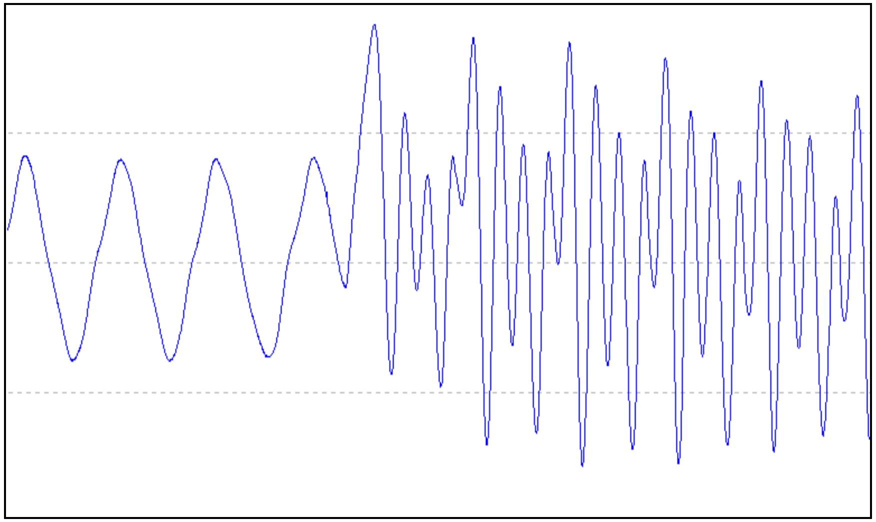
Harmonic Resonance

The "Self Correcting"
Problem

Blown Fuses

Failed Capacitors

Damaged Transformer



Harmonics = Wind (Excites Resonance)

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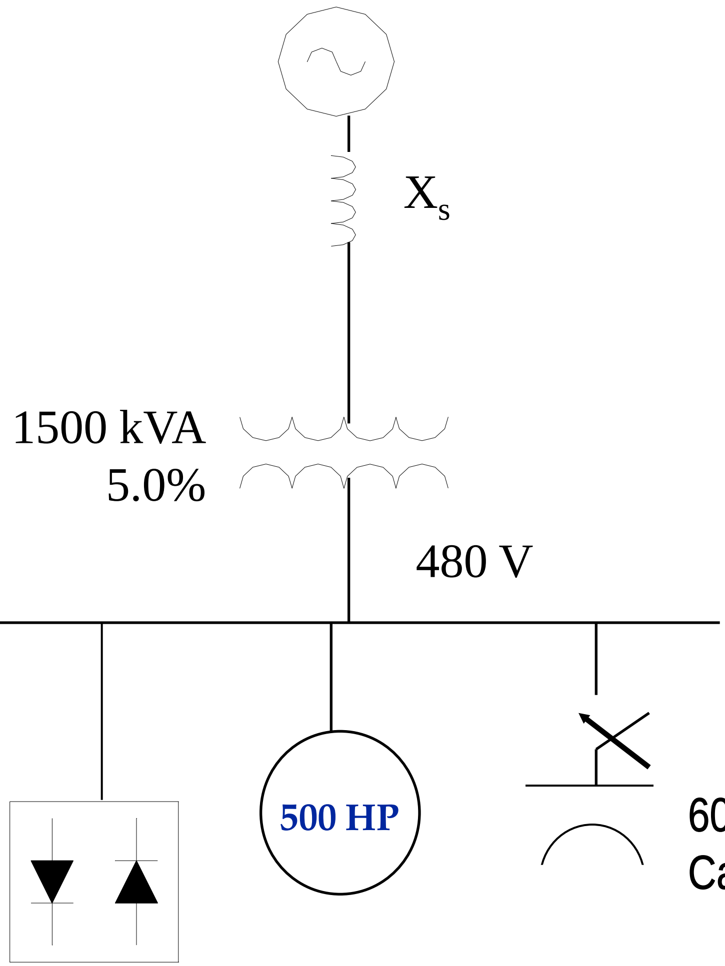
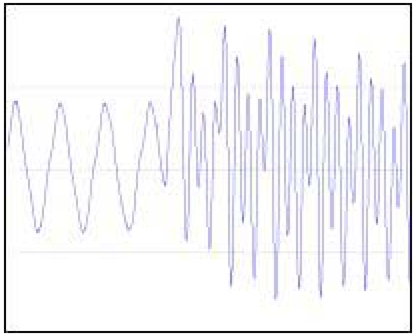
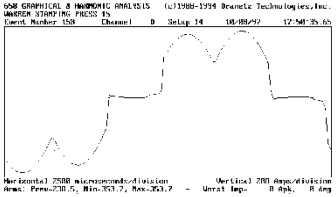
Harmonic Resonance

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



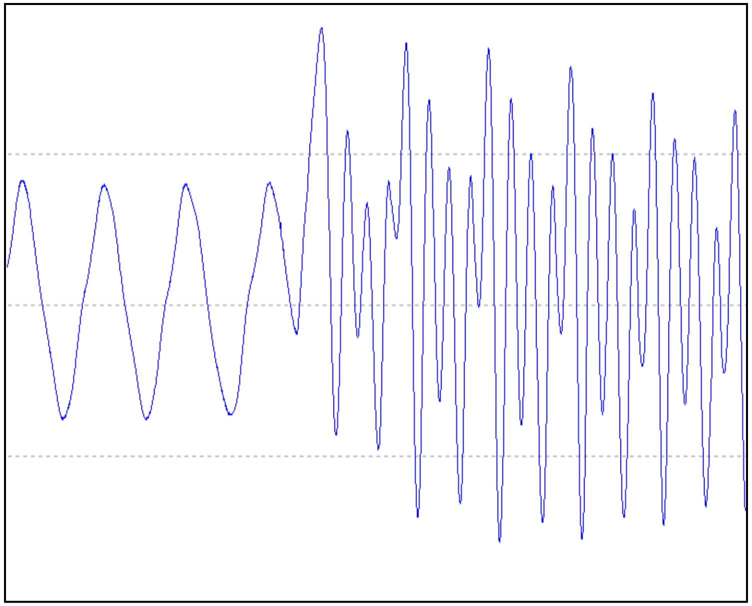




200 HP Drive
Source of Harmonics

600 kvar
Capacitor

Harmonic Resonance



If a capacitor exists on the power system

AND

Harmonic producing loads are in use

You MUST check for harmonic resonance (series and parallel)

Harmonic Resonance

- Capacitors not only supply reactive power to the loads in an electrical distribution system they also change the resonance frequency of the system.
- Capacitors are also a “sink” for harmonic currents present in a system (**series resonance**).
- When the resonance frequency of a system with PF correction capacitors is close to the frequency of a harmonic current generating load **parallel resonance** can occur.

Harmonic Resonance

- AC circuits characteristically have inductive and capacitive components and have the means to transfer energy between these components.
- Harmonic resonance occurs when the inductive reactance of a circuit is equal to the capacitive reactance. Resonance can be either series or parallel.
- Recall that inductive reactance increases as the power system frequency increases and the capacitive reactance decreases as the power system frequency increases by the following equations:

$$X_L = j2\pi f \times L = j\omega L$$

and

$$X_C = \frac{1}{j2\pi f \times C} = (-j)\frac{1}{\omega C}$$

where XL = inductive reactance in ohms

XC = capacitive reactance in ohms

f = power system frequency in Hz

L = component inductance in henries

C = component capacitance in farads.

- At 60 Hz, the capacitive components have a much higher impedance than the inductive components.

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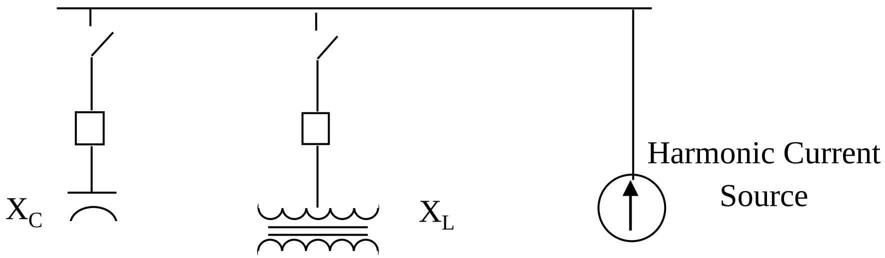
Parallel Resonance – "Amplifier"

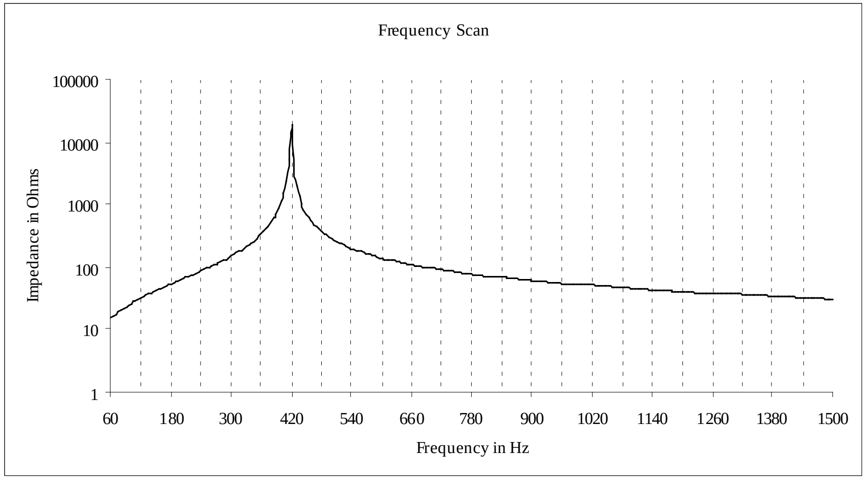
- The parallel combination of impedance is:

$$X_{EQUIVALENT} = \frac{jX_L \times (-j)X_C}{jX_L + (-j)X_C}$$

- Since XL and XC have opposite signs, the denominator can equal zero if XL = XC. In reality, the only limiting factor is the difference in resistance between the capacitor and reactor.

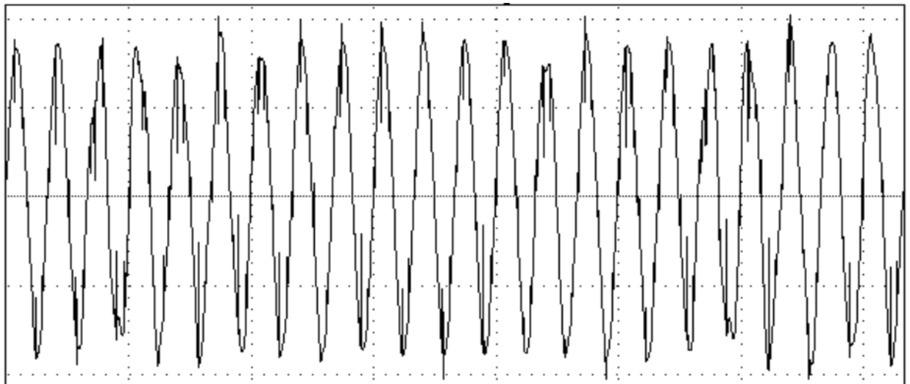


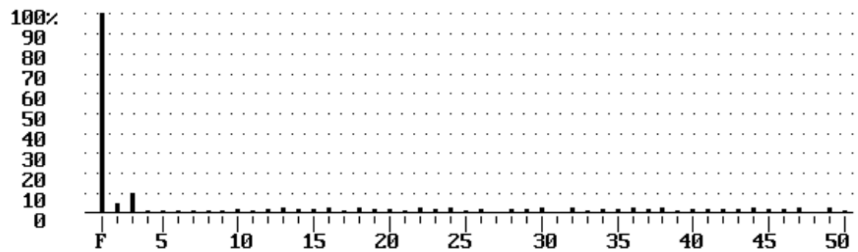
Equivalent Parallel Resonant Circuit



Frequency Scan for Parallel Resonant Circuit

Parallel Resonant Example
3rd Harmonic Voltage

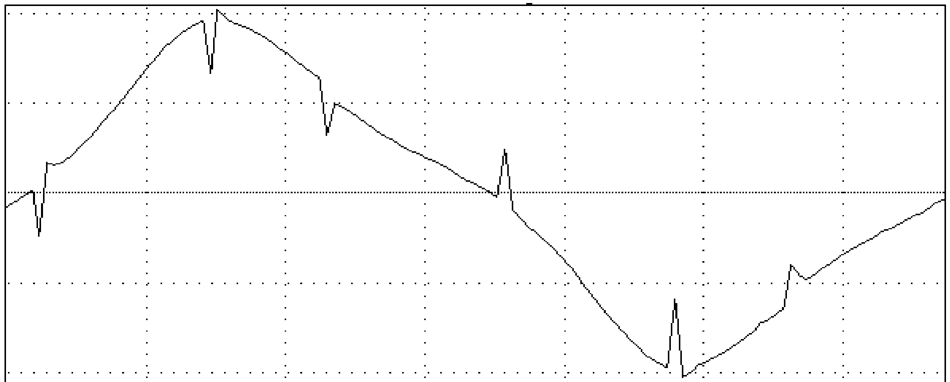


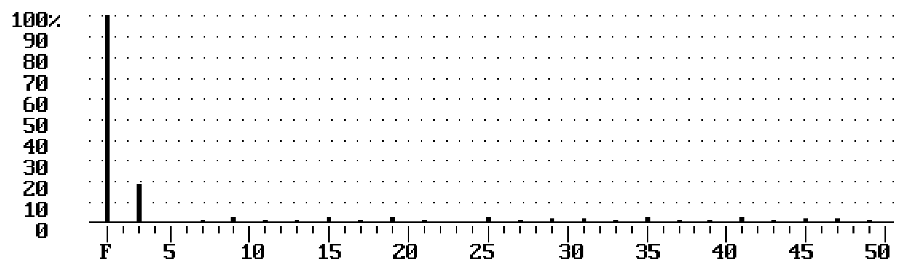


HARMONIC NUMBER:	50	3rd:	10.1% Phase: 275 degrees
TOTAL HARMONIC DISTORTION:	16.7%	2nd:	5.0% Phase: 111 degrees
ODD CONTRIBUTION:	12.6%	38th:	2.8% Phase: 195 degrees
EVEN CONTRIBUTION:	11.0%	32nd:	2.6% Phase: 129 degrees

Fnd:	585.29V 205 deg	18th:	2.2% 297 deg	35th:	2.0% 202 deg
2nd:	5.0% 111 deg	19th:	2.1% 216 deg	36th:	2.2% 146 deg
3rd:	10.1% 275 deg	20th:	1.9% 321 deg	37th:	1.5% 221 deg
4th:	1.3% 329 deg	21st:	1.0% 279 deg	38th:	2.8% 195 deg
5th:	1.1% 50 deg	22nd:	2.4% 328 deg	39th:	1.2% 326 deg
6th:	1.3% 198 deg	23rd:	1.5% 24 deg	40th:	1.9% 225 deg
7th:	0.9% 108 deg	24th:	2.4% 9 deg	41st:	2.0% 296 deg
8th:	1.2% 168 deg	25th:	0.9% 273 deg	42nd:	1.5% 212 deg
9th:	1.1% 199 deg	26th:	2.1% 51 deg	43rd:	2.1% 293 deg
10th:	1.8% 185 deg	27th:	0.6% 276 deg	44th:	2.3% 256 deg
11th:	1.2% 159 deg	28th:	2.0% 48 deg	45th:	1.6% 23 deg
12th:	1.6% 224 deg	29th:	1.8% 113 deg	46th:	2.0% 303 deg
13th:	2.5% 155 deg	30th:	2.5% 80 deg	47th:	2.4% 26 deg
14th:	2.0% 241 deg	31st:	0.5% 153 deg	48th:	0.6% 297 deg
15th:	1.5% 243 deg	32nd:	2.6% 129 deg	49th:	2.3% 16 deg
16th:	2.5% 257 deg	33rd:	0.9% 280 deg	50th:	1.3% 313 deg
17th:	1.2% 280 deg	34th:	1.8% 139 deg		

Parallel Resonant Example
3rd Harmonic Voltage

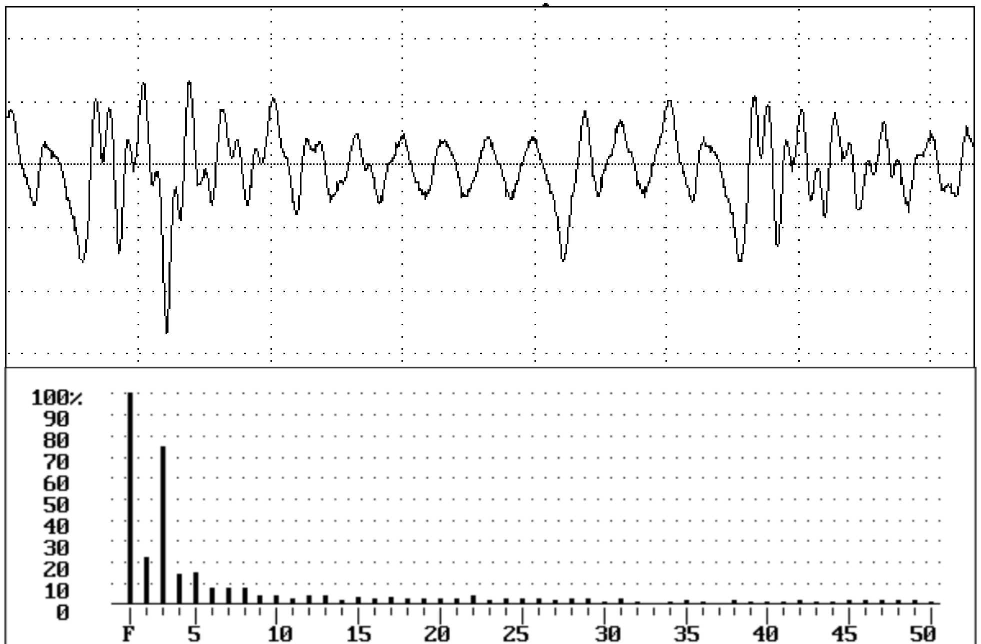




HARMONIC NUMBER:	50	3rd:	18.6% Phase: 171 degrees
TOTAL HARMONIC DISTORTION:	20.2%	9th:	2.8% Phase: 47 degrees
ODD CONTRIBUTION:	20.2%	25th:	2.8% Phase: 279 degrees
EVEN CONTRIBUTION:	1.7%	15th:	2.6% Phase: 3 degrees

Fnd:	568.66V	69 deg	18th:	0.1%	263 deg	35th:	2.3%	196 deg
2nd:	0.1%	241 deg	19th:	2.3%	329 deg	36th:	0.2%	265 deg
3rd:	18.6%	171 deg	20th:	0.3%	95 deg	37th:	1.3%	212 deg
4th:	0.5%	244 deg	21st:	1.2%	334 deg	38th:	0.4%	121 deg
5th:	0.3%	126 deg	22nd:	0.5%	254 deg	39th:	0.8%	195 deg
6th:	0.4%	31 deg	23rd:	0.6%	29 deg	40th:	0.5%	266 deg
7th:	1.4%	237 deg	24th:	0.3%	48 deg	41st:	2.3%	151 deg
8th:	0.3%	186 deg	25th:	2.8%	279 deg	42nd:	0.3%	112 deg
9th:	2.8%	47 deg	26th:	0.1%	241 deg	43rd:	1.1%	184 deg
10th:	0.2%	198 deg	27th:	0.7%	346 deg	44th:	0.1%	42 deg
11th:	0.7%	135 deg	28th:	0.3%	203 deg	45th:	1.4%	113 deg
12th:	0.4%	336 deg	29th:	1.4%	255 deg	46th:	0.4%	199 deg
13th:	0.8%	54 deg	30th:	0.4%	351 deg	47th:	1.9%	110 deg
14th:	0.5%	148 deg	31st:	2.1%	237 deg	48th:	0.4%	31 deg
15th:	2.6%	3 deg	32nd:	0.5%	180 deg	49th:	0.9%	127 deg
16th:	0.3%	294 deg	33rd:	0.7%	305 deg	50th:	0.3%	190 deg
17th:	1.2%	128 deg	34th:	0.1%	314 deg			

Parallel Resonant Example
3rd Harmonic Current



HARMONIC NUMBER:	50	3rd:	74.5% Phase: 75 degrees
TOTAL HARMONIC DISTORTION:	82.7%	2nd:	22.4% Phase: 242 degrees
ODD CONTRIBUTION:	77.0%	5th:	14.6% Phase: 103 degrees
EVEN CONTRIBUTION:	30.2%	4th:	13.9% Phase: 99 degrees

Fnd:	0.78A	328 deg	18th:	2.5%	65 deg	35th:	1.4%	11 deg
2nd:	22.4%	242 deg	19th:	2.4%	48 deg	36th:	0.7%	68 deg
3rd:	74.5%	75 deg	20th:	2.3%	100 deg	37th:	0.3%	48 deg
4th:	13.9%	99 deg	21st:	2.5%	54 deg	38th:	1.9%	25 deg
5th:	14.6%	103 deg	22nd:	3.8%	64 deg	39th:	1.1%	50 deg
6th:	7.3%	79 deg	23rd:	1.8%	58 deg	40th:	0.9%	43 deg
7th:	7.7%	98 deg	24th:	2.2%	55 deg	41st:	1.0%	32 deg
8th:	7.8%	71 deg	25th:	2.5%	53 deg	42nd:	1.7%	49 deg
9th:	3.9%	82 deg	26th:	2.5%	44 deg	43rd:	1.4%	66 deg
10th:	4.1%	61 deg	27th:	1.9%	42 deg	44th:	1.4%	6 deg
11th:	2.4%	87 deg	28th:	2.1%	13 deg	45th:	1.5%	18 deg
12th:	4.0%	79 deg	29th:	2.5%	55 deg	46th:	1.8%	56 deg
13th:	3.9%	86 deg	30th:	1.2%	35 deg	47th:	1.5%	19 deg
14th:	1.6%	42 deg	31st:	2.4%	7 deg	48th:	1.8%	6 deg
15th:	3.1%	77 deg	32nd:	1.1%	46 deg	49th:	1.8%	17 deg
16th:	2.6%	98 deg	33rd:	0.6%	22 deg	50th:	0.9%	39 deg
17th:	2.9%	72 deg	34th:	0.9%	35 deg			

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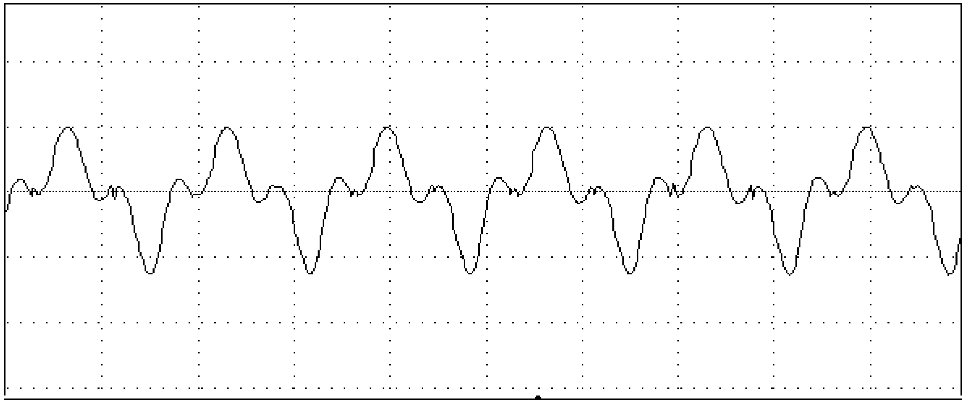
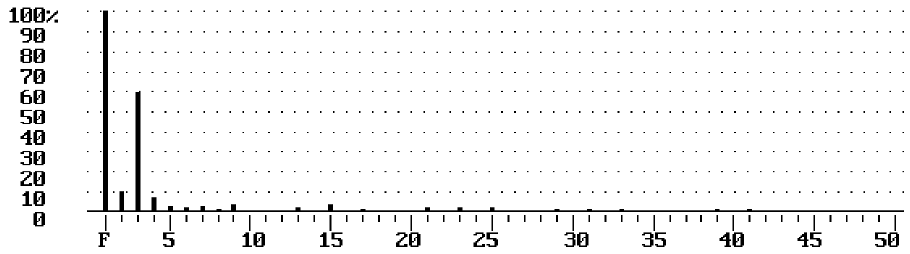
Parallel Resonant Example
3rd Harmonic Current





HARMONIC NUMBER:	50	3rd:	59.5% Phase: 60 degrees
TOTAL HARMONIC DISTORTION:	61.1%	2nd:	9.5% Phase: 114 degrees
ODD CONTRIBUTION:	59.9%	4th:	7.2% Phase: 57 degrees
EVEN CONTRIBUTION:	12.3%	9th:	3.0% Phase: 280 degrees

Fnd:	0.99A	136 deg	18th:	0.5%	250 deg	35th:	0.3%	357 deg
2nd:	9.5%	114 deg	19th:	0.6%	177 deg	36th:	0.4%	207 deg
3rd:	59.5%	60 deg	20th:	0.5%	326 deg	37th:	0.4%	98 deg
4th:	7.2%	57 deg	21st:	1.5%	208 deg	38th:	0.2%	182 deg
5th:	2.8%	7 deg	22nd:	0.4%	165 deg	39th:	0.8%	229 deg
6th:	2.0%	355 deg	23rd:	1.6%	348 deg	40th:	0.1%	240 deg
7th:	2.6%	93 deg	24th:	0.4%	247 deg	41st:	0.7%	0 deg
8th:	1.1%	314 deg	25th:	1.5%	152 deg	42nd:	0.2%	230 deg
9th:	3.0%	280 deg	26th:	0.3%	335 deg	43rd:	0.4%	141 deg
10th:	0.5%	16 deg	27th:	0.3%	253 deg	44th:	0.3%	73 deg
11th:	0.2%	256 deg	28th:	0.1%	7 deg	45th:	0.4%	248 deg
12th:	0.5%	289 deg	29th:	0.9%	326 deg	46th:	0.2%	126 deg
13th:	1.4%	81 deg	30th:	0.2%	270 deg	47th:	0.2%	310 deg
14th:	0.3%	359 deg	31st:	1.0%	105 deg	48th:	0.4%	331 deg
15th:	2.9%	235 deg	32nd:	0.4%	32 deg	49th:	0.4%	129 deg
16th:	0.3%	119 deg	33rd:	0.9%	260 deg	50th:	0.3%	36 deg
17th:	1.3%	26 deg	34th:	0.3%	128 deg			

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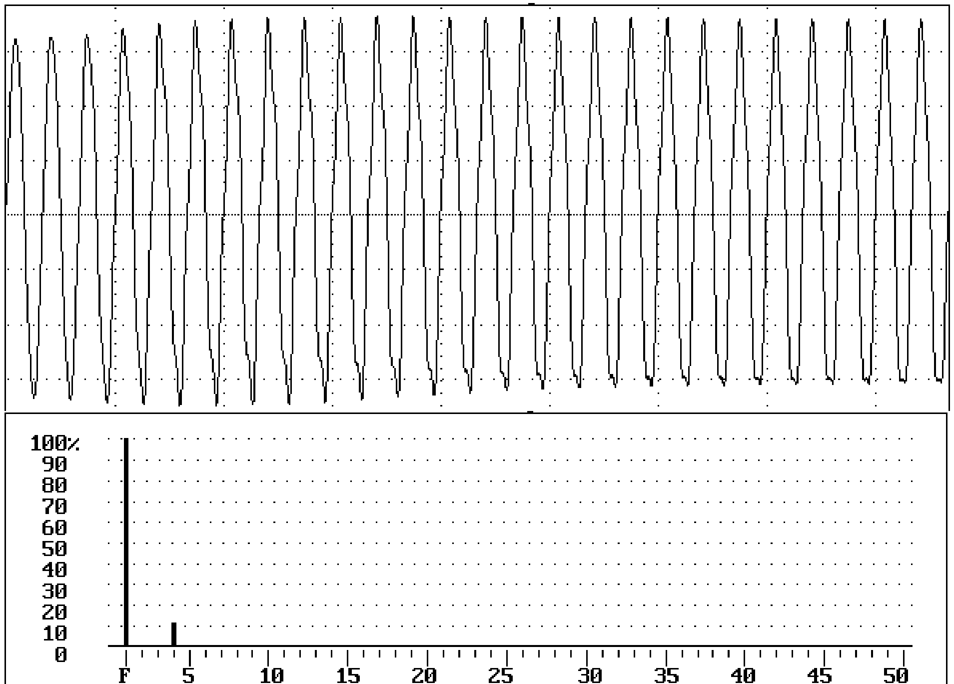
Parallel Resonant Example
4^{th} Harmonic Voltage



HARMONIC NUMBER:	50	4th:	11.0% Phase: 264 degrees
TOTAL HARMONIC DISTORTION:	11.0%	3rd:	0.3% Phase: 195 degrees
ODD CONTRIBUTION:	0.5%	2nd:	0.2% Phase: 316 degrees
EVEN CONTRIBUTION:	11.0%	7th:	0.2% Phase: 295 degrees

Fnd:	116.16V	252 deg	18th:	0.0%	198 deg	35th:	0.0%	95 deg
2nd:	0.2%	316 deg	19th:	0.0%	357 deg	36th:	0.0%	271 deg
3rd:	0.3%	195 deg	20th:	0.0%	191 deg	37th:	0.0%	171 deg
4th:	11.0%	264 deg	21st:	0.0%	299 deg	38th:	0.0%	346 deg
5th:	0.2%	321 deg	22nd:	0.0%	76 deg	39th:	0.0%	167 deg
6th:	0.2%	259 deg	23rd:	0.0%	41 deg	40th:	0.0%	134 deg
7th:	0.2%	295 deg	24th:	0.0%	89 deg	41st:	0.0%	49 deg
8th:	0.1%	7 deg	25th:	0.0%	238 deg	42nd:	0.0%	153 deg
9th:	0.2%	279 deg	26th:	0.1%	147 deg	43rd:	0.0%	276 deg
10th:	0.0%	252 deg	27th:	0.1%	236 deg	44th:	0.0%	339 deg
11th:	0.1%	338 deg	28th:	0.0%	177 deg	45th:	0.0%	120 deg
12th:	0.2%	276 deg	29th:	0.1%	84 deg	46th:	0.0%	161 deg
13th:	0.0%	227 deg	30th:	0.0%	90 deg	47th:	0.0%	162 deg
14th:	0.0%	259 deg	31st:	0.1%	188 deg	48th:	0.0%	329 deg
15th:	0.0%	196 deg	32nd:	0.0%	199 deg	49th:	0.0%	180 deg
16th:	0.0%	261 deg	33rd:	0.1%	235 deg	50th:	0.0%	72 deg
17th:	0.1%	352 deg	34th:	0.1%	227 deg			

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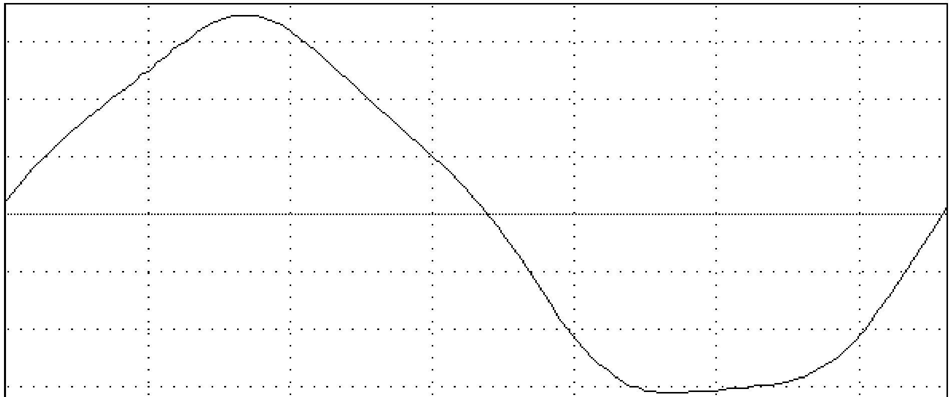
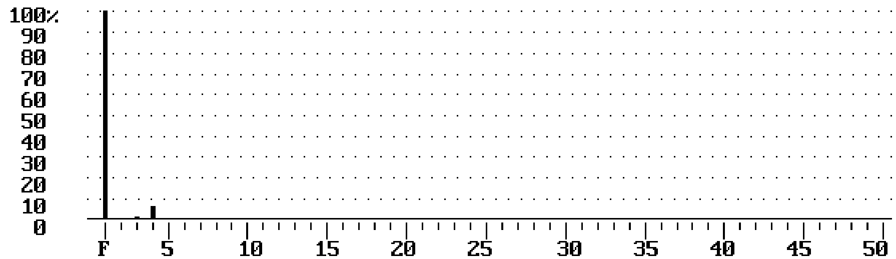
Parallel Resonant Example
4th Harmonic Voltage

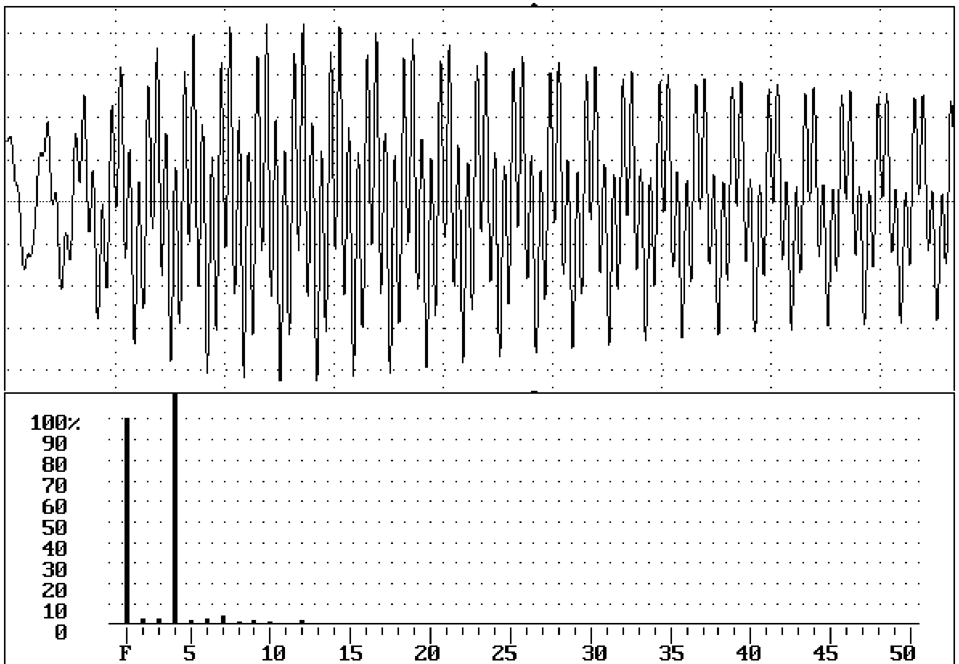




HARMONIC NUMBER:	50	4th:	6.4%	Phase:	11 degrees
TOTAL HARMONIC DISTORTION:	6.5%	3rd:	0.8%	Phase:	104 degrees
ODD CONTRIBUTION:	0.9%	7th:	0.2%	Phase:	293 degrees
EVEN CONTRIBUTION:	6.4%	2nd:	0.1%	Phase:	275 degrees

Fnd:	115.56V	89 deg	18th:	0.0%	68 deg	35th:	0.0%	77 deg
2nd:	0.1%	275 deg	19th:	0.0%	262 deg	36th:	0.0%	224 deg
3rd:	0.8%	104 deg	20th:	0.0%	199 deg	37th:	0.0%	291 deg
4th:	6.4%	11 deg	21st:	0.0%	201 deg	38th:	0.0%	148 deg
5th:	0.1%	281 deg	22nd:	0.0%	317 deg	39th:	0.0%	221 deg
6th:	0.0%	333 deg	23rd:	0.1%	237 deg	40th:	0.0%	180 deg
7th:	0.2%	293 deg	24th:	0.0%	202 deg	41st:	0.0%	140 deg
8th:	0.0%	138 deg	25th:	0.1%	259 deg	42nd:	0.0%	246 deg
9th:	0.1%	312 deg	26th:	0.1%	235 deg	43rd:	0.1%	326 deg
10th:	0.0%	141 deg	27th:	0.0%	332 deg	44th:	0.0%	272 deg
11th:	0.1%	317 deg	28th:	0.1%	343 deg	45th:	0.0%	142 deg
12th:	0.0%	210 deg	29th:	0.0%	5 deg	46th:	0.0%	143 deg
13th:	0.0%	190 deg	30th:	0.0%	319 deg	47th:	0.1%	165 deg
14th:	0.1%	301 deg	31st:	0.1%	209 deg	48th:	0.0%	206 deg
15th:	0.0%	246 deg	32nd:	0.1%	165 deg	49th:	0.1%	278 deg
16th:	0.0%	305 deg	33rd:	0.1%	289 deg	50th:	0.0%	275 deg
17th:	0.0%	70 deg	34th:	0.0%	42 deg			

Parallel Resonant Example
4th Harmonic Current



HARMONIC NUMBER:	50	4th:	171.1%	Phase: 323 degrees
TOTAL HARMONIC DISTORTION:	171.3%	7th:	4.1%	Phase: 149 degrees
ODD CONTRIBUTION:	5.6%	2nd:	2.8%	Phase: 162 degrees
EVEN CONTRIBUTION:	171.2%	3rd:	2.6%	Phase: 214 degrees

Fnd:	2.19A	142 deg	18th:	0.3%	264 deg	35th:	0.1%	247 deg
2nd:	2.8%	162 deg	19th:	0.2%	266 deg	36th:	0.2%	248 deg
3rd:	2.6%	214 deg	20th:	0.3%	224 deg	37th:	0.1%	234 deg
4th:	171.1%	323 deg	21st:	0.2%	233 deg	38th:	0.1%	194 deg
5th:	2.0%	146 deg	22nd:	0.1%	162 deg	39th:	0.0%	227 deg
6th:	2.5%	309 deg	23rd:	0.2%	286 deg	40th:	0.1%	180 deg
7th:	4.1%	149 deg	24th:	0.1%	216 deg	41st:	0.1%	151 deg
8th:	0.7%	287 deg	25th:	0.3%	254 deg	42nd:	0.2%	205 deg
9th:	1.8%	49 deg	26th:	0.1%	204 deg	43rd:	0.1%	175 deg
10th:	1.0%	295 deg	27th:	0.1%	298 deg	44th:	0.0%	195 deg
11th:	0.4%	298 deg	28th:	0.1%	318 deg	45th:	0.2%	146 deg
12th:	1.7%	245 deg	29th:	0.1%	254 deg	46th:	0.1%	222 deg
13th:	0.2%	293 deg	30th:	0.0%	315 deg	47th:	0.1%	246 deg
14th:	0.4%	230 deg	31st:	0.2%	283 deg	48th:	0.1%	252 deg
15th:	0.3%	62 deg	32nd:	0.2%	251 deg	49th:	0.0%	149 deg
16th:	0.3%	250 deg	33rd:	0.2%	237 deg	50th:	0.1%	289 deg
17th:	0.3%	326 deg	34th:	0.0%	27 deg			

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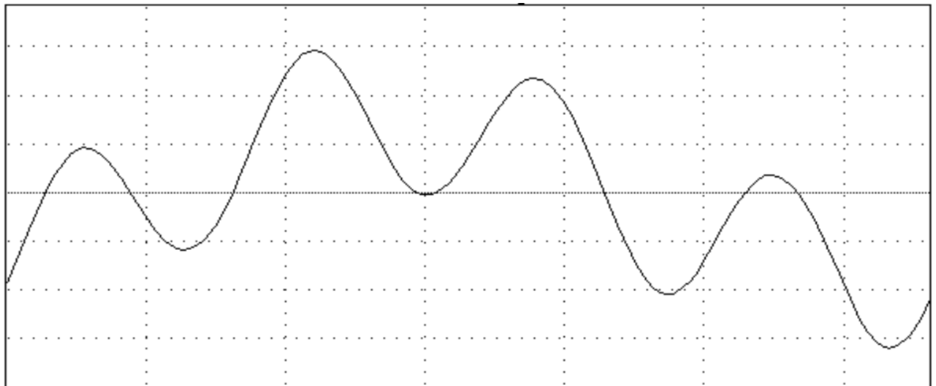
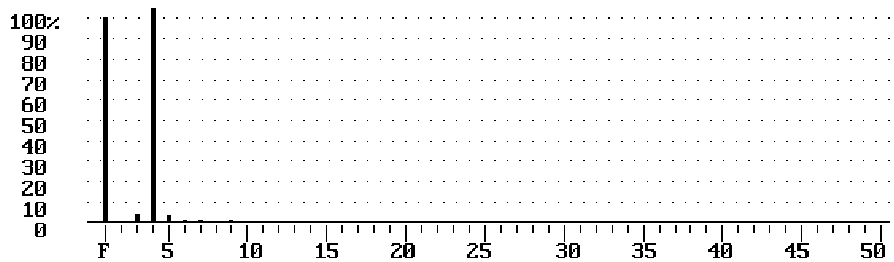
Parallel Resonant Example
4th Harmonic Current

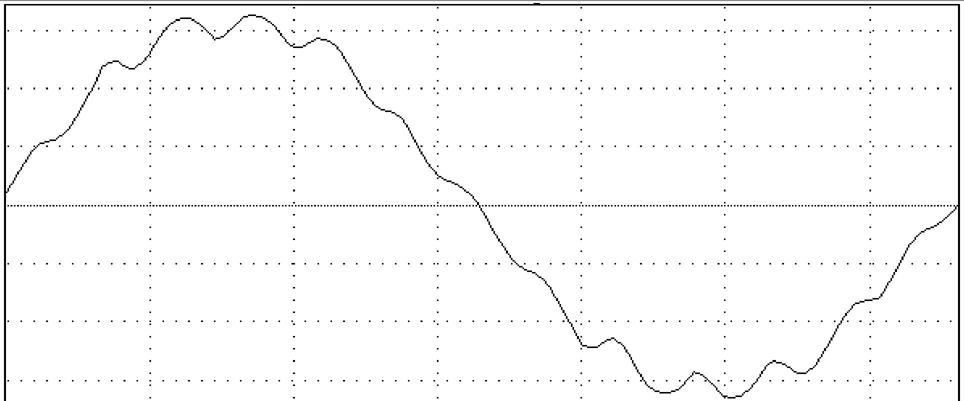


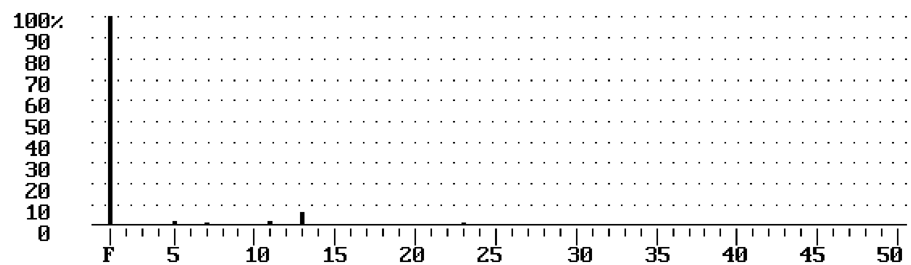


HARMONIC NUMBER:	50	4th:	104.7%	Phase:	109 degrees
TOTAL HARMONIC DISTORTION:	104.8%	3rd:	3.8%	Phase:	174 degrees
ODD CONTRIBUTION:	5.0%	5th:	2.9%	Phase:	107 degrees
EVEN CONTRIBUTION:	104.7%	7th:	1.2%	Phase:	128 degrees

Fnd:	2.16A	147 deg	18th:	0.2%	31 deg	35th:	0.1%	100 deg
2nd:	0.3%	237 deg	19th:	0.1%	138 deg	36th:	0.1%	145 deg
3rd:	3.8%	174 deg	20th:	0.1%	180 deg	37th:	0.1%	162 deg
4th:	104.7%	109 deg	21st:	0.1%	342 deg	38th:	0.1%	313 deg
5th:	2.9%	107 deg	22nd:	0.1%	15 deg	39th:	0.1%	228 deg
6th:	1.2%	50 deg	23rd:	0.1%	88 deg	40th:	0.0%	76 deg
7th:	1.2%	128 deg	24th:	0.1%	7 deg	41st:	0.1%	264 deg
8th:	0.4%	45 deg	25th:	0.1%	181 deg	42nd:	0.0%	116 deg
9th:	0.7%	353 deg	26th:	0.1%	88 deg	43rd:	0.0%	143 deg
10th:	0.4%	28 deg	27th:	0.1%	57 deg	44th:	0.1%	287 deg
11th:	0.2%	299 deg	28th:	0.1%	242 deg	45th:	0.1%	105 deg
12th:	0.3%	358 deg	29th:	0.0%	85 deg	46th:	0.0%	55 deg
13th:	0.0%	241 deg	30th:	0.1%	56 deg	47th:	0.1%	50 deg
14th:	0.0%	73 deg	31st:	0.1%	123 deg	48th:	0.1%	17 deg
15th:	0.0%	299 deg	32nd:	0.1%	164 deg	49th:	0.1%	200 deg
16th:	0.1%	91 deg	33rd:	0.1%	292 deg	50th:	0.1%	194 deg
17th:	0.2%	196 deg	34th:	0.1%	241 deg			

Parallel Resonant Example
13th Harmonic Voltage





HARMONIC NUMBER:	50	13th:	6.0% Phase: 126 degrees
TOTAL HARMONIC DISTORTION:	6.7%	11th:	2.0% Phase: 340 degrees
ODD CONTRIBUTION:	6.7%	5th:	1.5% Phase: 238 degrees
EVEN CONTRIBUTION:	0.7%	7th:	1.0% Phase: 136 degrees

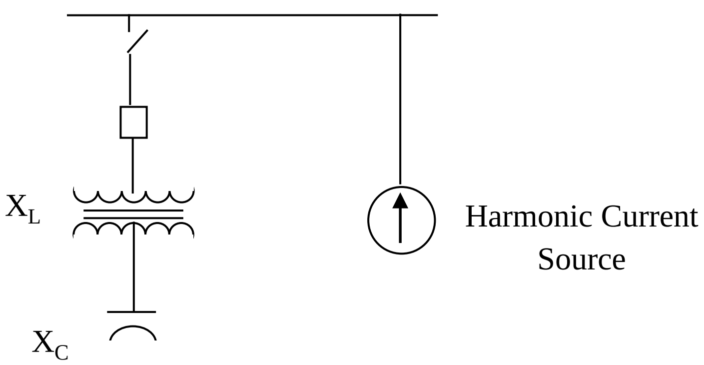
Fnd:	111.87V	85 deg	18th:	0.1%	160 deg	35th:	0.0%	126 deg
2nd:	0.0%	174 deg	19th:	0.4%	352 deg	36th:	0.0%	60 deg
3rd:	0.1%	33 deg	20th:	0.0%	150 deg	37th:	0.0%	141 deg
4th:	0.1%	178 deg	21st:	0.1%	95 deg	38th:	0.0%	11 deg
5th:	1.5%	238 deg	22nd:	0.0%	40 deg	39th:	0.1%	328 deg
6th:	0.5%	331 deg	23rd:	0.8%	196 deg	40th:	0.0%	251 deg
7th:	1.0%	136 deg	24th:	0.0%	122 deg	41st:	0.1%	53 deg
8th:	0.3%	12 deg	25th:	0.5%	333 deg	42nd:	0.0%	26 deg
9th:	0.1%	341 deg	26th:	0.0%	272 deg	43rd:	0.0%	46 deg
10th:	0.0%	98 deg	27th:	0.1%	135 deg	44th:	0.0%	149 deg
11th:	2.0%	340 deg	28th:	0.1%	354 deg	45th:	0.1%	162 deg
12th:	0.4%	197 deg	29th:	0.2%	348 deg	46th:	0.0%	166 deg
13th:	6.0%	126 deg	30th:	0.0%	262 deg	47th:	0.1%	236 deg
14th:	0.1%	91 deg	31st:	0.1%	95 deg	48th:	0.0%	348 deg
15th:	0.3%	64 deg	32nd:	0.0%	21 deg	49th:	0.1%	308 deg
16th:	0.1%	284 deg	33rd:	0.0%	185 deg	50th:	0.0%	352 deg
17th:	0.5%	305 deg	34th:	0.0%	75 deg			

Series Resonance – “Accidental Filter”

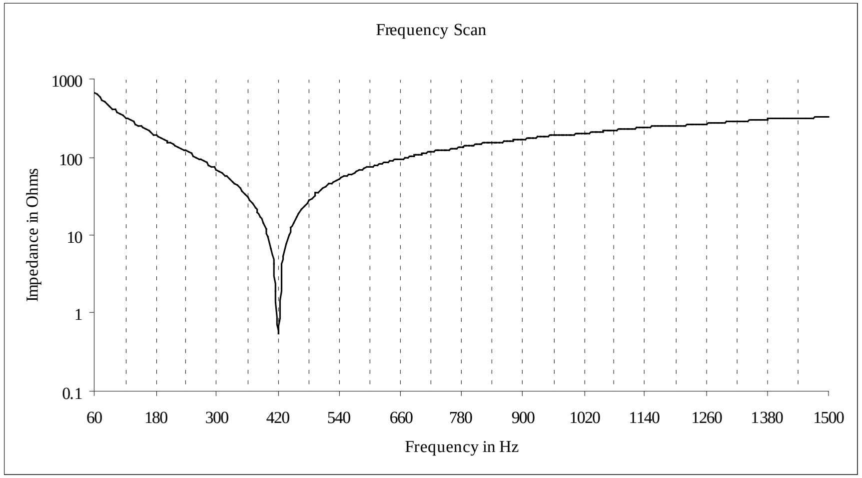
The series combination of impedance is:

$$X_{EQUIVALENT} = jX_L + (-j)X_C$$

Since XL and XC have opposite signs, the summation can equal zero if XL = XC. In reality, the only limiting factor is the difference in resistance between the capacitor and reactor.

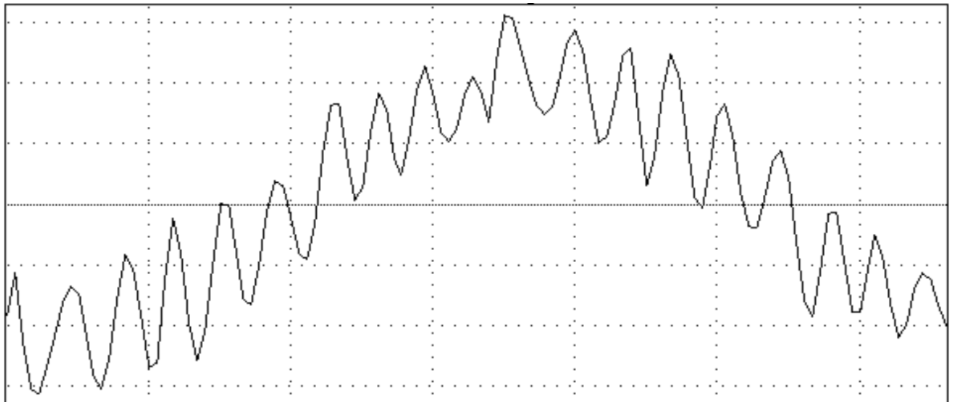


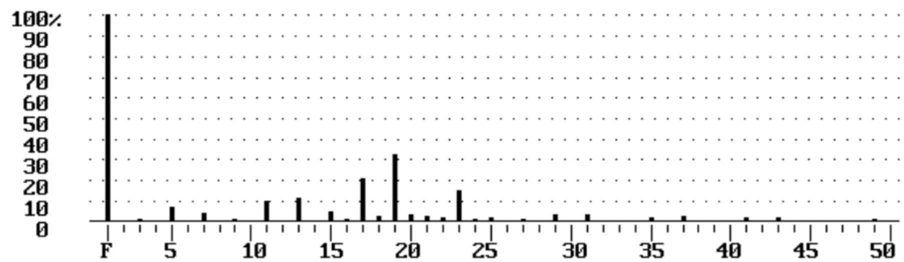
Equivalent Series Resonant Circuit



Frequency Scan for Series Resonant Circuit

Series Resonant Example
19th Harmonic Current



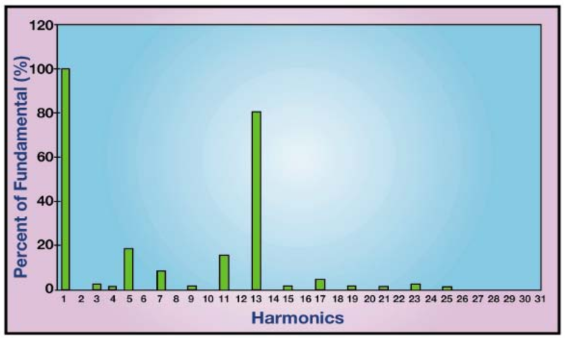


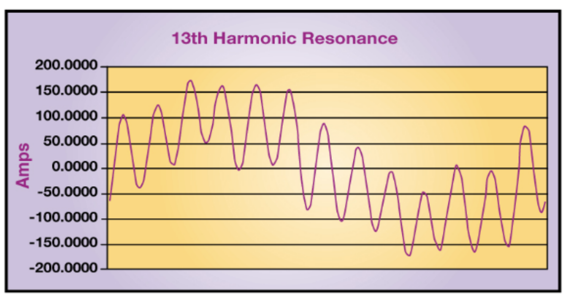
HARMONIC NUMBER:	50	19th:	32.3%	Phase: 142 degrees
TOTAL HARMONIC DISTORTION:	45.5%	17th:	21.0%	Phase: 342 degrees
ODD CONTRIBUTION:	45.3%	23rd:	15.1%	Phase: 32 degrees
EVEN CONTRIBUTION:	4.7%	13th:	10.9%	Phase: 279 degrees

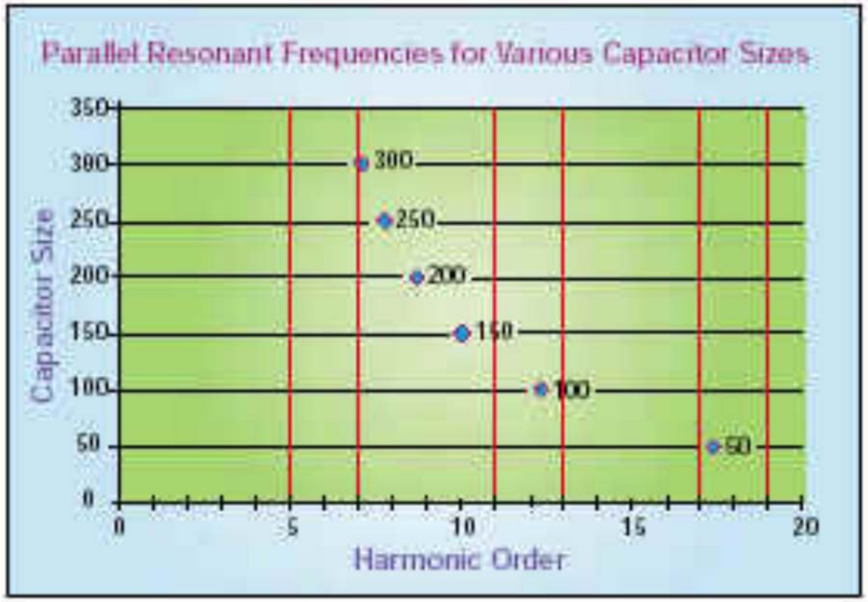
Fnd:	745.71A	201 deg	18th:	2.2%	341 deg	35th:	2.0%	79 deg
2nd:	0.4%	7 deg	19th:	32.3%	142 deg	36th:	0.1%	21 deg
3rd:	0.8%	347 deg	20th:	3.0%	181 deg	37th:	2.3%	128 deg
4th:	0.6%	358 deg	21st:	2.4%	64 deg	38th:	0.3%	122 deg
5th:	6.6%	275 deg	22nd:	1.6%	190 deg	39th:	0.6%	166 deg
6th:	0.3%	353 deg	23rd:	15.1%	32 deg	40th:	0.2%	178 deg
7th:	4.3%	239 deg	24th:	1.0%	61 deg	41st:	1.6%	98 deg
8th:	0.3%	34 deg	25th:	1.4%	80 deg	42nd:	0.1%	121 deg
9th:	0.7%	353 deg	26th:	0.1%	353 deg	43rd:	1.5%	129 deg
10th:	0.5%	26 deg	27th:	0.7%	138 deg	44th:	0.3%	118 deg
11th:	9.5%	277 deg	28th:	0.2%	212 deg	45th:	0.6%	153 deg
12th:	0.5%	26 deg	29th:	3.3%	73 deg	46th:	0.3%	148 deg
13th:	10.9%	279 deg	30th:	0.1%	345 deg	47th:	0.2%	223 deg
14th:	0.6%	338 deg	31st:	3.1%	119 deg	48th:	0.0%	321 deg
15th:	4.5%	17 deg	32nd:	0.3%	110 deg	49th:	0.9%	139 deg
16th:	1.4%	18 deg	33rd:	0.6%	157 deg	50th:	0.2%	138 deg
17th:	21.0%	342 deg	34th:	0.3%	177 deg			

Harmonic Resonance - Solutions

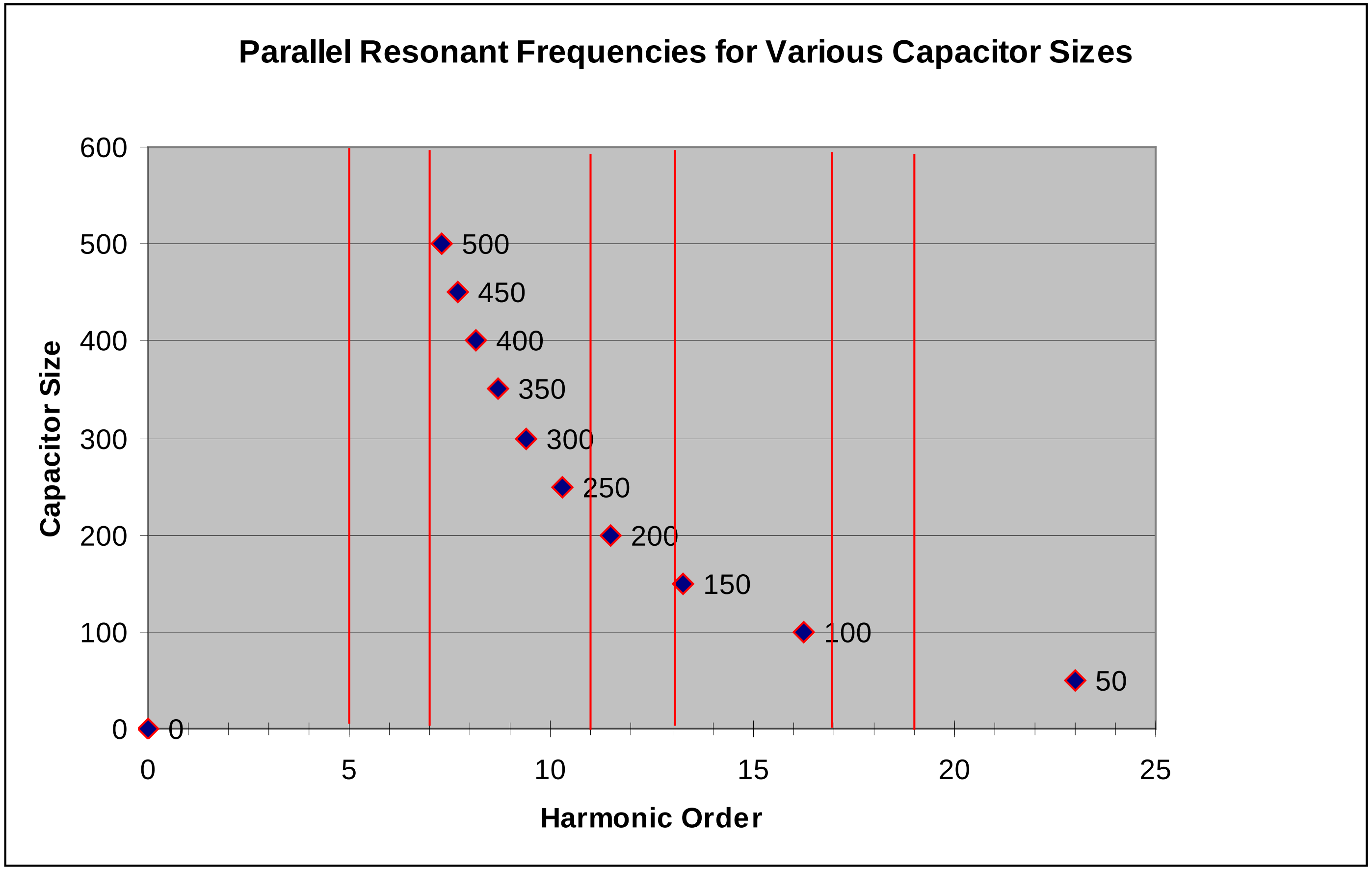
1. **Change the method** of kvar compensation (harmonic filter, active filter, etc.)
2. **Change the size** of the capacitor bank to over-compensate or under-compensate for the required kvar and live with the ramifications (i.e. overvoltage or PF penalty).







Harmonic Resonance Switched Capacitor



Rules of Thumb for Capacitors

Are there harmonics? THDIw/ocap >10% or THDVw/ocap > 3% ?	YES: filtered cap bank NO: standard cap bank
Are there 3rd harmonic currents and is THDI3 > 0.2 THDI5 ?	YES: 2.67 tuned cap NO: 4.2 detuned or 4.7 tuned bank
Is Isc/ IL < 20 ?	Yes : use detuned 3.78 or 4.2 bank NO: use tuned 4.7 bank
Are there any large size VFDs?	Yes : Smallest cap size >40% of largest VFD size
Are there any soft starters	Yes : use filtered cap banks or use standard caps in line with electromechanical bypass with time delay.
Is total cap capacity > 15% of Transformer kVA	Yes : Check for Resonance

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Ferroresonance

Ferroresonance is a special form of resonance which occurs between the magnetizing reactance of a transformer and the system capacitance. Because the state of the magnetizing flux in a transformer may change from cycle to cycle, the resonant waveshape can also change from cycle to cycle.

Ferroresonance is classified as system overvoltage rather than as a harmonic. The waveform is very distorted but a distinct 60 Hz frequency is present. The voltage magnitude can exceed 2.0 per unit and is sustained.

Most Common with Potential Transformers (PT's)

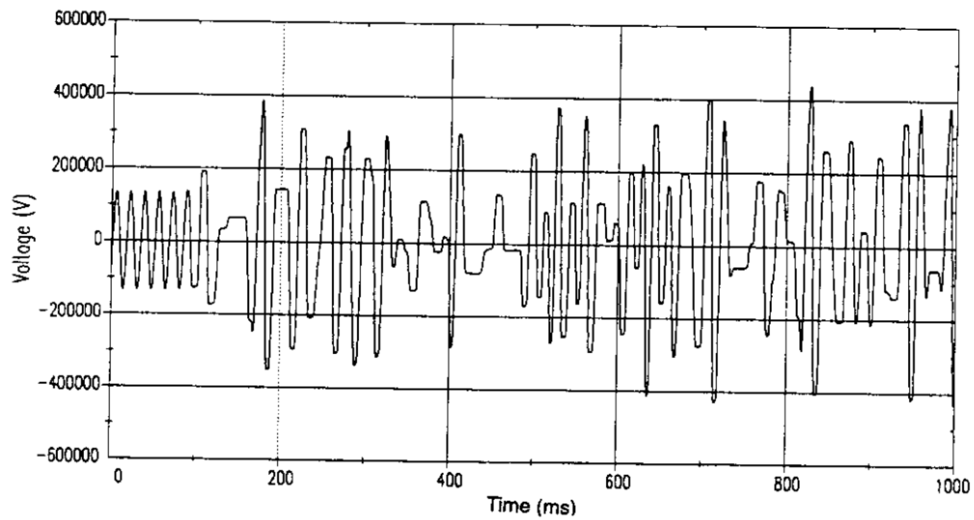
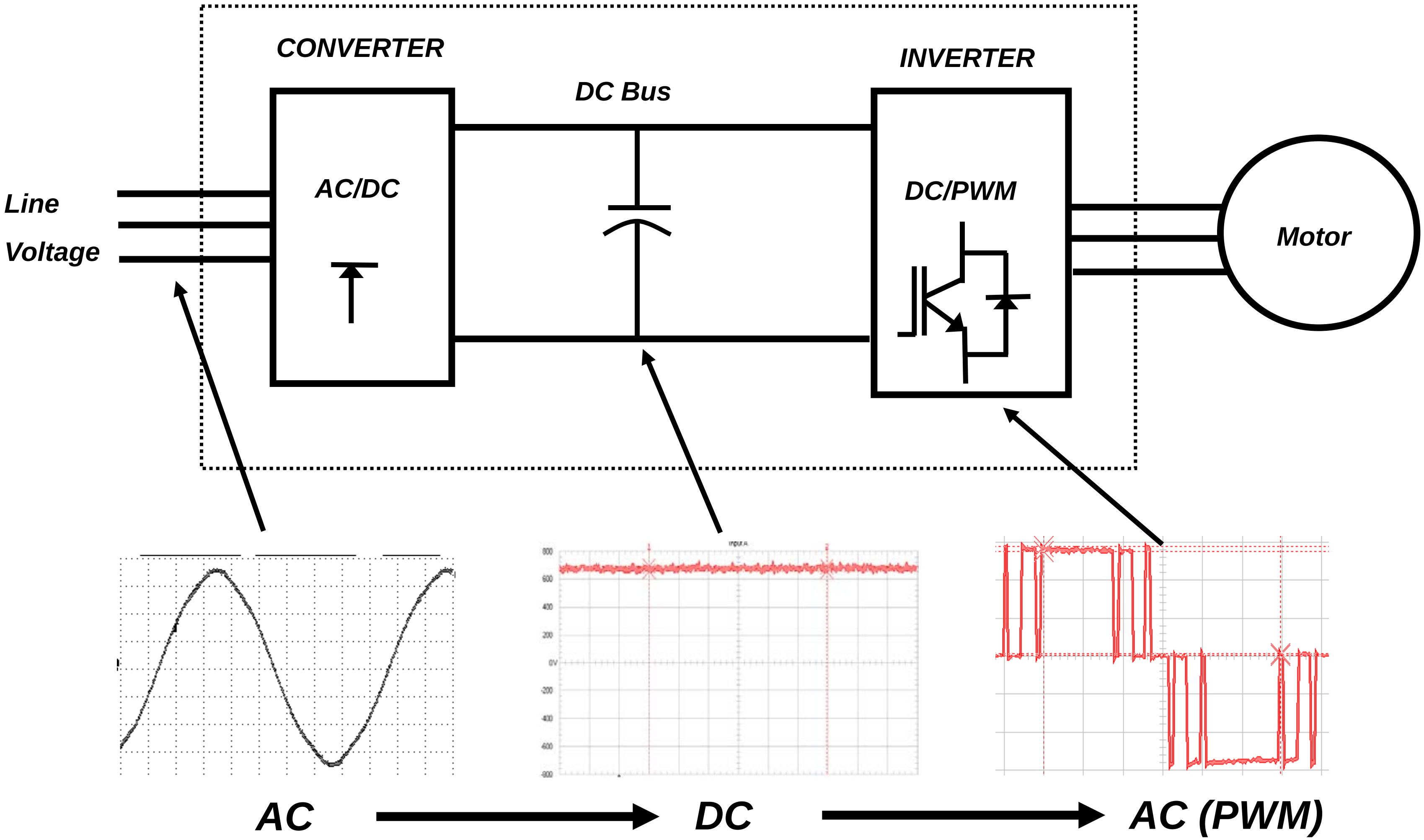


Figure 4—Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer

Harmonic Solutions – Product Mix	Eaton Products	Partner Products	Access to Products
Harmonic Studies and Design	X		
Tuned Filters (LV/MV – Fixed/Switched)	X		
De-Tuned Filters	X		
Harmonically Hardened Capacitors	X		
Active Filters (LV)	X		
Harmonic Mitigating Transformers	X		
K-Factor Transformers	X		
Clean Power (18 Pulse) Drives	X		
3^{rd} Harmonic Blocking Filter			X
Broadband Drive Filters		X	
Line Reactors		X	
Static Switched (Transient Free) Filters	X		
Drive Isolation Transformers	X		
UPS Filter	X		
UPS Active Front End (9390/9395)	X		
Zero Sequence Trap			X
DC Choke (Drives)			X
MV Static VAR Compensator			X
MV 24 Pulse Drives	X		

AC Drive Block Diagram



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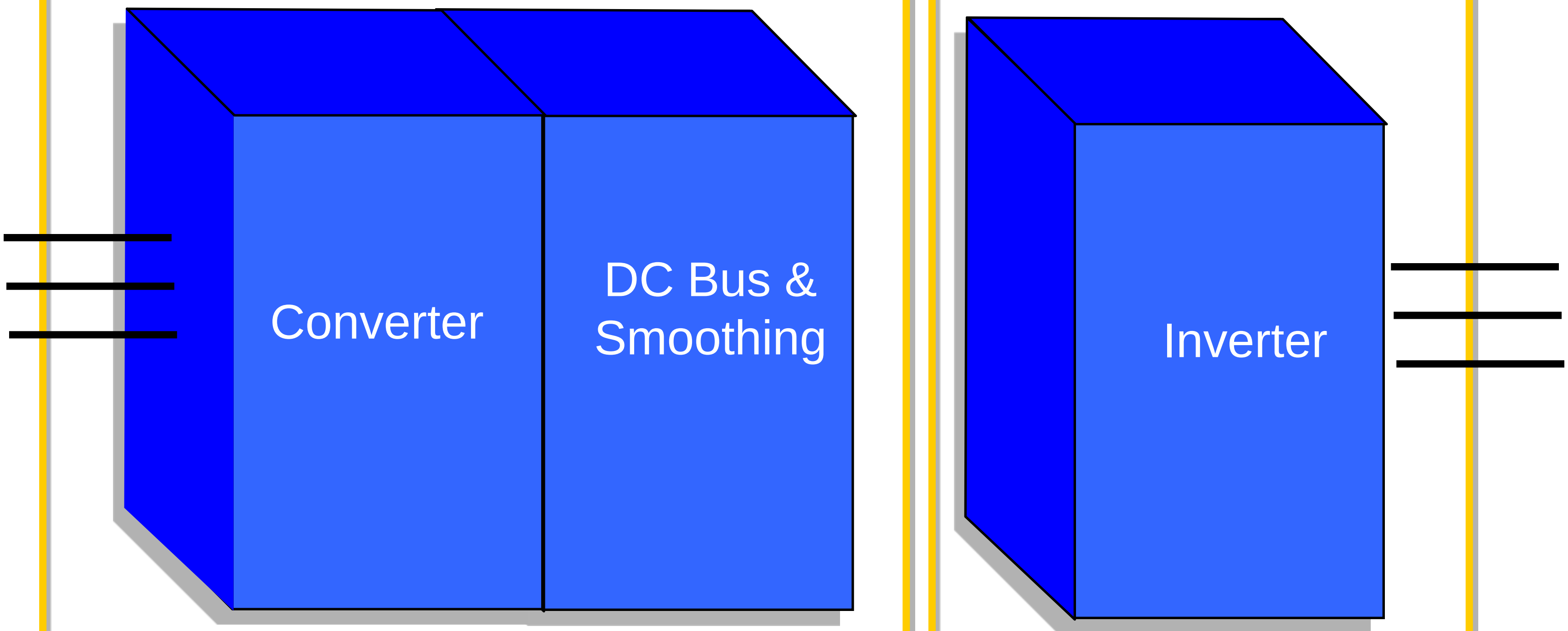
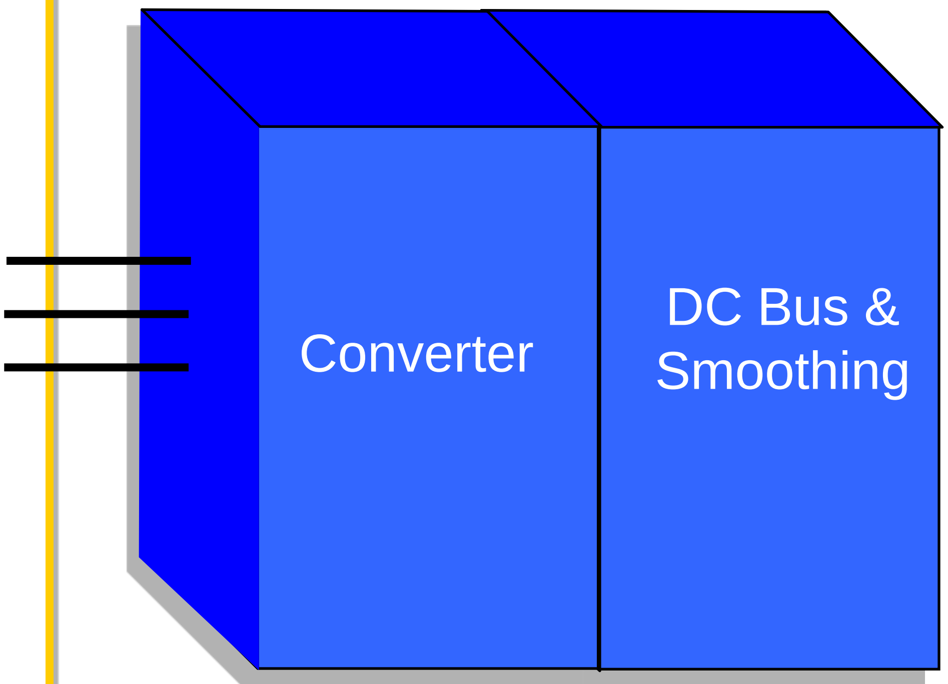
AC Drives and Harmonics



Determine the line-side harmonics

Determines load-side Distortion

AC Drives and Harmonics



Determine the line-side harmonics

Line-side harmonics can have far-reaching effects on the power system:

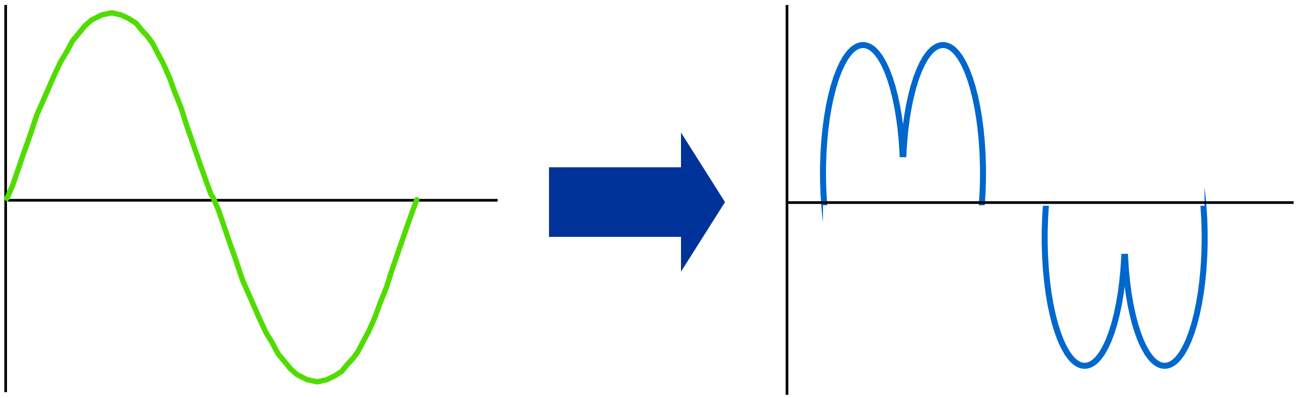
- Distribution transformers
- Standby generators
- Communications equipment
- Switchgear and relays
- Computers, computer systems
- Diagnostic equipment

Who Cares About Harmonics?

- Utilities
- Users
- Maintenance and 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

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

Users

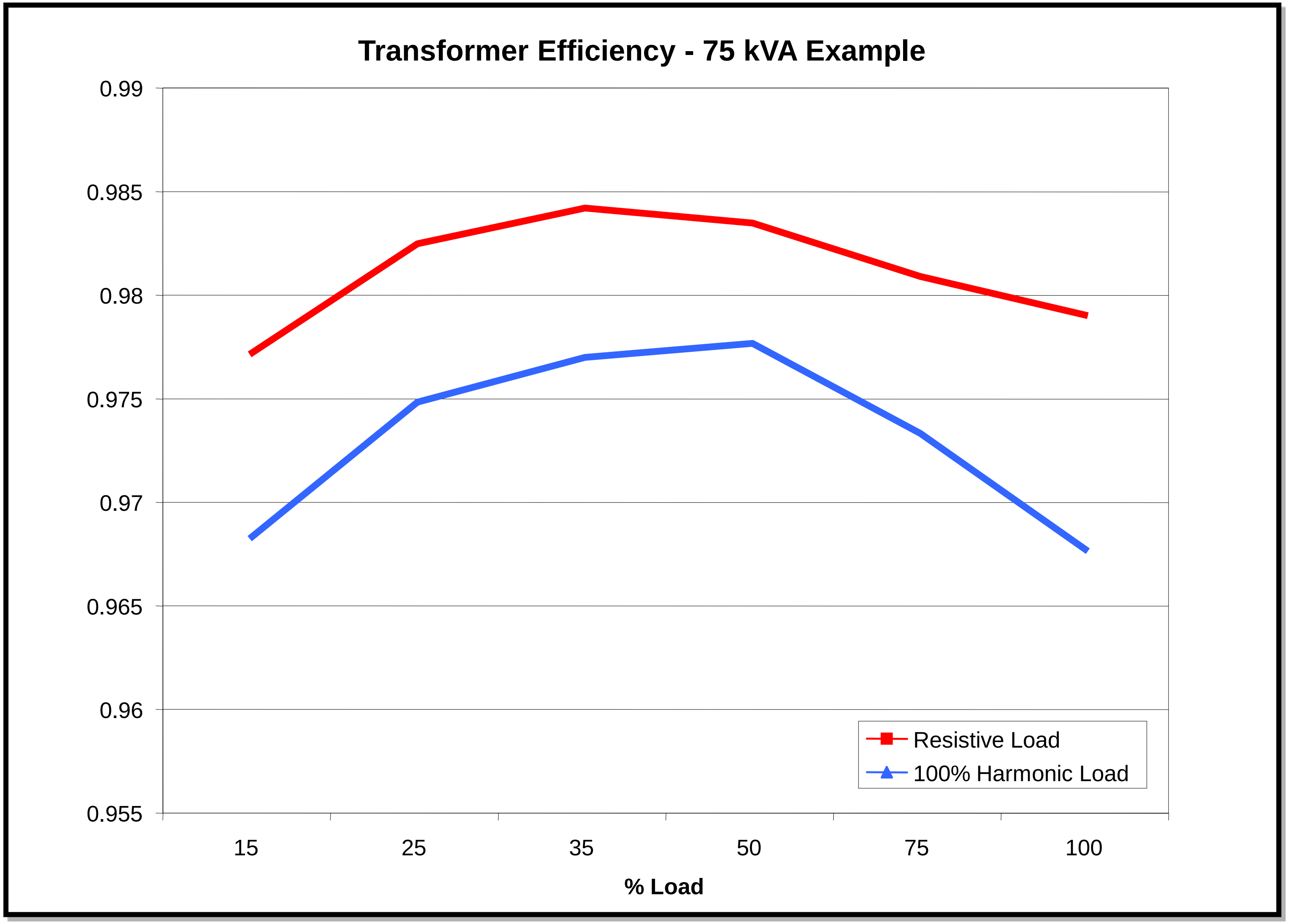
- Control capital expenses
- Needs to be a good citizen in the electrical community via IEEE-519 compliance
- Seek increased uptime and profits
- Want to protect electrical assets
- Work to add value to facilities
- Desire reduced energy expenses

Maintenance and Facility Engineers

Harmonics can have far-reaching effects on the power system:

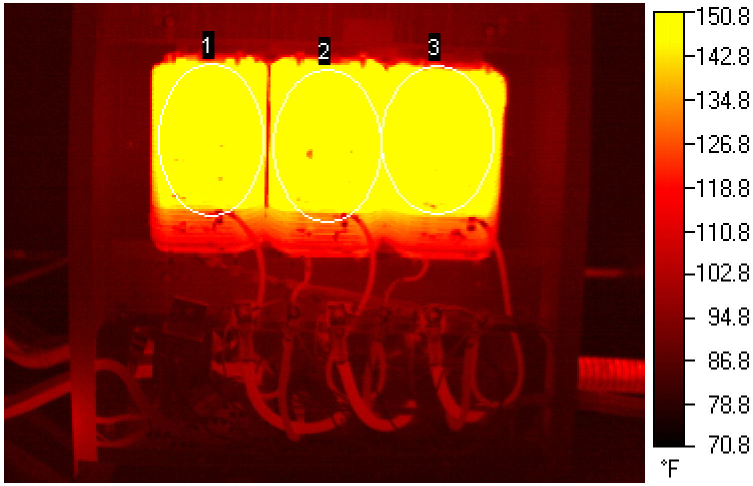
System	Concern
Distribution transformers	Overheating and efficiency loss, leads to Over-sizing and more increased losses
Standby generator	Distortion dramatically reduces capacity, Synch issues with zero crossings for relays
Communications equipment	Downtime and loss of productivity
Computers and computer systems	Nuisance tripping and downtime
Diagnostic equipment	Nuisance tripping and erroneous results
Utility	Charges for harmonic pollution

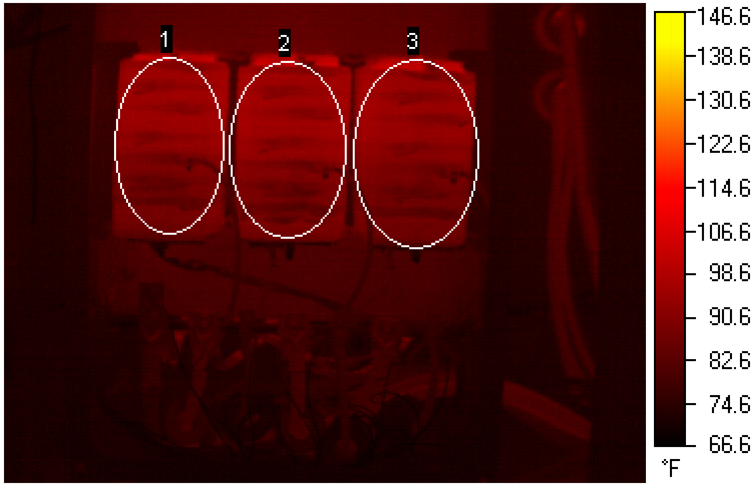
System Inefficiency with Harmonics



Harmonics and Heating

Load 100% Harmonics

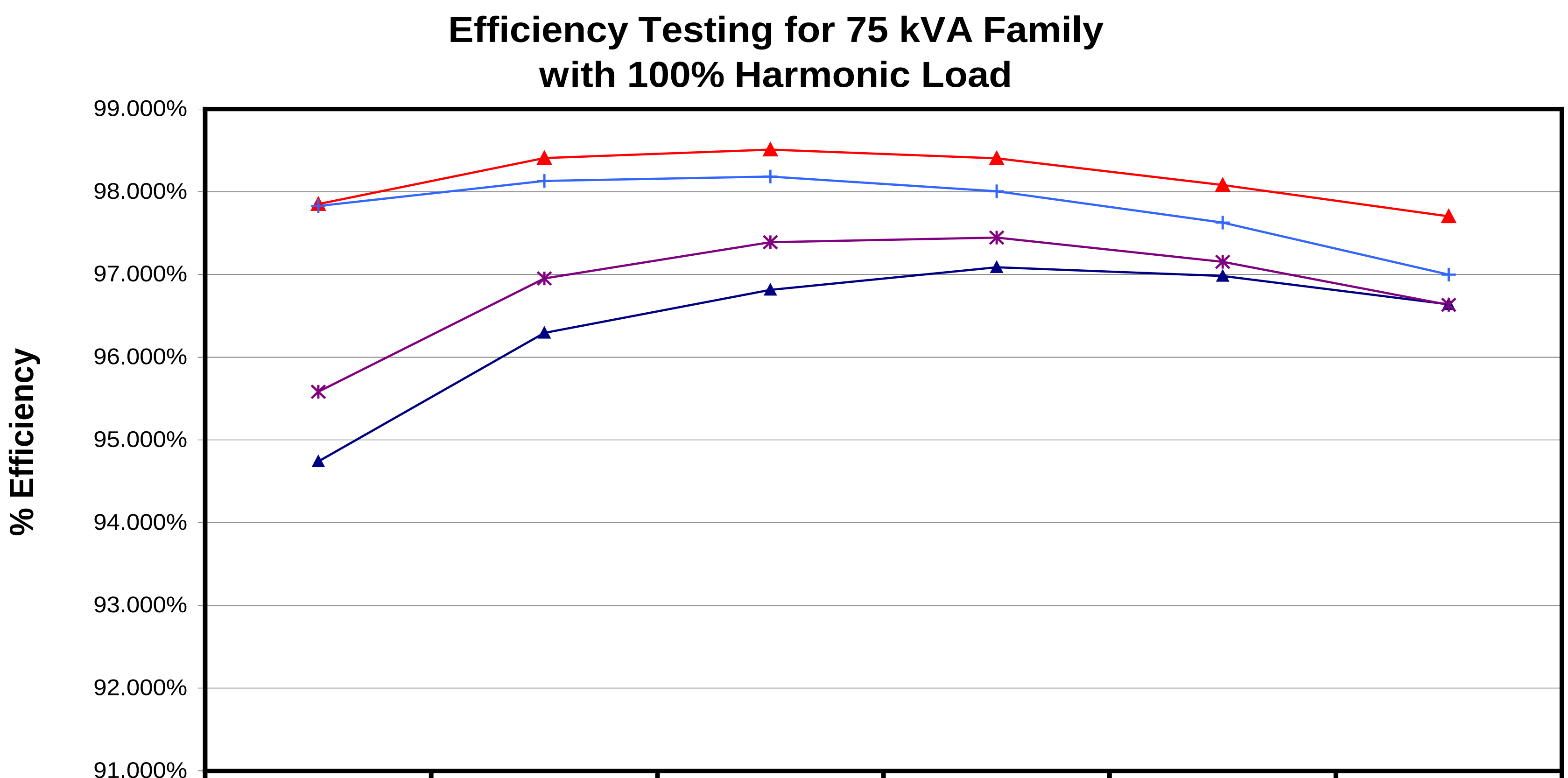




Std Transformer – Max Temp – 176 F

HMT – Max Temp – 105 F

Transformer Family Testing –
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%

Nominal % of Full Load

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What Will It Take?

- Begin with a facility analysis
- Then interpret the IEEE-519 as it applies to your facility
- Now select the most cost effective harmonic mitigation technique
- Finally, be sure to analyze the proposed facility design again and celebrate the cost savings and increased efficiency of optimum harmonic mitigation

Facility Analysis

- May be as simple as making a determination of the ratio of drive load to the capacity of the utility transformer (harmonic dilution)
  - If 10% or less, no problem
  - If 10 – 20%, conduct a harmonic analysis study
  - If above 20%, mitigation required
- When further study is required, a system analysis service can recommend cost effective harmonic mitigation solutions based on a facility single line diagram.

How to Eliminate Harmonics

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

- Passive filters
- Additional inductive reactance
- Phase-shifted sources
- 12 pulse converters
- Active filters
- The 18 Pulse Clean Power converter
- 24 Pulse MV Drives

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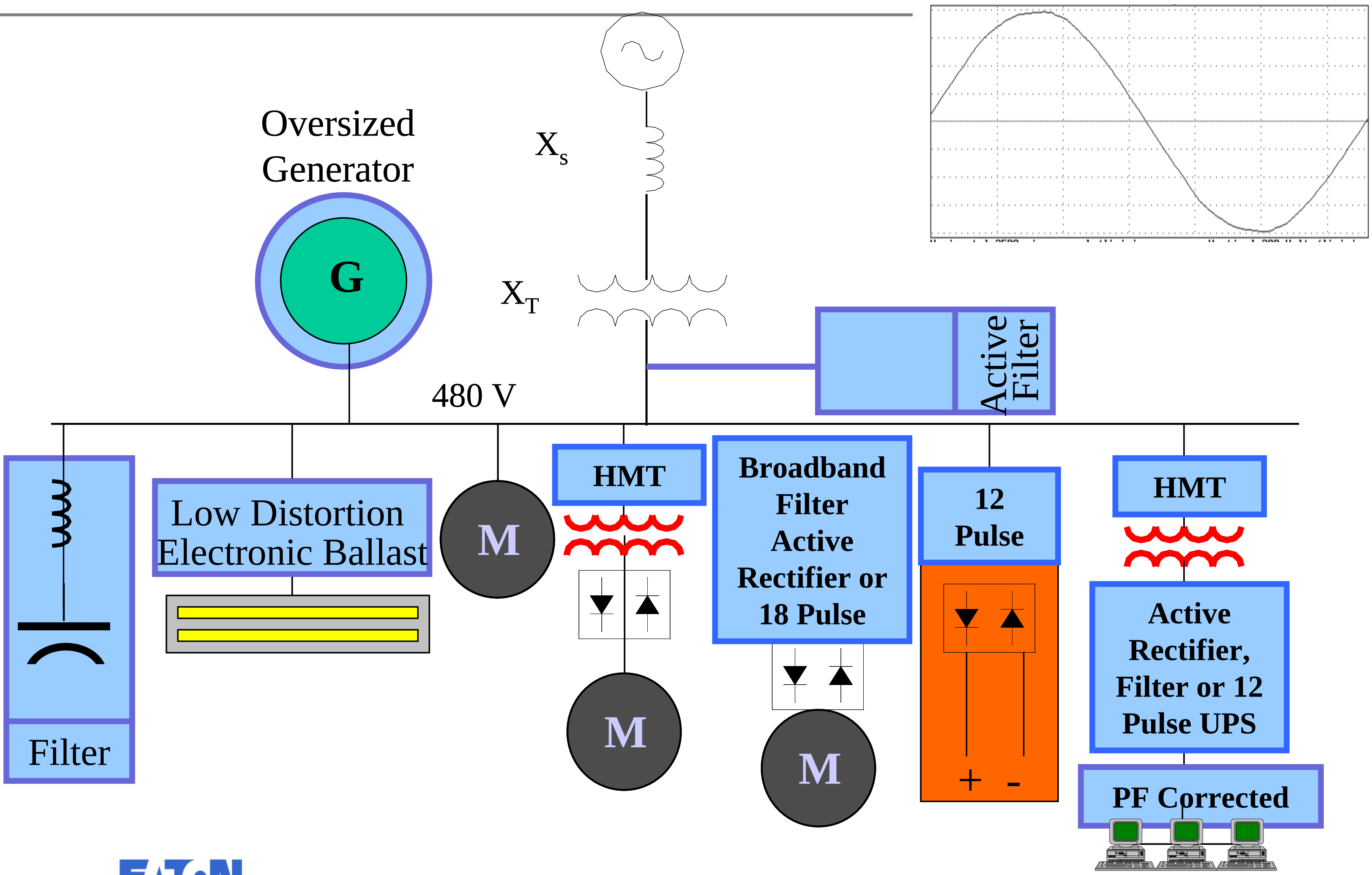
Harmonic Solutions

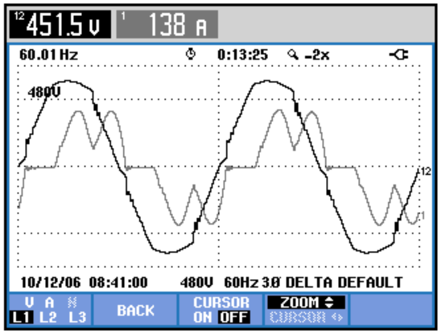


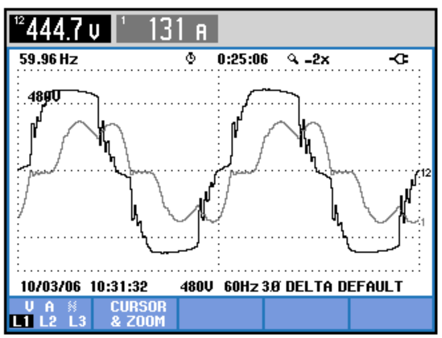
Harmonic Solutions - Commercial

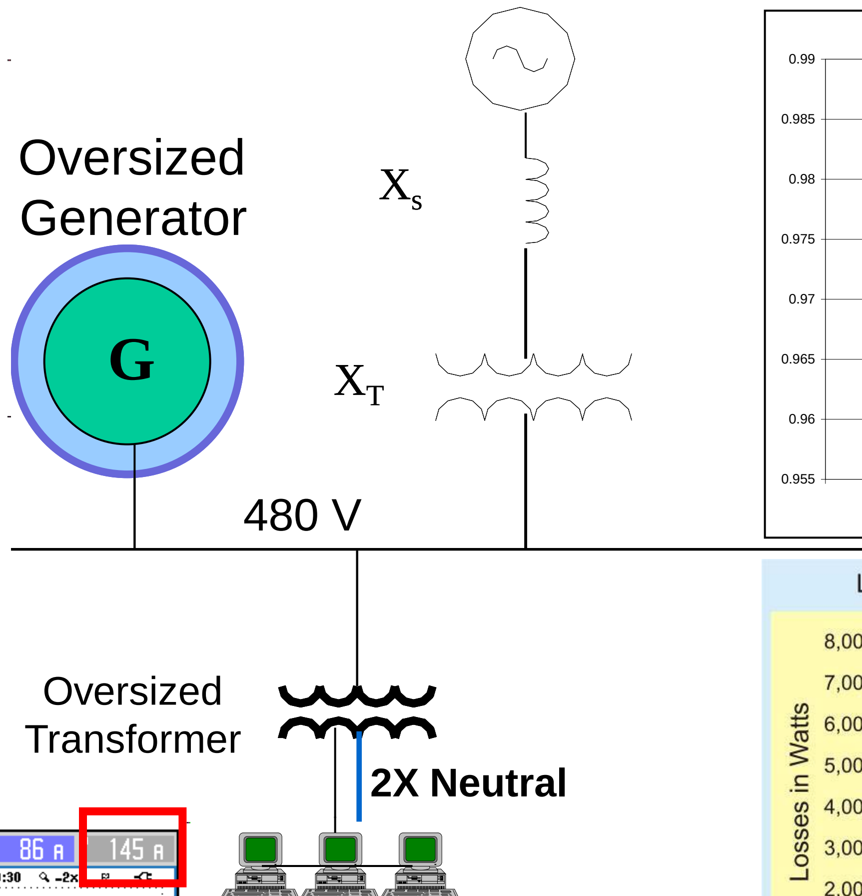
Commercial Power Systems (and Data Centers)

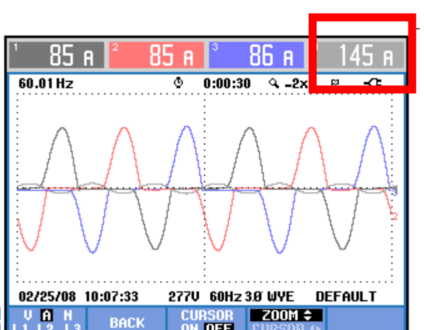
- Oversized Equipment (generator, transformers, neutrals)
- K-Rated Transformers
- Harmonic Mitigating Transformers
- 3rd Harmonic Blocking Filter
- Harmonic Filters (required for PF Correction)
- UPS Filter
- Low Distortion Loads
  - UPS Active Rectifier
  - PF Corrected Power Supplies
  - Low Distortion Lighting Ballasts

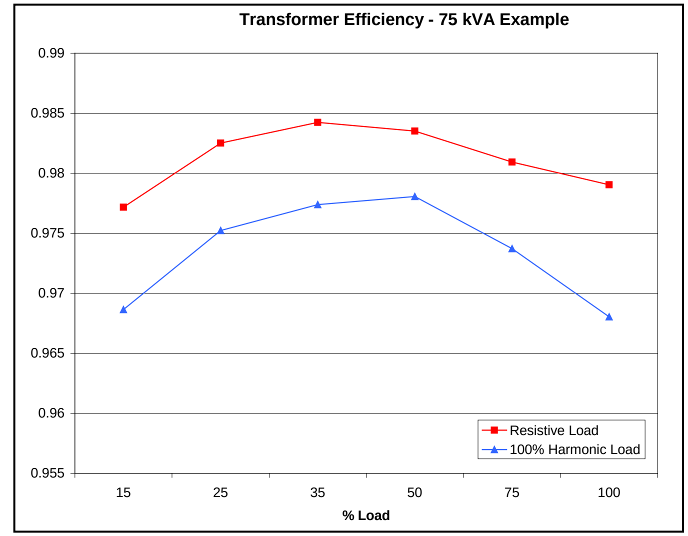
Oversized Equipment

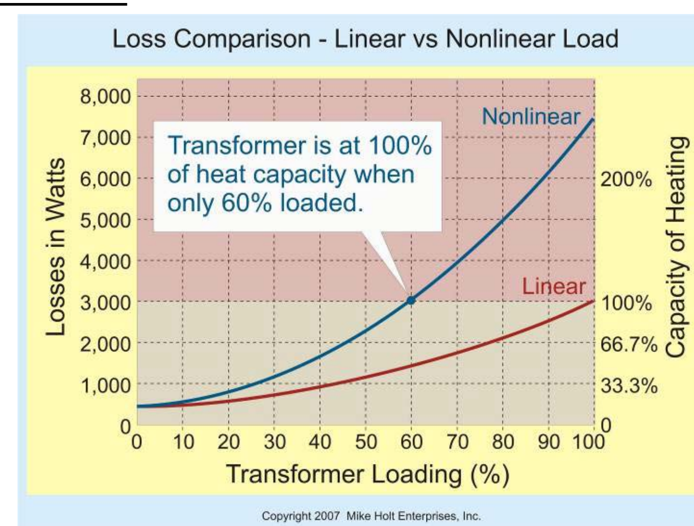




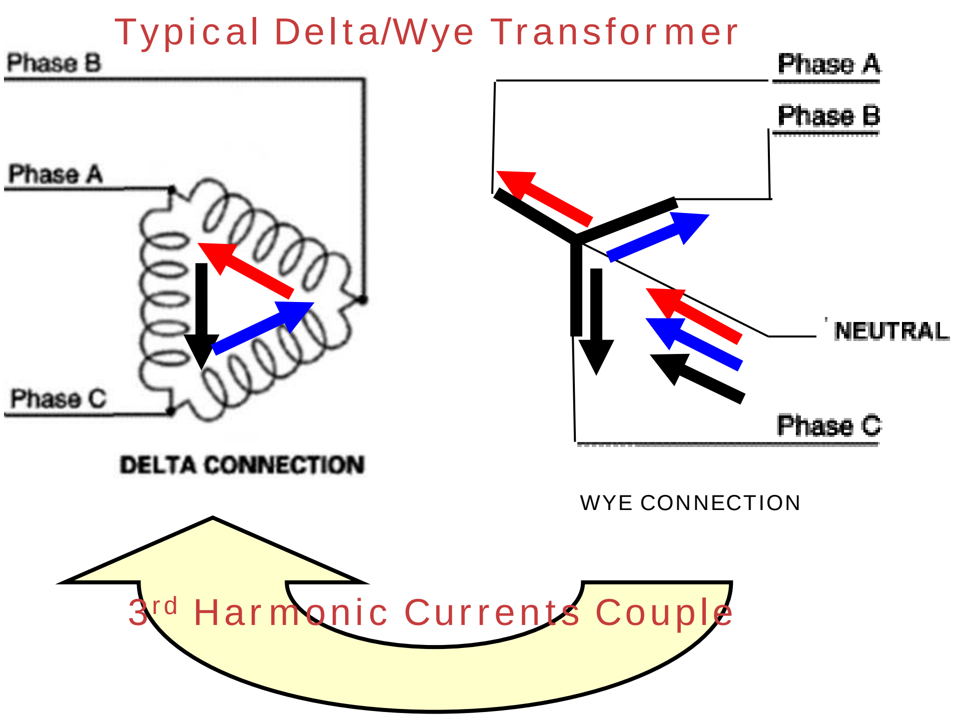




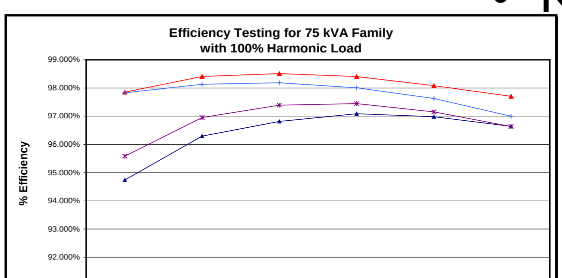




Standard and K-Rated Transformers



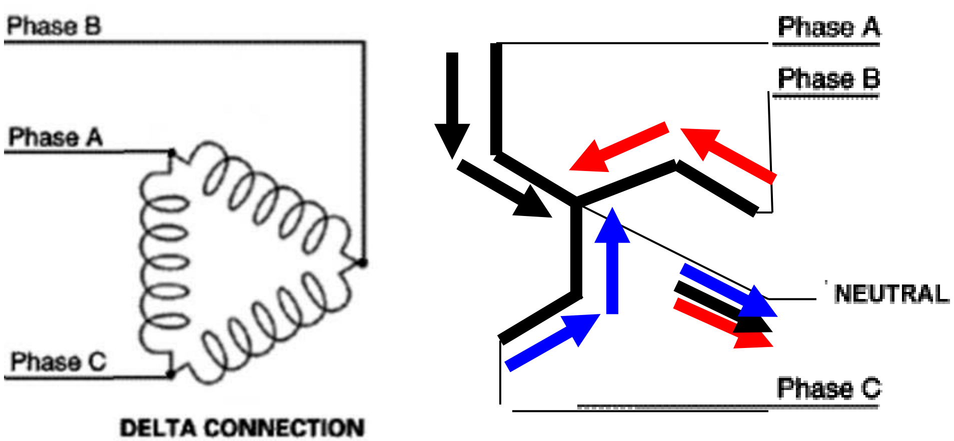
- 3rd harmonic current flowing in the phases adds up in neutral.
- On primary, 3rd current is trapped in delta if balanced. Otherwise, the difference flows in the phases.
- Balanced 3rd currents are called "triplen" harmonics (3rd, 9th, etc.)
- Delta-wye transformers are said to "trap" triplen harmonics in delta. They do not eliminate other harmonics.
- K-rated are typically delta-wye.
  - K-4 – Drives
  - K-13 – Computer Loads
  - > K-13 (K-20, etc.) – Overkill
  - Historically, K-rated = low 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%

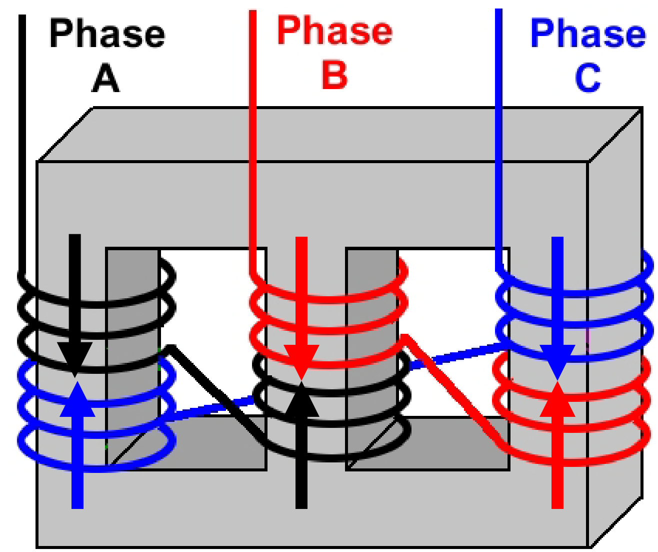
Secondary Treatment of Triplens (HMT's)

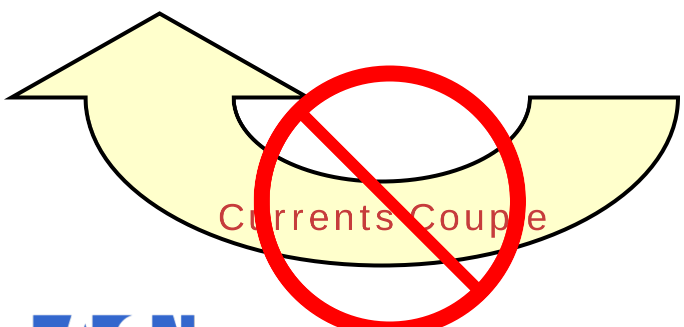
Harmonic Mitigating Transformer (HMT)



ZIG-ZAG CONNECTION

HMT Secondary

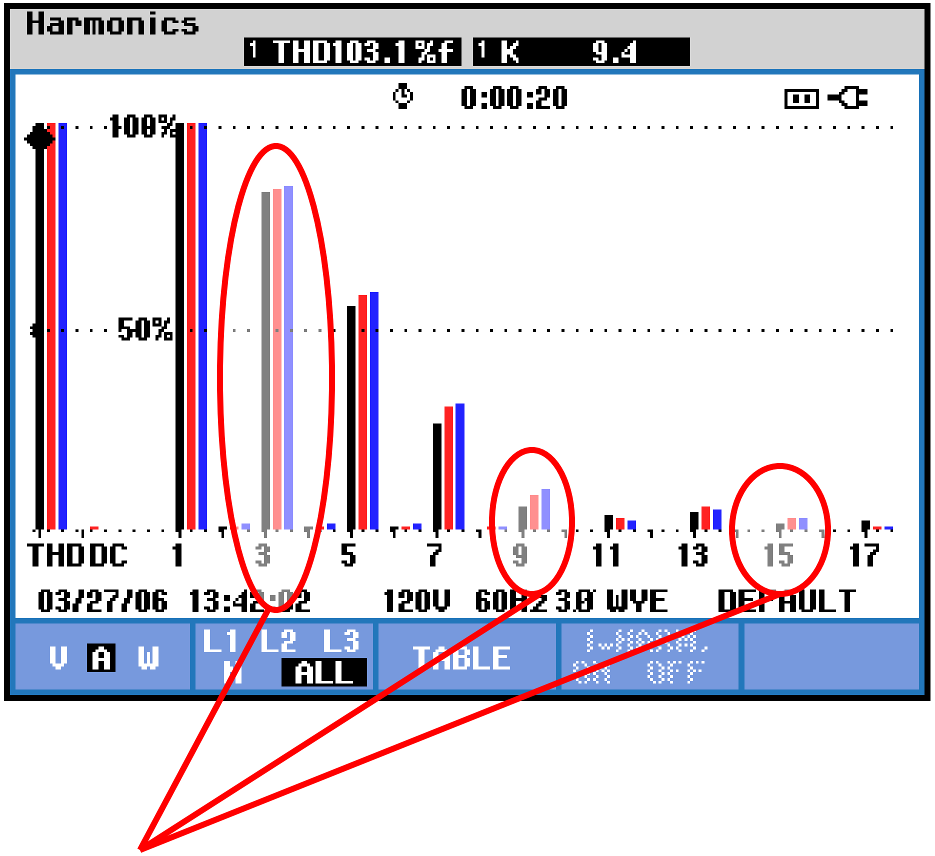




- Opposing magnetic fields – *triplens* aren't magnetically coupled to primary
- Loads continue to operate as designed
- Minimizing impact on electrical infrastructure

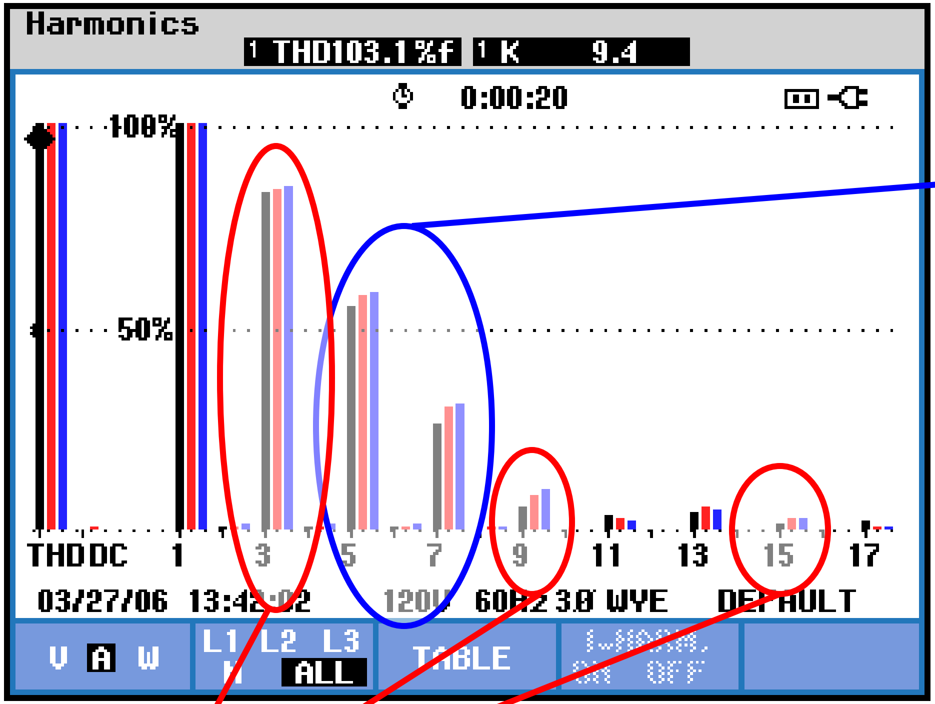
Harmonic Mitigating Transformers

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



Triplen Harmonics

Harmonic Mitigating Transformers



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

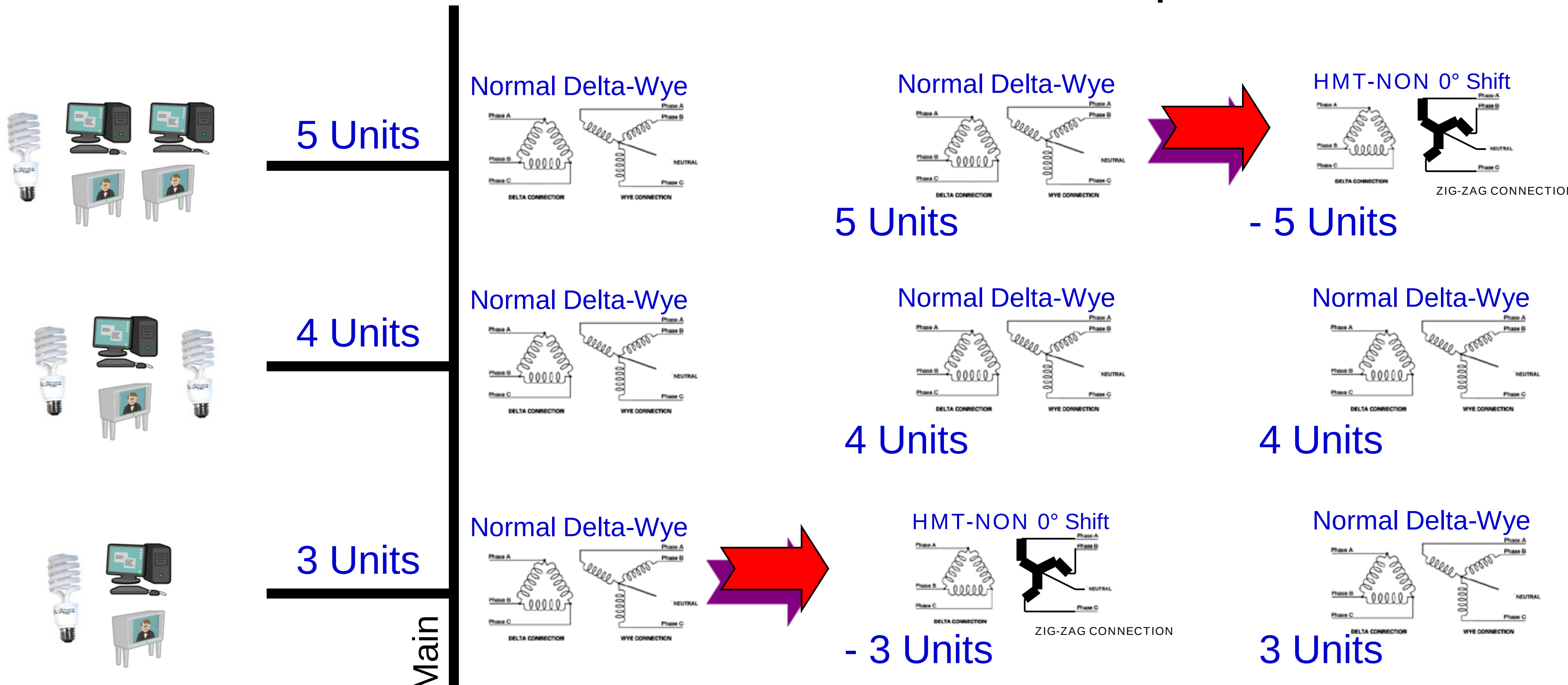
5^{th} & 7^{th} harmonics

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

Triplen Harmonics

HMT 5th and 7th Cancellation

Say we have a three story building with a variety of loading. How much 5th and 7th cancellation can we expect?



Case 1
5+ 4+ 3= **12 Units**

Case 2
5+ 4 **-** 3= **6 Units**

Case 3
- 5+ 4 +3= **2 Units**

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!
- Similar thinking to using a Compact Fluorescent vs. Incandescent Lamp
- ***Most appropriate for New Construction***

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Harmonic Filter (PF Correction)

Commercial facilities requiring PF correction for utility penalties often use one of the following compensation methods:

- PF Capacitors (standard or switched) – risk of harmonic resonance
- “Harmonically hardened” capacitors – like “K-rated” transformer
- Harmonic Filter
  - Tuned – to reduce overall harmonic distortion (typically 4.7^{th} “tuning”)
  - De-tuned – to avoid resonance (typically 4.2^{nd} “tuning”)
- Active Harmonic Filter (both harmonic compensation and PF correction)

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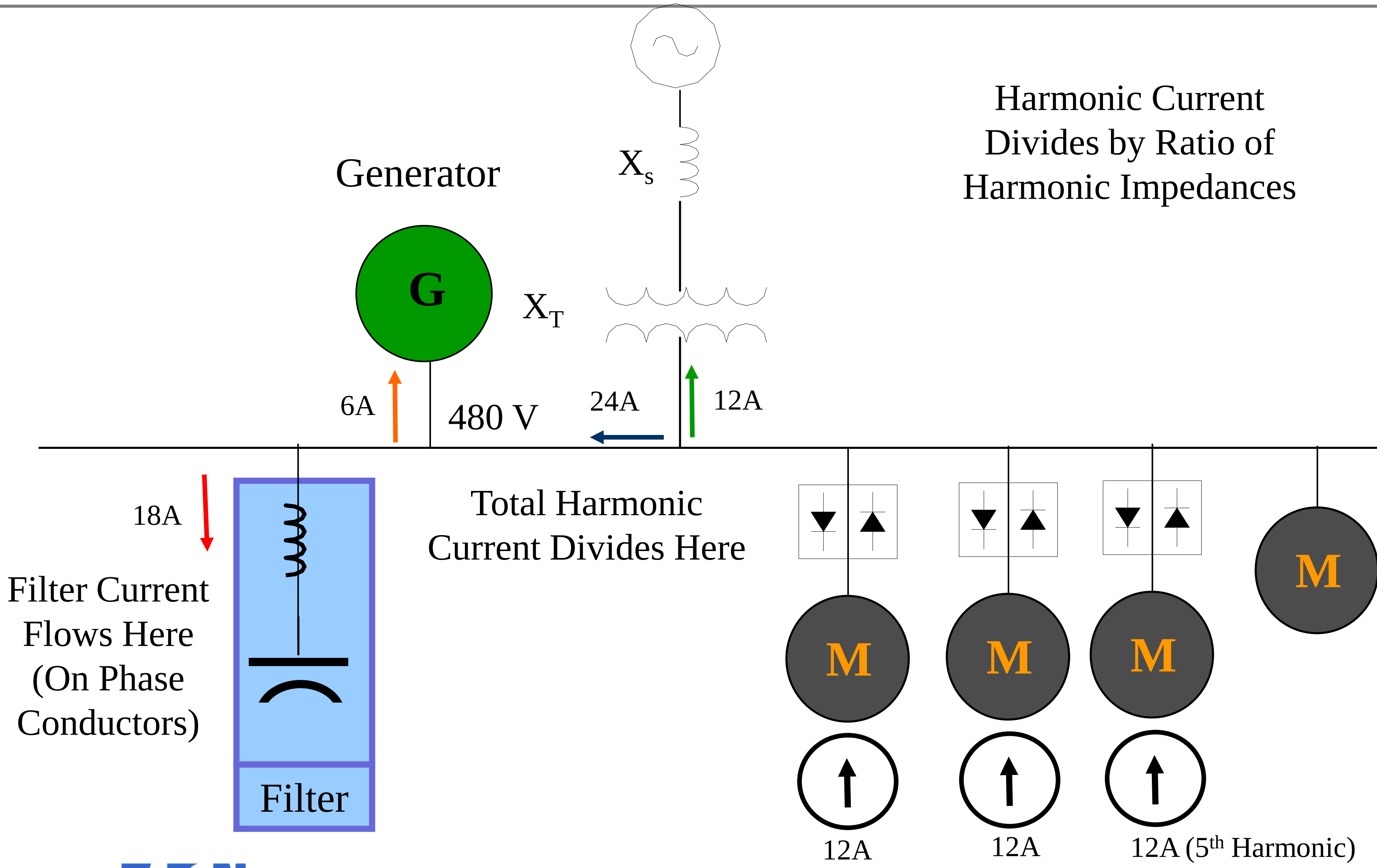
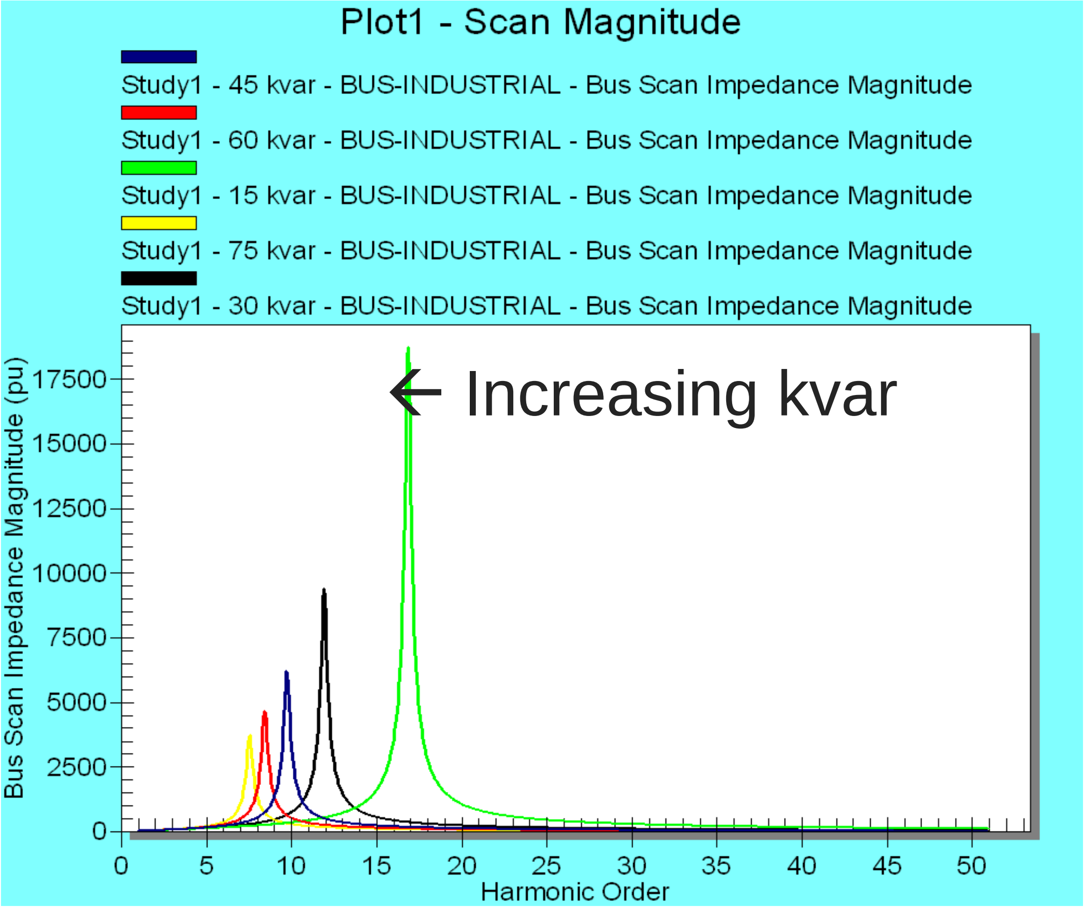
How Does a Filter Work?



Computer Simulation/Modeling

Parallel Resonance with Capacitors

Parallel resonance causes “amplification” of harmonic currents and high voltage distortion



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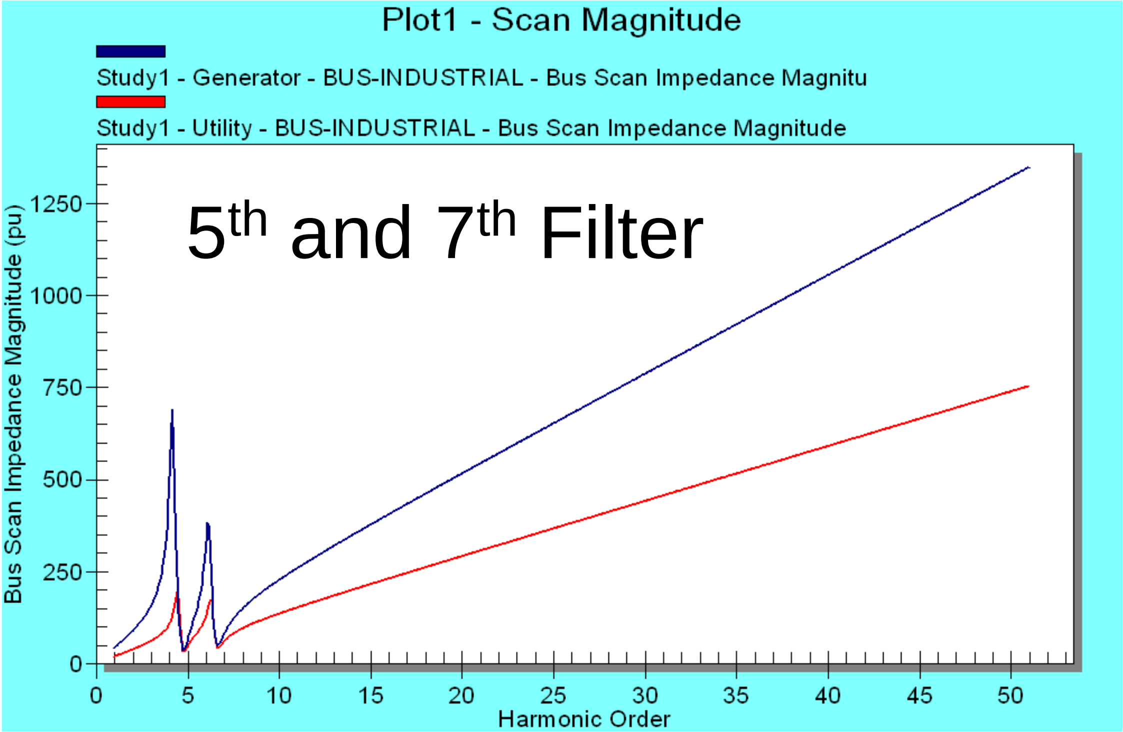
Filter Design Considerations

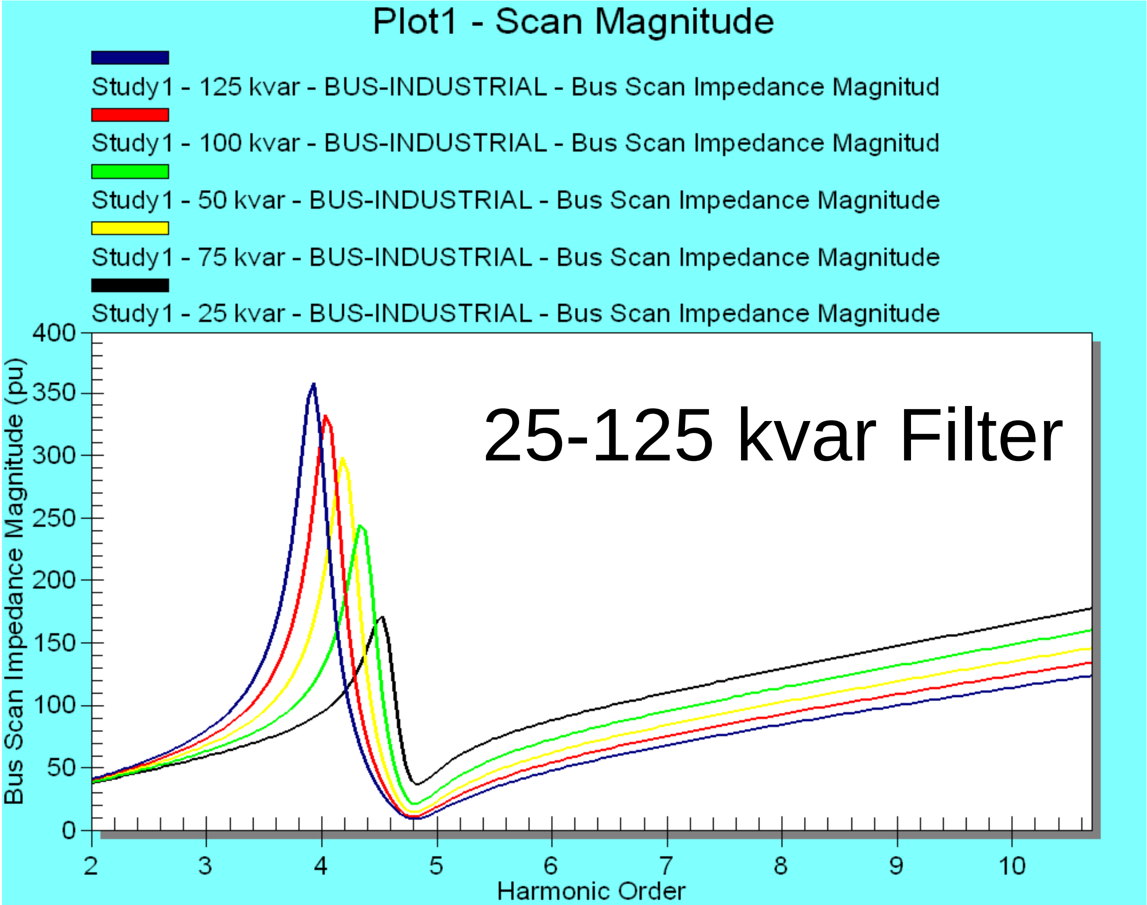
Frequency Scan (Normal and Generator Source)

Filters control resonance, redirect harmonic currents and reduce voltage distortion



Filters Control Parallel Resonance Point

Frequency Scan – Staged Filter



Parallel resonance harmonic is usually about 1 order below the “tuning” frequency

UPS Filter

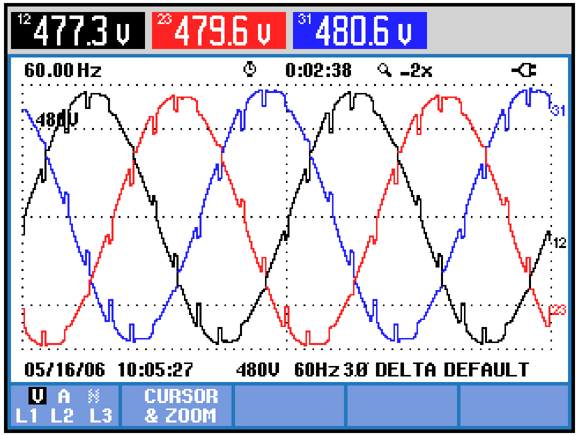
UPS front end (rectifier) tuned filter

- 6-pulse – tuned to 5th
- 12-pulse – tuned to 11th

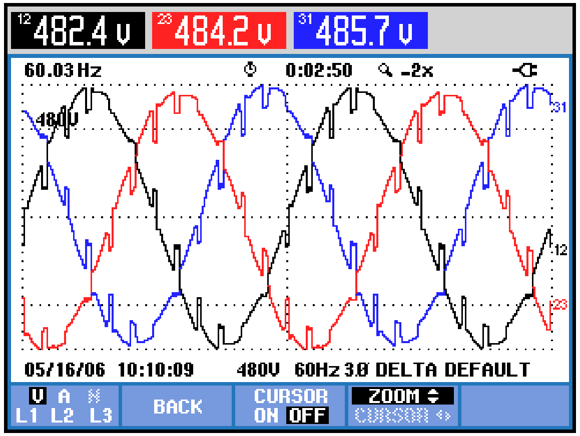
Generally switched on/off at 25-35% load

May be turned off when on generator (avoid leading PF)

Harmonic Filter ON



Harmonic Filter OFF



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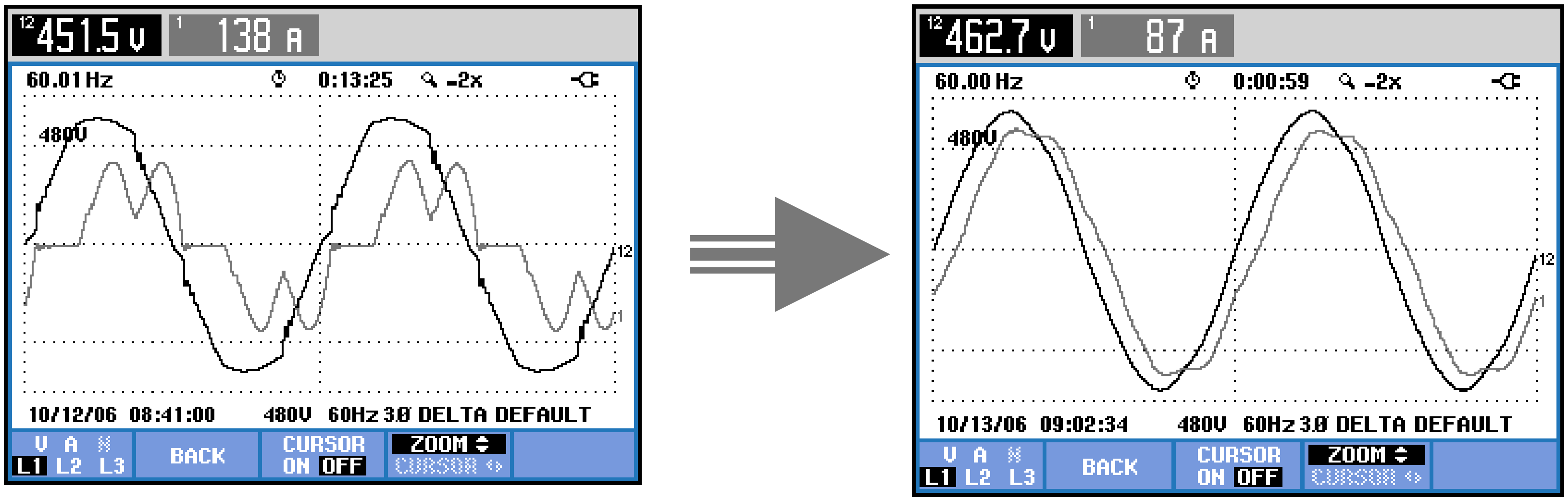
Low Distortion Loads

- Rectifier Solutions – UPS, Drives, Battery Chargers
  - Active front end on UPS (Powerware 9390/9395) and some drives
  - Industry driven toward component (load) solutions

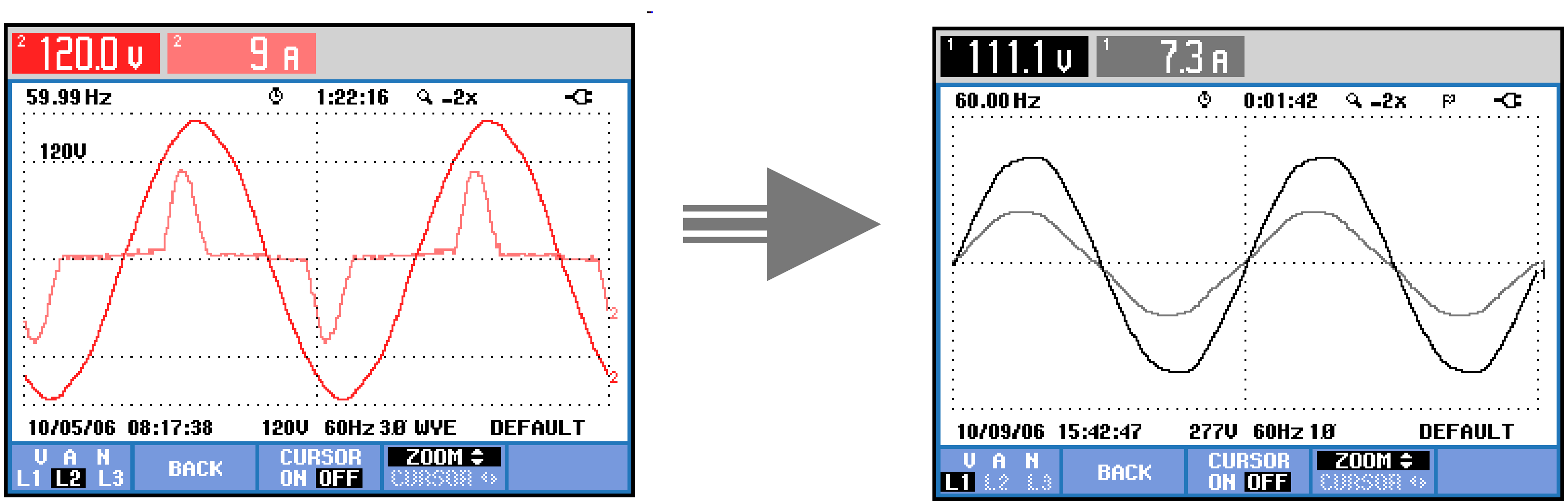


- Generators do not need to be oversized with Active Rectifier UPS

Low Distortion Loads

Data Centers/Servers – PF Corrected (Harmonic Filter)

- Switch Mode Power Supplies (SMPS) have changed over to PF Corrected Power Supplies



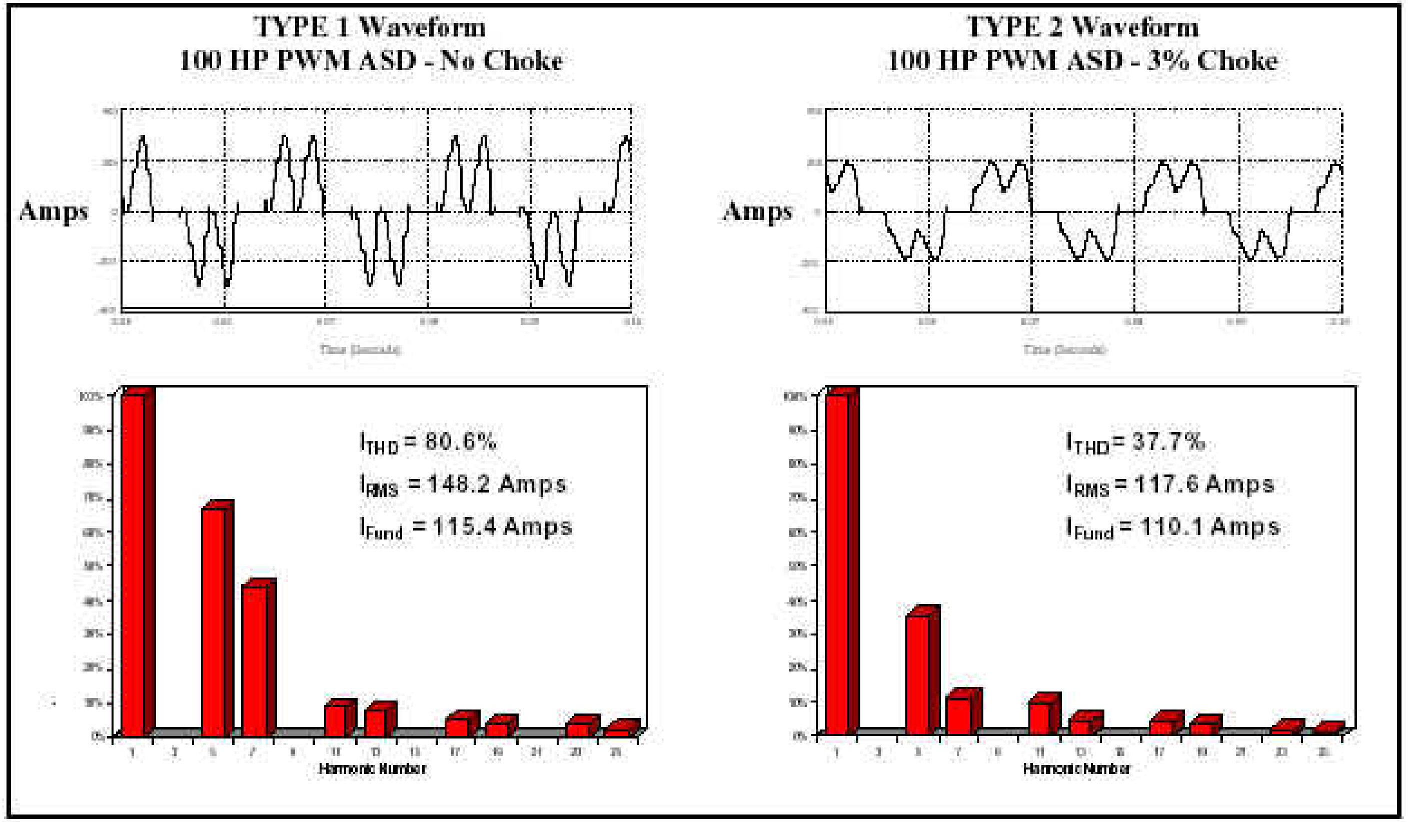
Industry driven toward component (load) solutions

Harmonic Solutions – Industrial

Industrial System (Drives and Rectifiers)

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

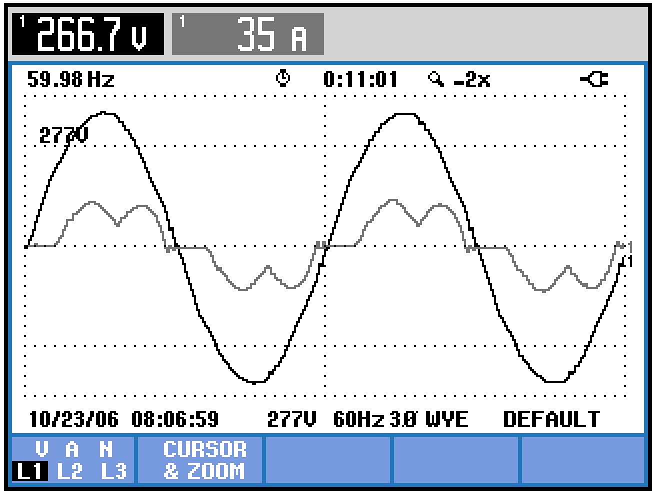
Drive and Rectifier Solutions

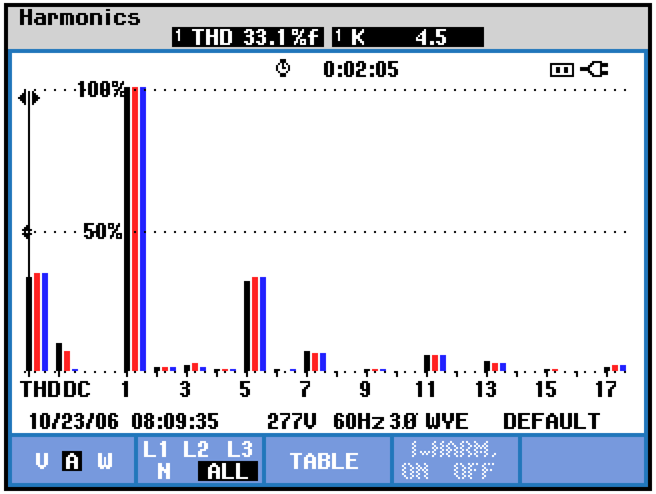


Drive without line reactor   Drive with line reactor

Best "cost/kVA" solution for drive harmonics

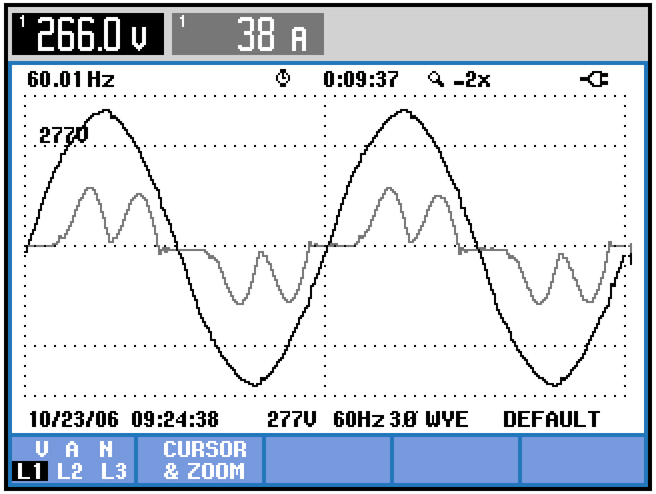
Reactor/Isolation Transformer

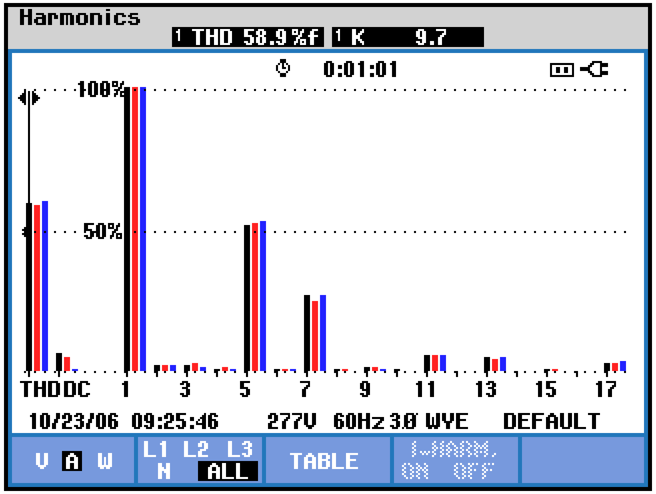




w/ isola trans

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

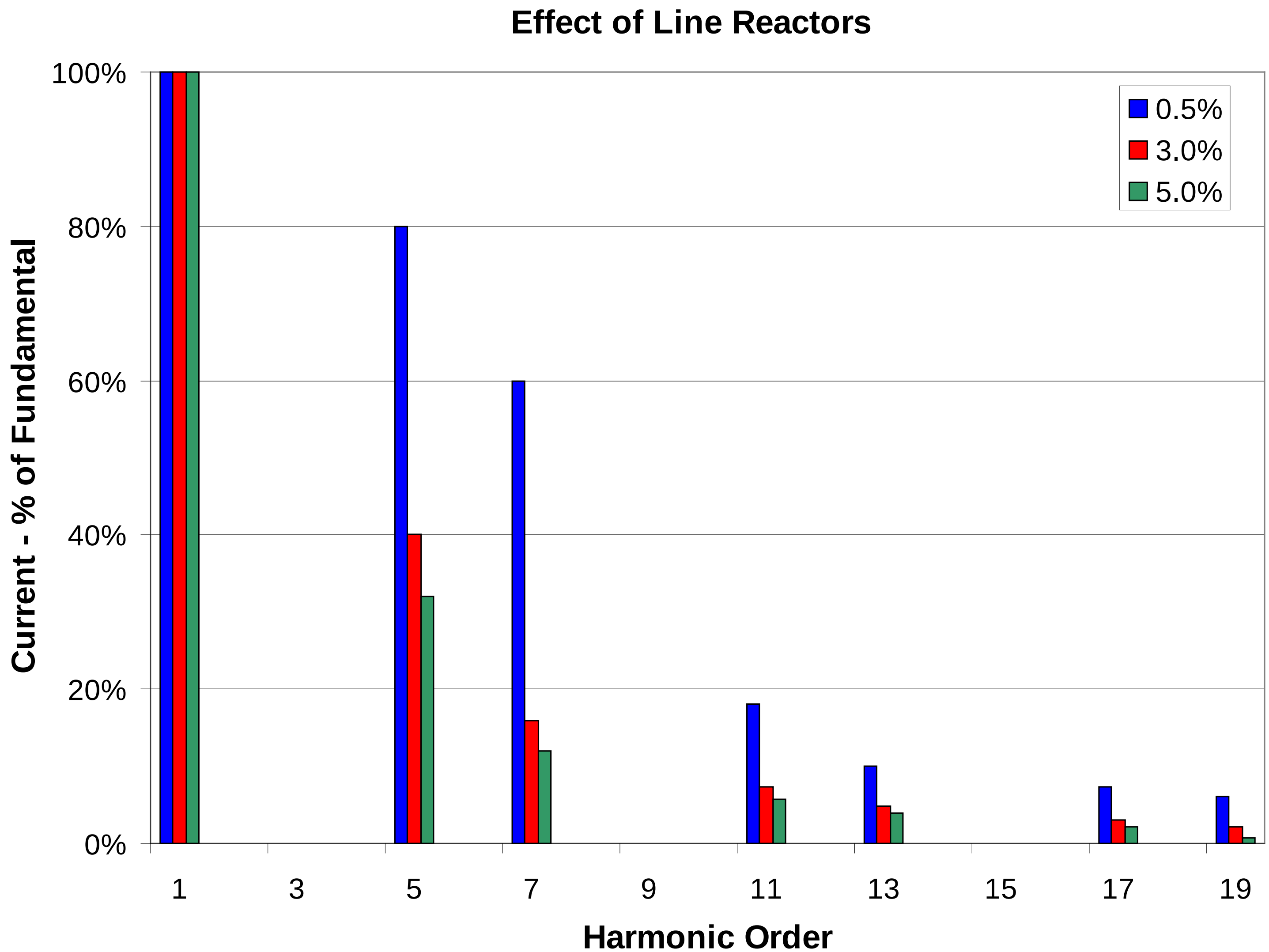




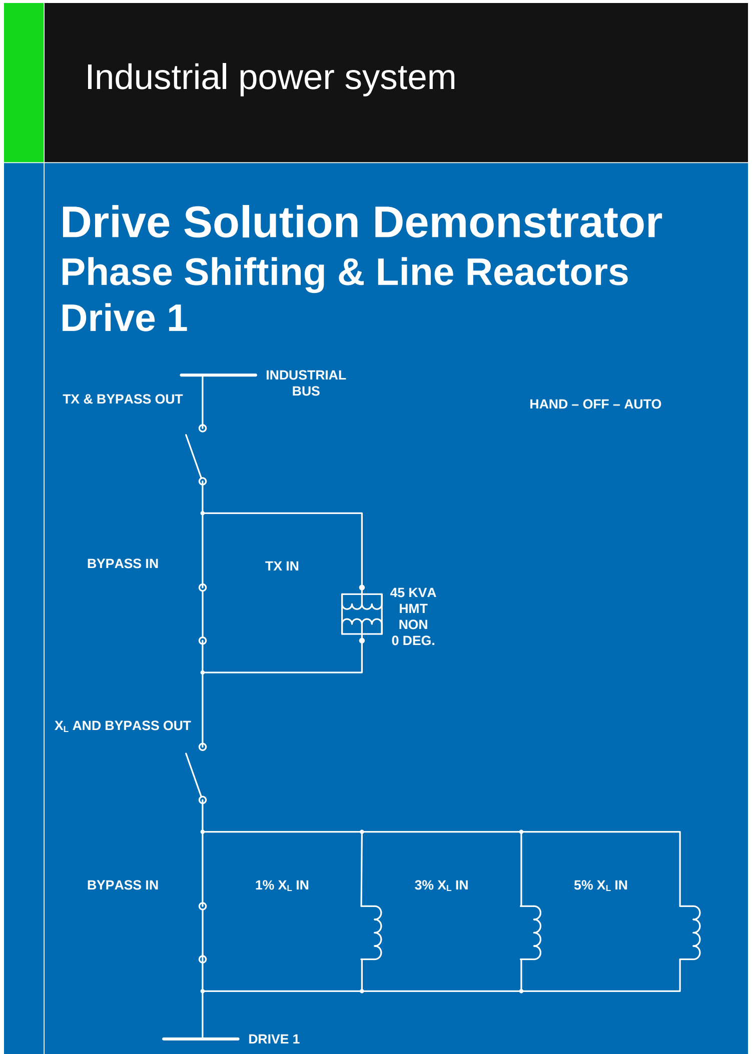
w/o isola trans

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

Effect of Drive Line Reactors



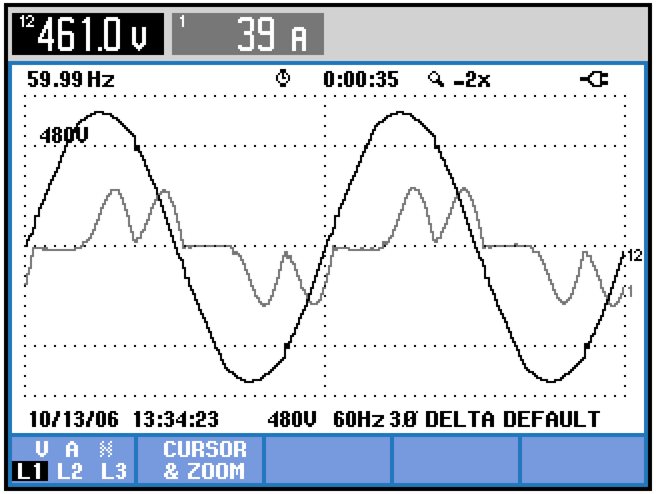
SVX Drives – Equivalent Reactance



500V	Type	480 V 60 Hz
Fr4	0003	0.65%
	0004	0.98%
	0005	1.31%
	0007	1.63%
	0009	1.33%
	0012	1.71%
Fr5	0016	1.63%
	0022	2.18%
	0031	2.99%
Fr6	0038	3.16%
	0045	3.88%
	0061	4.59%
Fr7	0072	3.73%
	0087	4.41%
	0105	5.33%
Fr8	0140	3.00%
	0168	4.00%
	0205	4.80%
Fr9	0261	3.35%
	0300	4.26%
Fr10	0385	2.94%
	0460	3.77%
	0520	3.75%
	590	2.89%

AC Drives and Harmonics

6-pulse converter with 3% Reactor waveform:



Harmonic Content

h_5 = 42.5%

h_7 = 29.38%

h_{11} = 6.10%

h_{13} = 4.06%

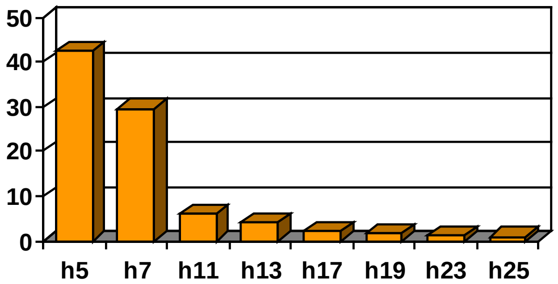
h_{17} = 2.26%

h_{19} = 1.77%

h_{23} = 1.12%

h_{25} = 0.86%

Harmonic Distribution



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.

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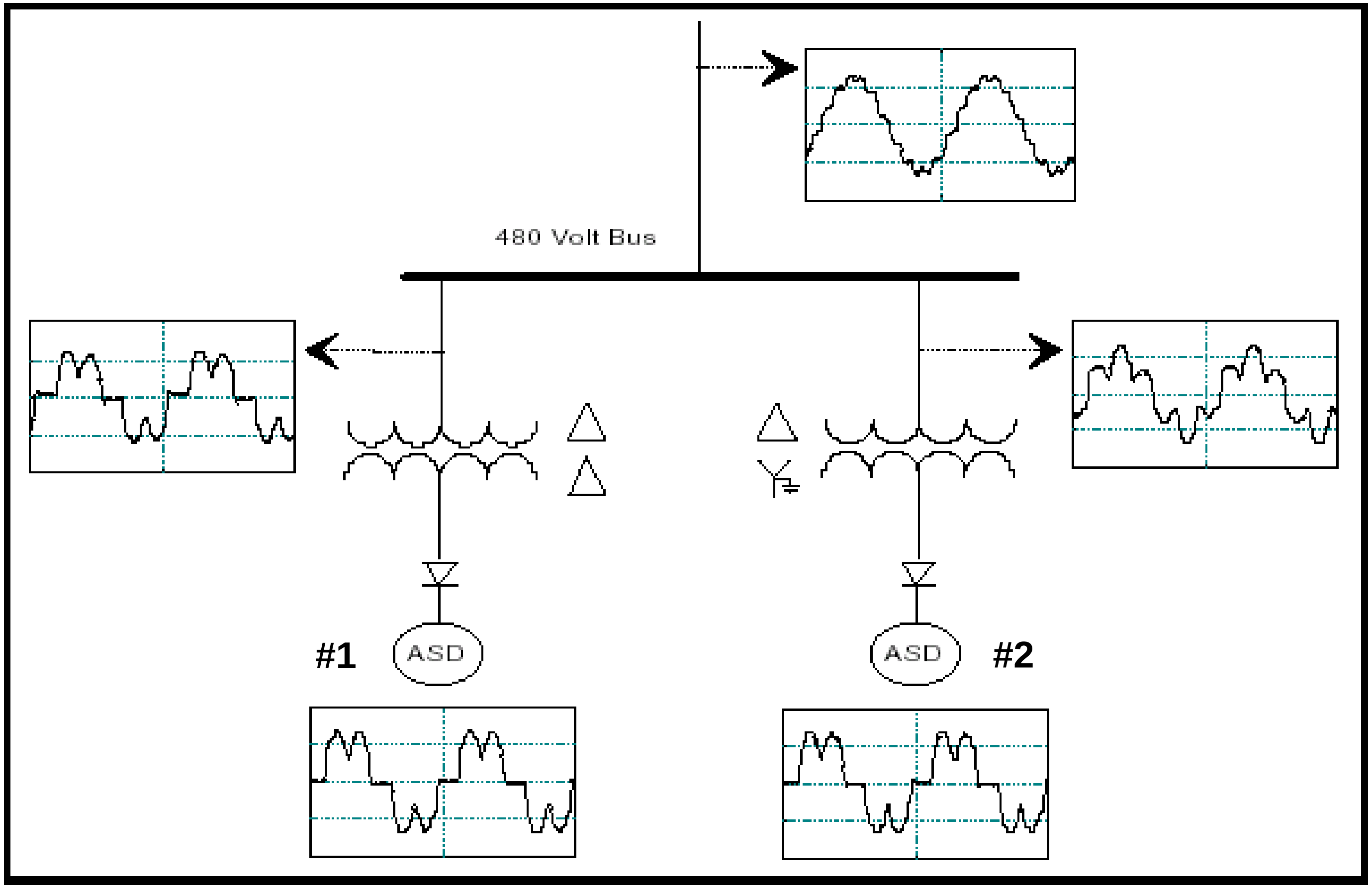
Phase Shifting/Cancellation

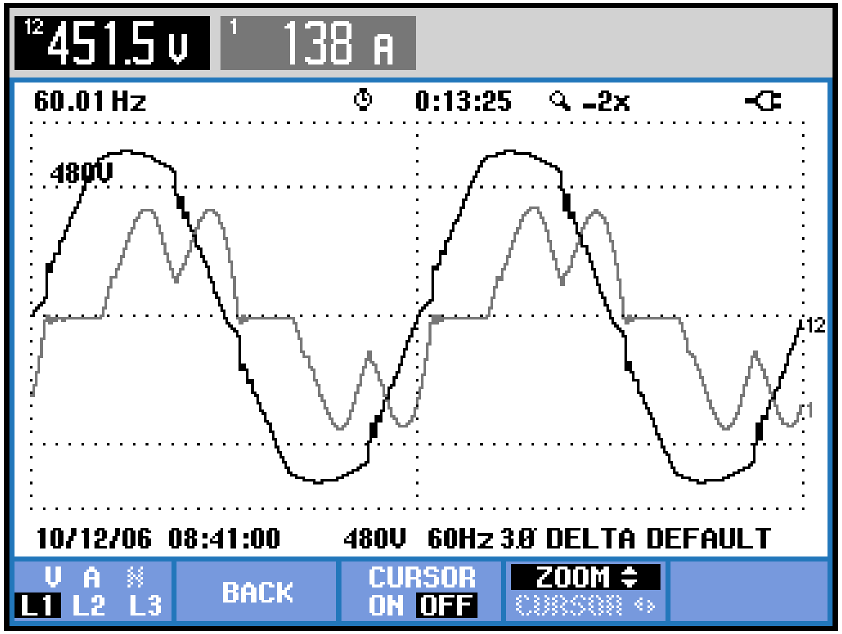
12 Pulse, 18 Pulse or 24 Pulse Cancellation by Design



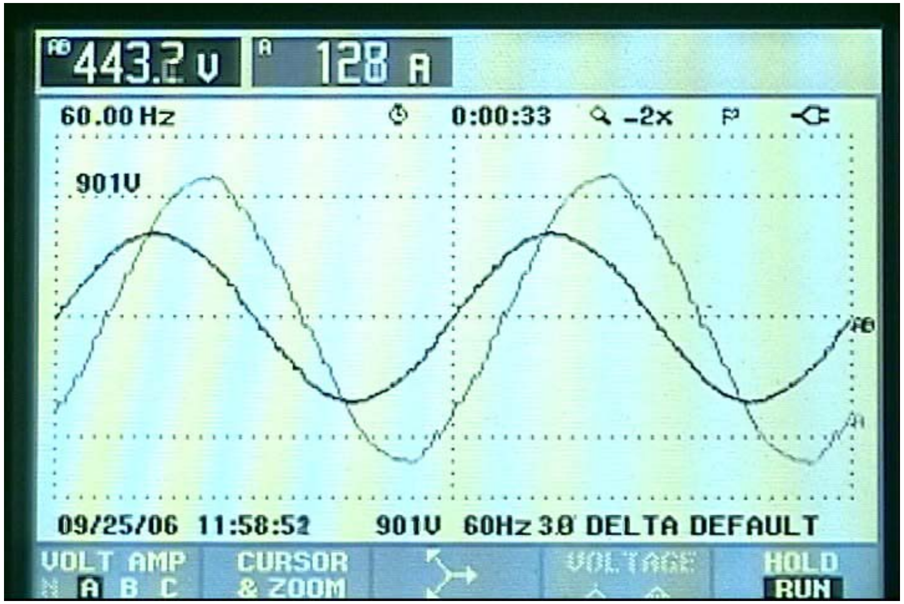
12 Pulse Example

Harmonics and Cancellation

Without Cancellation



24 Pulse Cancellation



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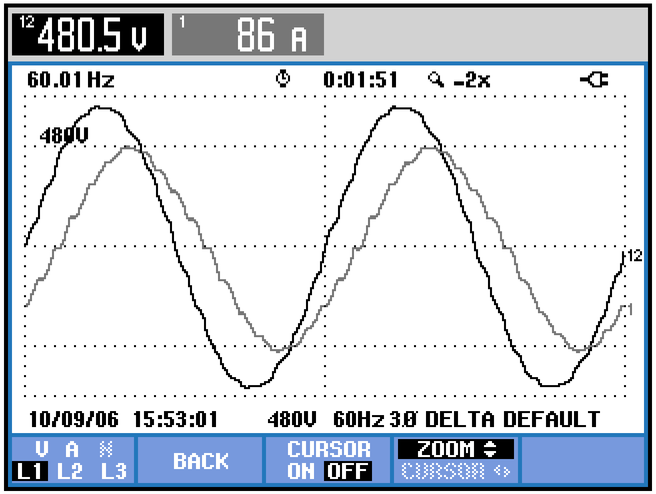
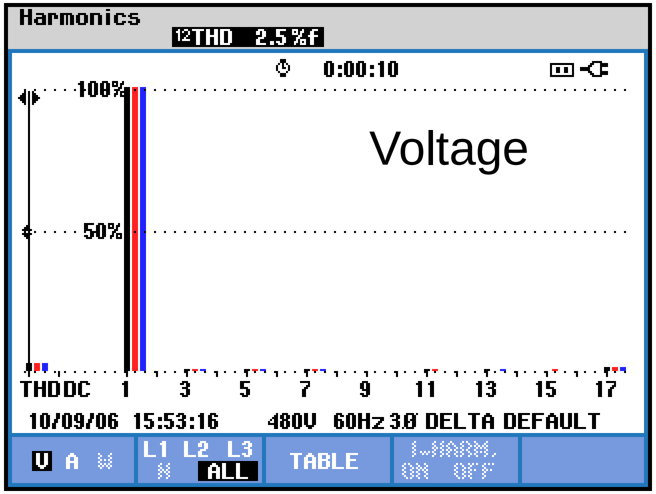
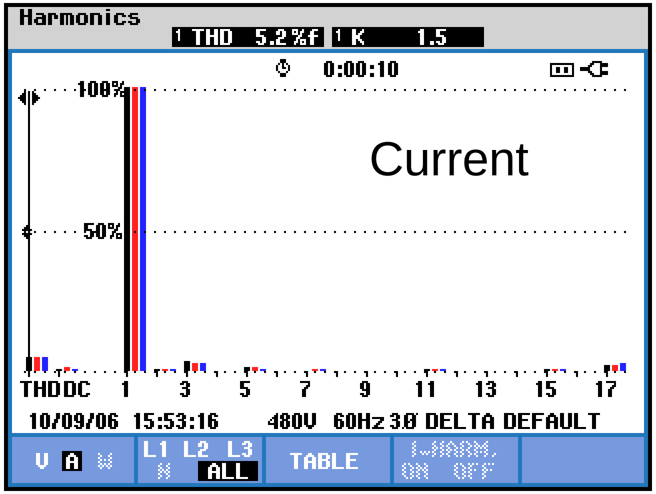
18 Pulse Rectifier

18 Pulse Design







Eaton "Clean Power Drive" – CPX9000

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18 Pulse Converters

Method

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

Benefits

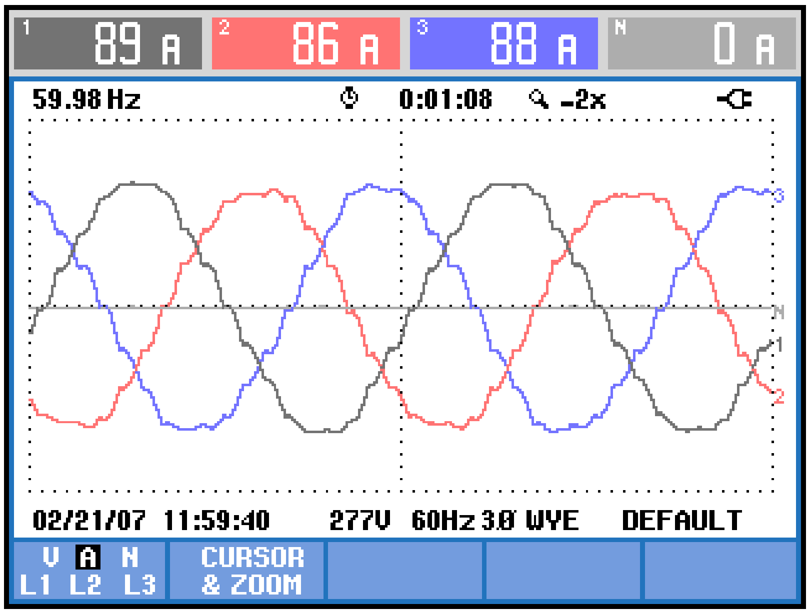
- Meets the IEEE standards in every case
- Attenuates all harmonics up to the 35th
- Insensitive to future system changes
- Increases life of drive through incredibly stable DC bus voltage (18 small inputs instead of 6 large ones)

Concerns

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

AC Drives and Harmonics

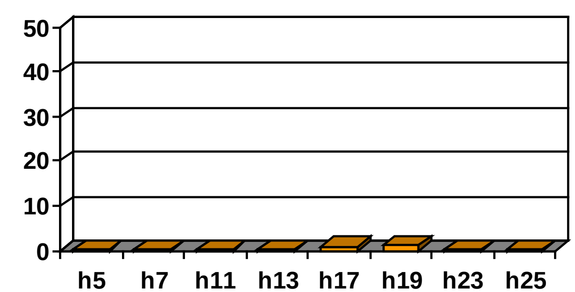
18-pulse “Clean Power” waveform:



Harmonic Content

h_5 = .16%
h_7 = .03%
h_{11} = .24%
h_{13} = .10%
h_{17} = .86%
h_{19} = 1.00%
h_{23} = 0.05%
h_{25} = 0.05%

Harmonic Distribution



Note that the reduction in harmonics is so dramatic below 17th harmonic that the scale actually drops to 1.0 as max. 18 pulse clean power drives will meet IEEE519 in all practical instances, with some sizes as low as 3% I_{THD}

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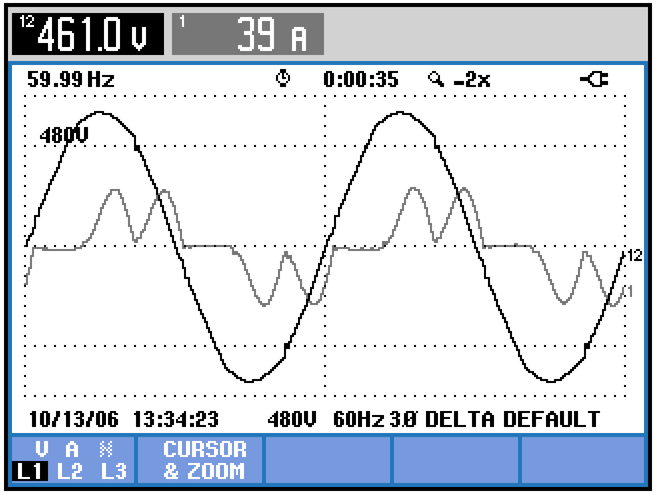
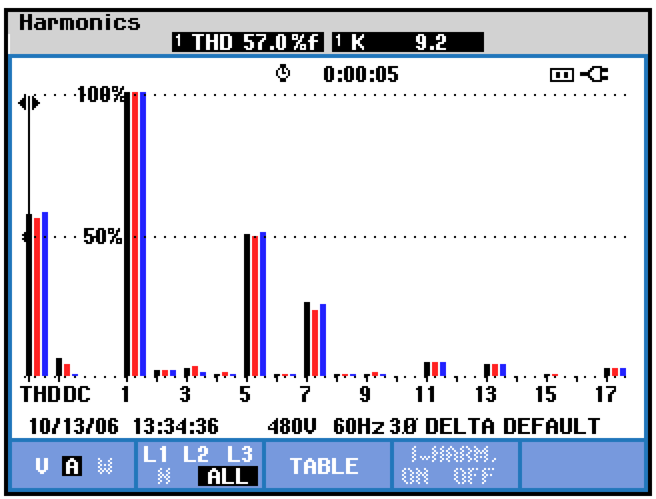
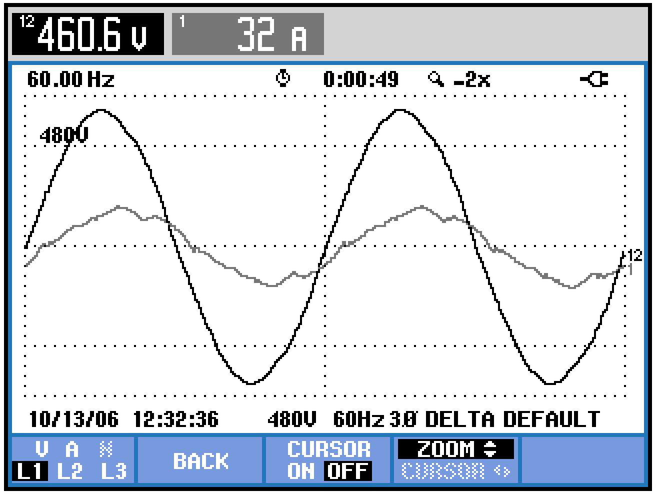
Drive Dedicated (Broadband) Filter

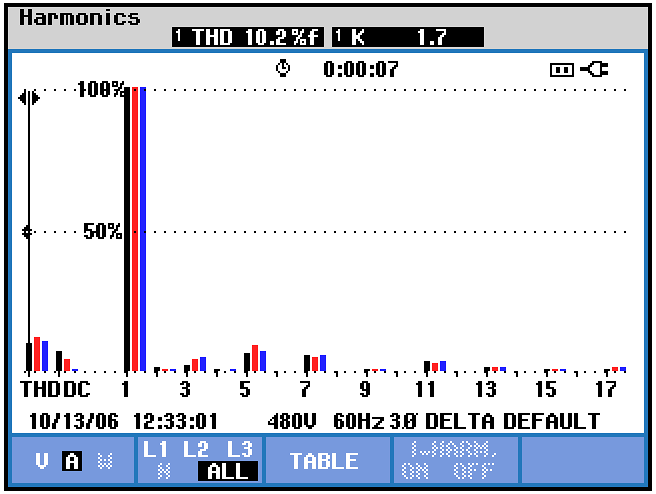
Standard Drive





Drive with Dedicated Filter





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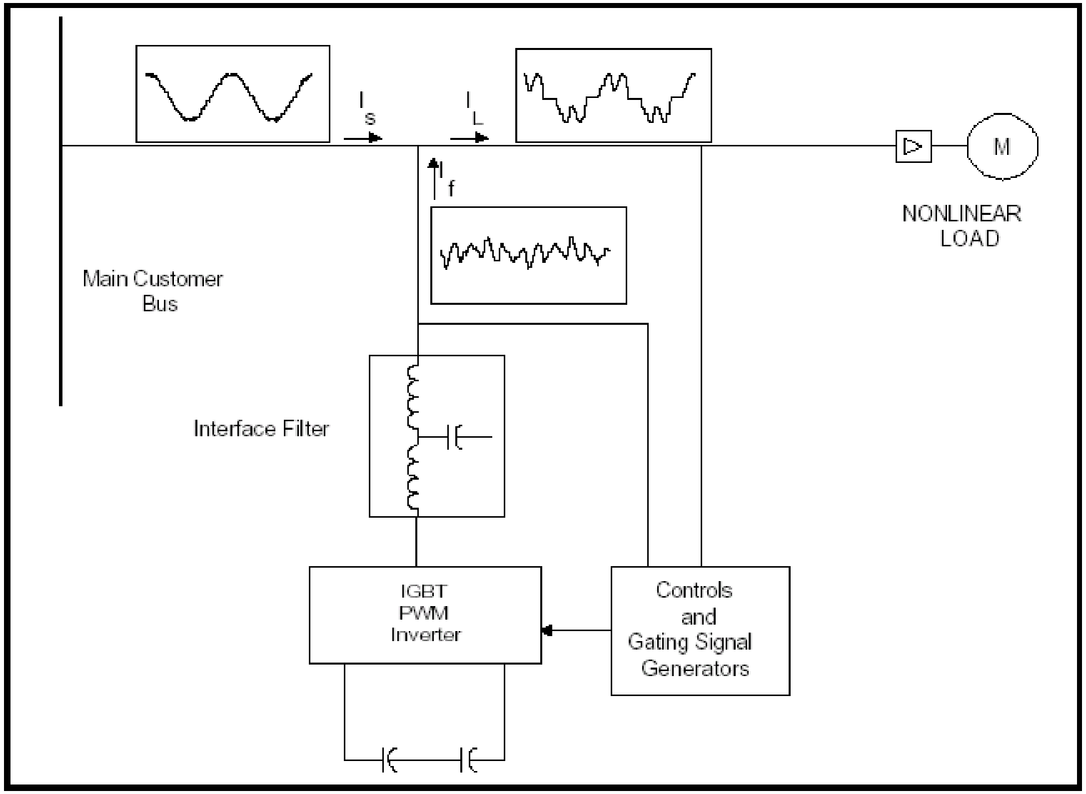
Active Filters

- “Senses” harmonics and injects equal and opposite harmonic current into the line
- Tests PF and corrects by injecting phase displaced fundamental current
- Fast response for dynamic loads
- Typically highest cost



From IEEE519A Draft

Lab Simulations and Videos

http://www.eaton.com/experience

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

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		

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Conclusion

- Useful to measure and limit harmonics
- IEEE Std 519-1992 defines limits
- Confusion on how to apply the limits
- Be clear when discussing harmonics
  - Current or voltage?
  - Expressed as percent or in actual quantities?
  - If percent, % of I_1 or % of I_L?

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Conclusion

- Intent of IEEE-519
  - Ensure utility provides a “clean” voltage
  - Limit harmonic current from customers
- Goal of IEEE-519
  - Prevent one customer from causing problems for another, or for the utility

Conclusion

- Limits assessed at the PCC
- PCC is the point where another customer can be served
  - Regardless of metering location
  - Regardless of equipment (transformer) ownership
- I_{SC}/I_L ratio must be known to determine which harmonic current limits apply

Conclusion

- TDD versus THD
  - TDD: Harmonics expressed as % of I_L
  - THD: Harmonics expressed as % of I_1
- IEEE 519 harmonic current limits written in terms of TDD, and % of I_L
  - Prevents users from being unfairly penalized during periods of light load

Help (for Harmonics)!

- SKM Harmonics
  - Taught by Carnovale/Dionise – Warrendale
  - http://www.skm.com/training.shtml (Oct. 5-6, 2011)
- EESS
  - Tom Dionise
  - Visuth Lorch
  - David Shipp
- Products (Capacitors and Harmonic Filters)
  - Shree Sathe
  - Dave Simmons

Wrap Up

- Harmonic solutions vary greatly in effectiveness and cost (technical vs. economic tradeoff)
- Commercial power systems often involve single phase harmonics (from lighting and computer loads).
  - Transformers are usually the most appropriate solution for commercial systems
- Industrial power system harmonics are usually caused by drives and other 3-phase rectifier loads.
  - Line reactors and harmonic filters are generally used in conjunction with phase shifting transformers for Industrial systems.
- Energy savings has become the buzz with PF correction and harmonic solutions – be careful…
- Learn more at: www.eaton.com/experience

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