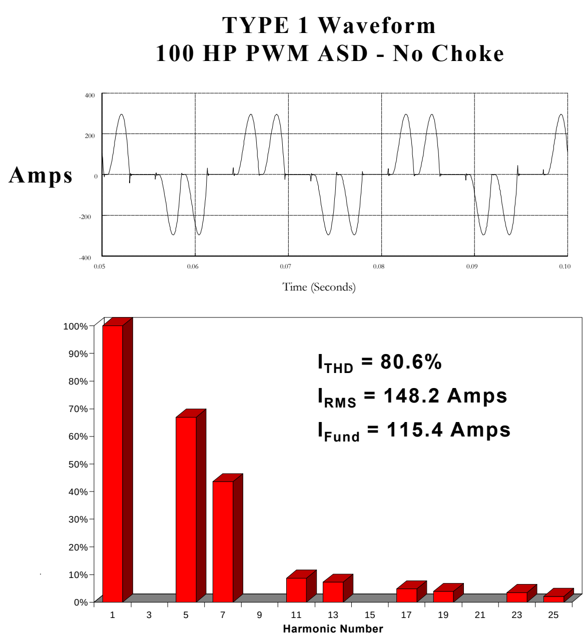
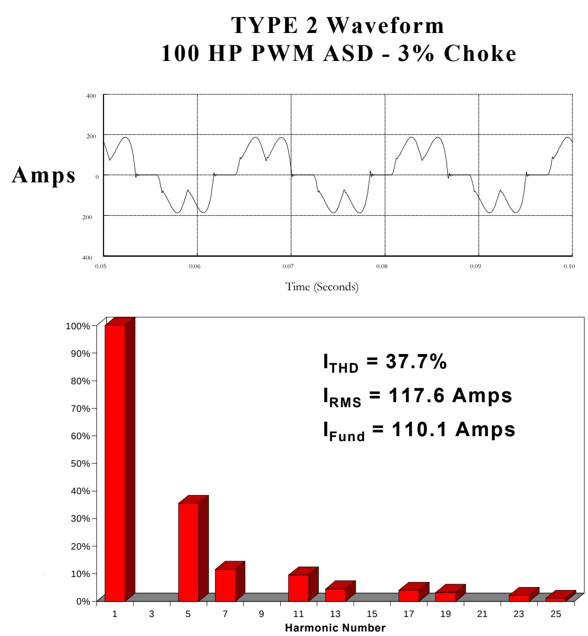
Contemporary Topics in Power System Harmonics

Electrotek Concepts, Inc.



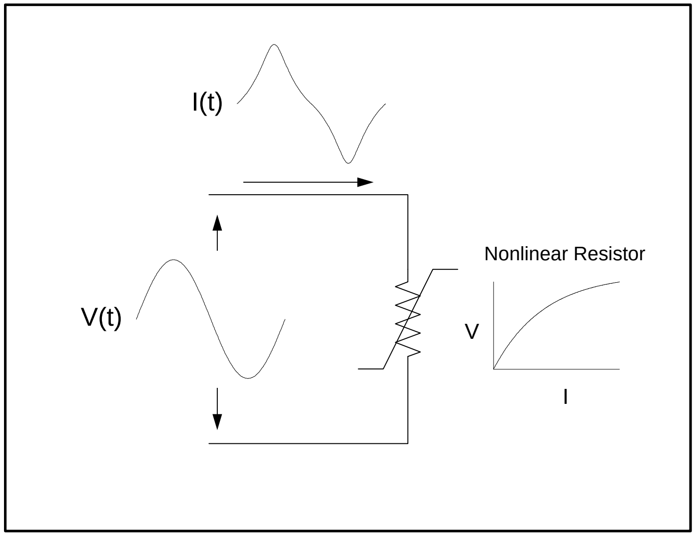


April 2000

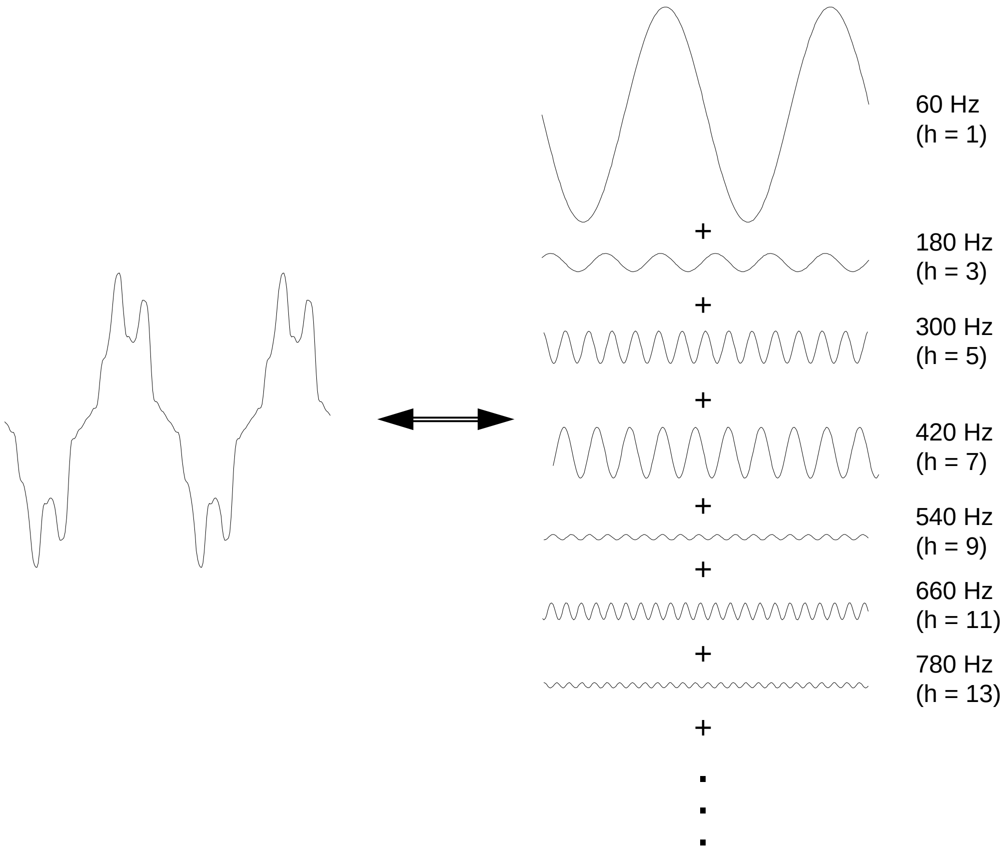
Harmonics Fundamentals

What Are Harmonics

- Harmonics are due to *periodic* distortion of the voltage or current waveform
- The distortion comes from *nonlinear* devices, principally loads



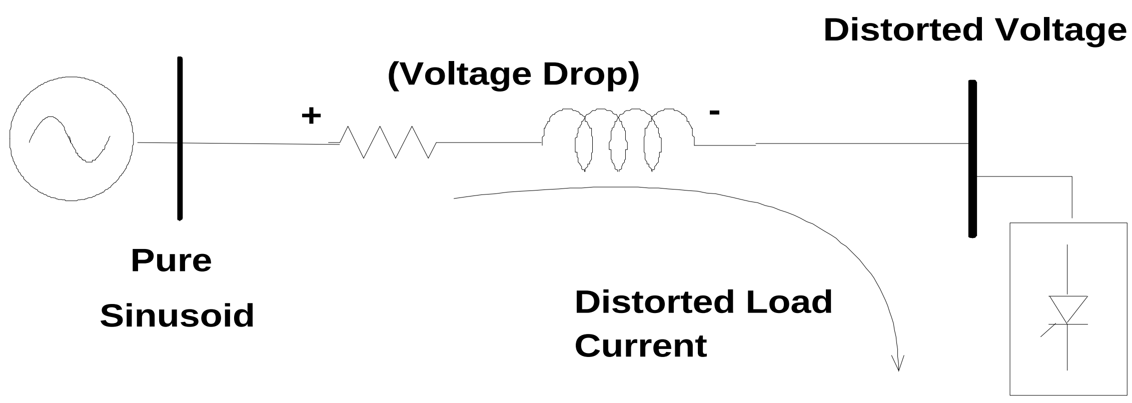
Decomposition into Harmonic Components



Why are harmonics important?

- Fundamental objective of electric utility operations is to supply each electric customer with a fairly constant sinusoidal voltage
- Present trends in the electric power industry have placed an increased emphasis on the impact of nonlinear equipment. These include:
  - The increasing size and application of nonlinear equipment
  - Increased application of capacitors
  - Modern architectural/construction practices
- Load equipment sensitivity (microprocessor-based)

Current vs. Voltage Harmonics



Harmonic currents flowing through the system impedance results in harmonic voltages at the load

Harmonics vs. Transients

- Harmonics are Steady-State and persistent
  - Frequency components are multiples of a base frequency
- Transients are due to changes in state
  - Frequency components are natural frequencies of the system

THD - Total Harmonic Distortion

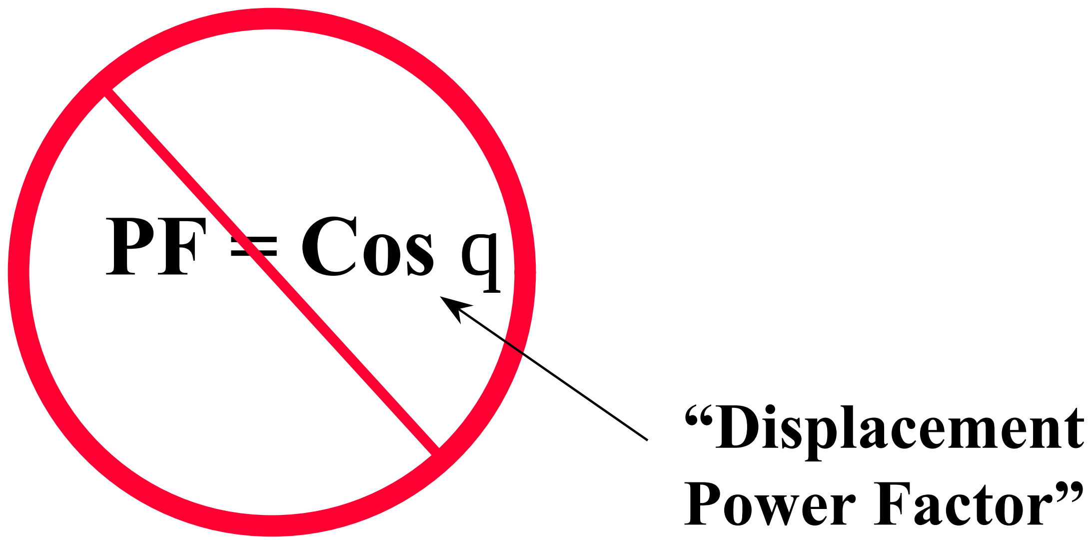
- Measure of the *effective (rms)* value of the harmonic distortion

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{\max}} {M_h}^2}}{M_1}$$

$$RMS = \sqrt{\sum_{h=1}^{h_{\max}} {M_h}^2} = M_1 \cdot \sqrt{1 + THD^2}$$

Power and Power Factor

- When significant distortion is present



Power and Power Factor

- Can’t use conventional concepts
- P = Active Power
  - Represents energy consumption
- S = Apparent Power
  - Represents required system capacity
- Q = Reactive Power = ???
  - Reactive component is not a conservative quantity

True Power Factor

$$PF = \frac{P}{S}$$

Where: $$S = V_{rms} I_{rms}$$

$$P = \frac{1}{T}\int_0^T v(t)i(t)dt$$

Displacement Power Factor

- When V is not distorted

$$P = \frac{V_1 I_1}{2} Cos\theta_1 = V_{1rms} I_{1rms} Cos\theta_1$$

Displacement power factor is due to the phase shift between the *fundamental* frequency components

Remains useful for sizing capacitors

Distortion Voltamperes (D)

- A common way to represent the power quantities under distortion is to introduce a new quantity: D

$$S = \sqrt{P^2 + Q^2 + D^2}$$

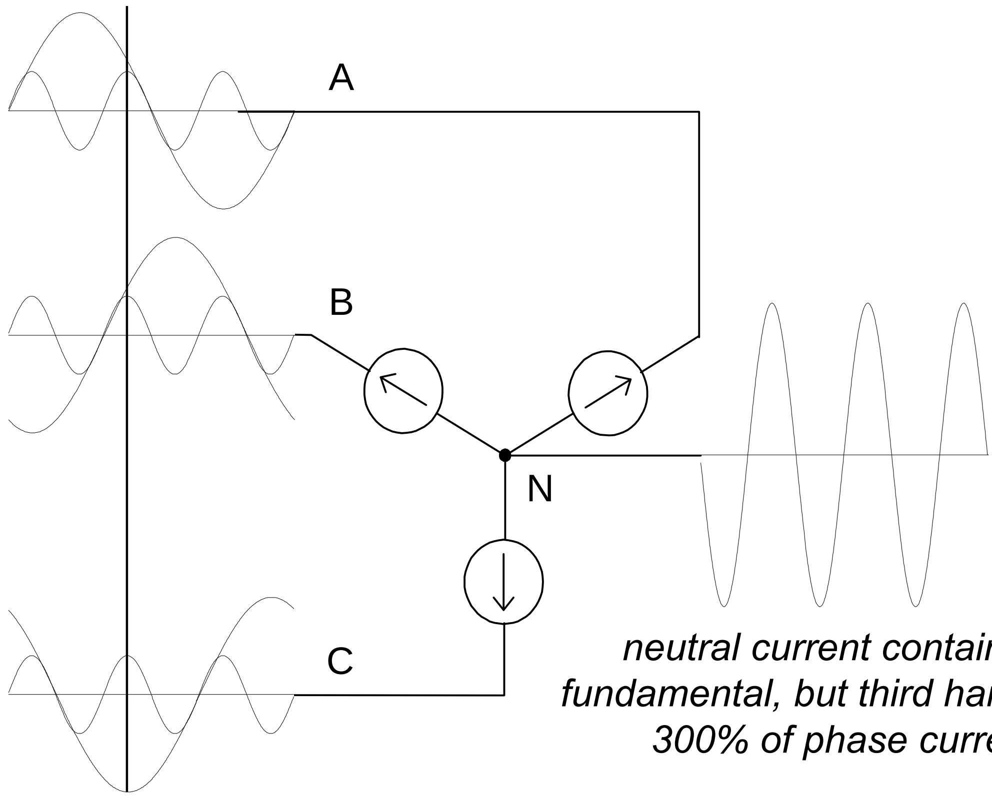
$$Q = \sum_k V_k I_k Sin\mathbf{q}_k$$

$$D = \sqrt{S^2 - P^2 - Q^2}$$

This quantity is not conserved!!

Triplen Harmonics

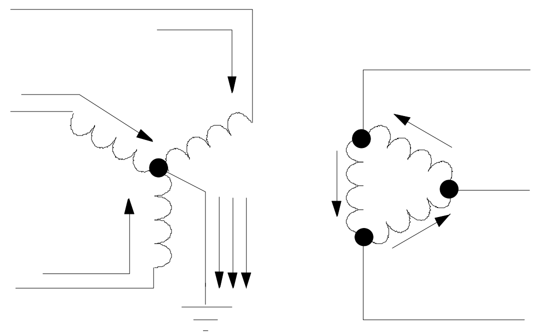
balanced fundamental currents sum to 0,
but balanced third harmonic currents coincide



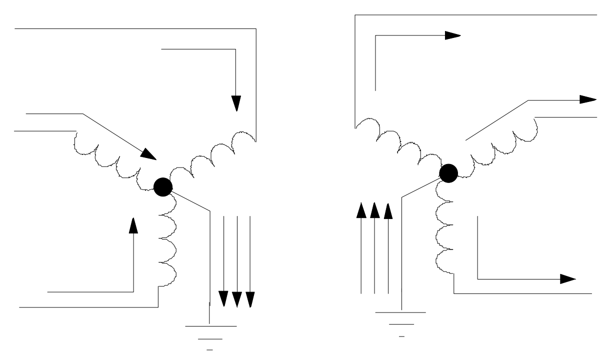
neutral current contains no fundamental, but third harmonic is 300% of phase current

Flow of Triplens in Transformers

Grounded WYE-
DELTA



Grounded WYE-
Grounded WYE

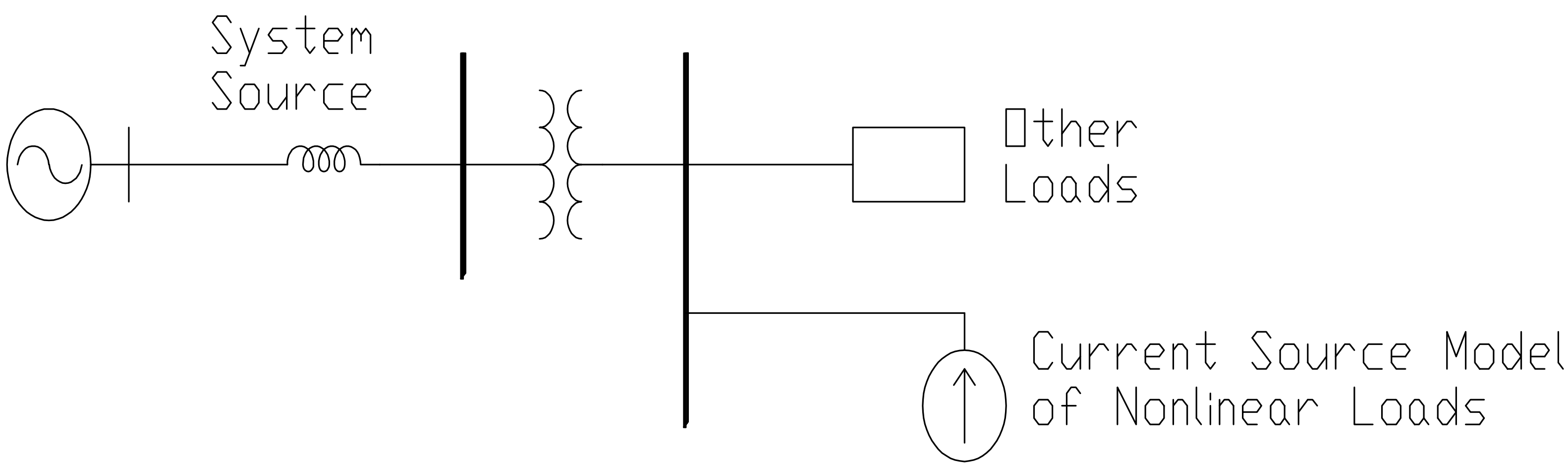


Sources of Harmonics

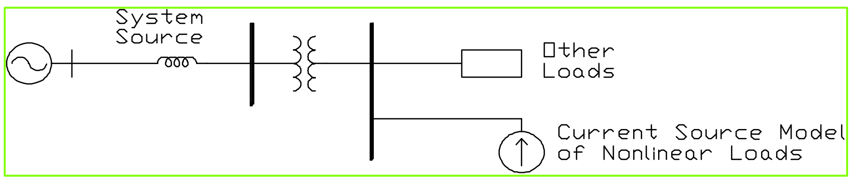
- Saturable devices - transformers and nonlinear reactors
- Arcing devices - arc furnaces, welders and fluorescent lighting
- Power electronics equipment - adjustable speed motor drives, dc motor drives and electronic power supplies

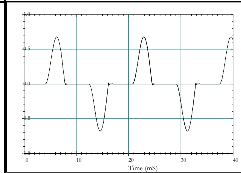
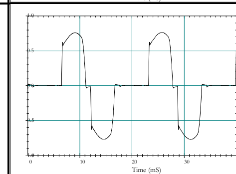
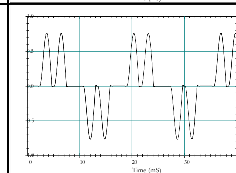
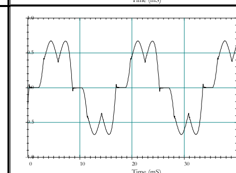
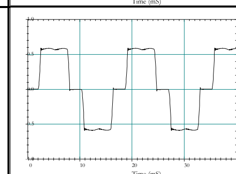
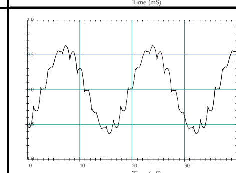
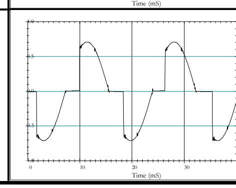
Representation of Nonlinear Loads

- In general, a nonlinear load can be represented
  as a source of harmonic currents:

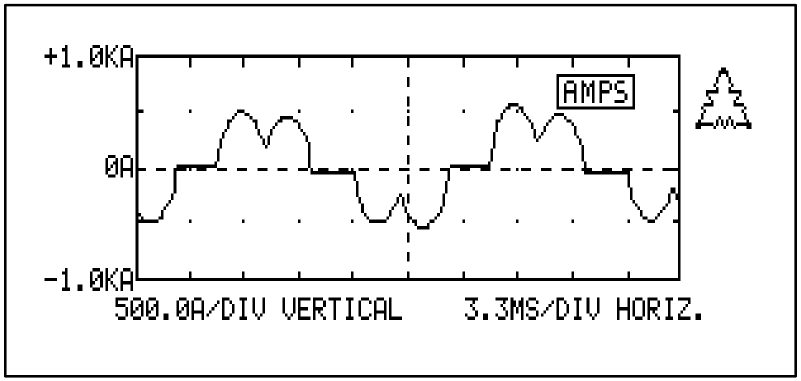


Sources of Harmonics



Type of Load	Typical Waveform	Current Distortion	Weighting Factor (W_i)
Single Phase Power Supply		80% (high 3rd)	2.5
Semiconverter		high 2nd,3rd, 4th at partial loads	2.5
6 Pulse Converter, capacitive smoothing, no series inductance		80%	2.0
6 Pulse Converter, capacitive smoothing with series inductance > 3%, or dc drive		40%	1.0
6 Pulse Converter with large inductor for current smoothing		28%	0.8
12 Pulse Converter		15%	0.5
ac Voltage Regulator		varies with firing angle	0.7

Example 1 - dc drive



PHASE A CURRENT SPECTRUM 11:20:42 AM
Fundamental amps: 319.6 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	-75°	2nd	4.8%	-64°
3rd	1.2%	28°	4th	1.5%	164°
5th	33.6%	156°	6th		
7th	1.6%	29°	8th	1.7%	-170°
9th	0.4%	-91°	10th	0.3%	96°
11th	8.7%	49°	12th		
13th	1.2%	54°	14th	1.3%	86°
15th	0.3%	148°	16th	0.2%	51°
17th	4.5%	-57°	18th		
19th	1.3%	-46°	20th	1.1%	-18°
21st	0.3%	34°	22nd	0.3%	-31°
23rd	2.8%	-163°	24th		
25th	1.2%	-149°	26th	0.9%	-123°
27th	0.3%	-75°	28th	0.3%	-128°
29th	2.0%	90°	30th		
31st	1.0%	107°	32nd	0.8%	133°
33rd	0.3%	173°	34th	0.3%	135°
35th	1.4%	-17°	36th		
37th	1.0%	2°	38th	0.8%	28°
39th	0.3%	63°	40th	0.3%	31°
41st	1.1%	-123°	42nd		
43rd	0.9%	-104°	44th	0.8%	-75°
45th	0.3%	-47°	46th	0.3%	-70°
47th	1.0%	128°	48th	0.2%	102°
49th	0.9%	152°	50th	0.7%	-179°
ODD	35.4%		EVEN	5.9%	
THD:	35.9%				

VOLTAGE & CURRENT SNAPSHOT 11:21:16 AM

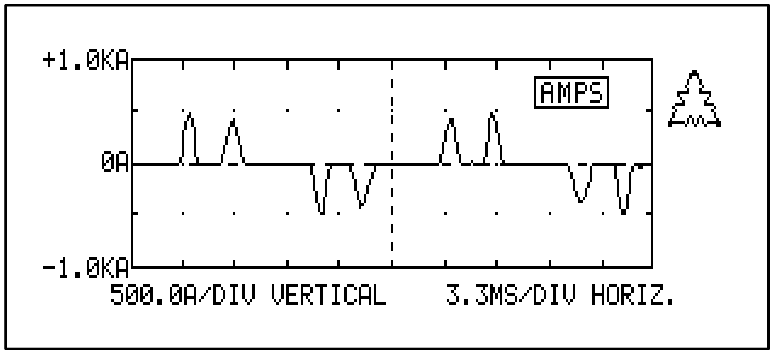
VOLTAGE 458.9 Vrms

- Phase A-B: 459.3 Vrms, 0°(ref)
- Phase B-C: 461.0 Vrms, 120°
- Phase C-A: 456.5 Vrms, -121°
- Imbalance: 0.4%

CURRENT 945.6 A rms

- Phase A: 339.5 A rms, -75°
- Phase B: 347.8 A rms, 40°
- Phase C: 258.3 A rms, 157°
- Imbalance: 9.4%

Example 2 - PWM drive, no choke



VOLTAGE & CURRENT SNAPSHOT 11:50:56 AM

VOLTAGE 495.5 Vrms

Phase A-B: 494.1 Vrms, 0°(ref)
Phase B-C: 493.0 Vrms, -120°
Phase C-A: 499.3 Vrms, 120°
Imbalance: 0.8%

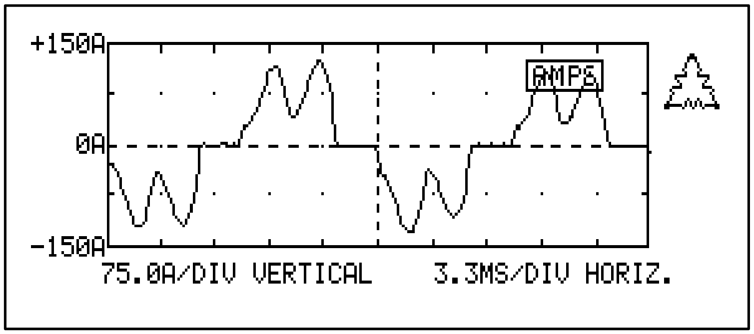
CURRENT 289.6 A rms

Phase A: 171.5 A rms, 10°
Phase B: 164.9 A rms, -111°
Phase C: 165.2 A rms, 131°
Imbalance: 2.6%

PHASE A CURRENT SPECTRUM 11:49:06 AM
Fundamental amps: 103.8 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	10°	2nd	1.1%	78°
3rd	3.9%	-122°	4th	0.5%	167°
5th	82.8%	-125°	6th	1.7%	-56°
7th	77.5%	79°	8th	1.2%	131°
9th	7.6%	-80°	10th	0.7%	112°
11th	46.3%	-52°	12th	1.0%	-48°
13th	41.2%	149°	14th		
15th	5.7%	-26°	16th	0.3%	172°
17th	14.2%	19°	18th	0.4%	78°
19th	9.7%	-145°	20th	0.4%	-138°
21st	2.3%	19°	22nd	0.5%	-14°
23rd	1.5%	-148°	24th	0.5%	89°
25th	2.5%	108°	26th	0.7%	-135°
27th	0.9%	-29°	28th	0.3%	9°
29th	2.0%	-29°	30th	0.2%	55°
31st	2.0%	169°	32nd	0.3%	149°
33rd	0.5%	-19°	34th	0.4%	-61°
35th	0.3%	-147°	36th	0.1%	25°
37th	0.8%	75°	38th	0.3%	148°
39th	0.5%	-58°	40th		
41st	0.6%	-100°	42nd		
43rd	0.7%	114°	44th	0.1%	113°
45th	0.4%	-59°	46th	0.1%	-32°
47th	0.2%	165°	48th		
49th	0.4%	44°	50th	0.3%	144°
ODD	130.9%		EVEN	3.0%	
THD:	130.9%				

Example 3 - PWM drive with choke2



HARMONICS SNAPSHOT 2:22:55 PM
Fundamental freq: 60.0 Hz
VOLTAGE THD 3.3% THD avg

Phase A-Nm Volt:	3.2%	THD
Phase B-Nm Volt:	3.3%	THD
Phase C-Nm Volt:	3.4%	THD

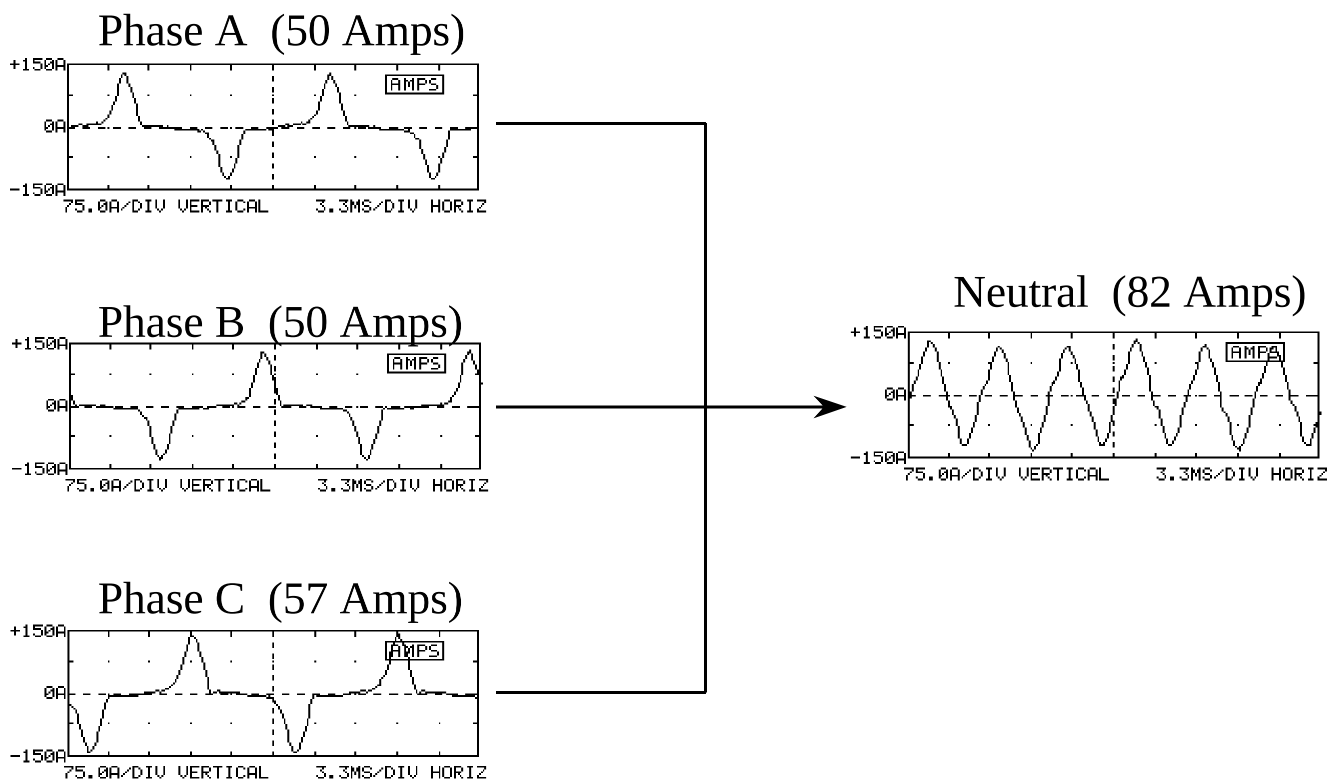
CURRENT THD 47.6% THD avg

Phase A Current:	49.8%	THD
Phase B Current:	45.1%	THD
Phase C Current:	48.0%	THD

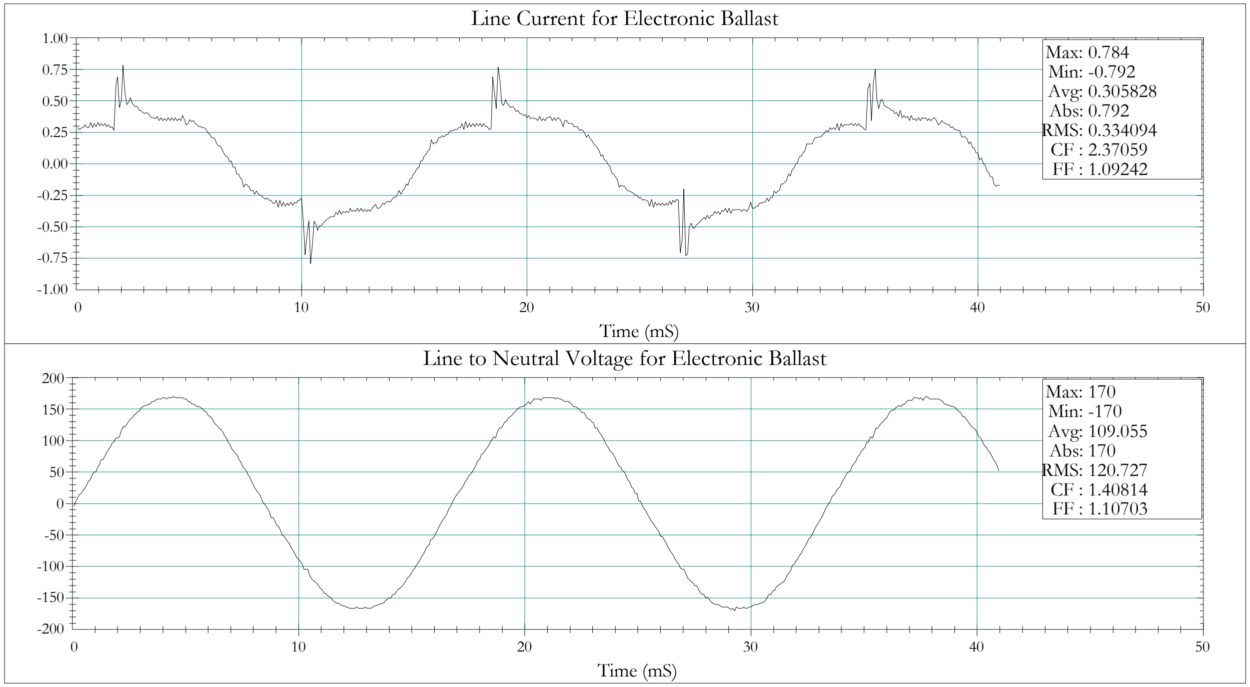
PHASE B CURRENT SPECTRUM 2:23:40 PM
Fundamental amps: 61.2 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	-128°	2nd	1.0%	145°
3rd	3.9%	-149°	4th	0.4%	-57°
5th	39.7%	-122°	6th	0.8%	175°
7th	18.9%	122°	8th	0.2%	10°
9th	0.8%	47°	10th	0.2%	159°
11th	6.8%	67°	12th	0.4%	-27°
13th	3.8%	-118°	14th	0.3%	111°
15th	0.4%	-140°	16th	0.4%	6°
17th	3.2%	-144°	18th	0.4%	109°
19th	2.3%	10°	20th	0.3%	2°
21st	0.3%	29°	22nd	0.2%	141°
23rd	1.8%	11°	24th	0.2%	-79°
25th	1.7%	145°	26th	0.2%	124°
27th	0.2%	-165°	28th	0.1%	-81°
29th	1.1%	160°	30th	0.1%	68°
31st	1.3%	-74°	32nd	0.1%	-112°
33rd	0.2%	-32°	34th	0.1%	81°
35th	0.7%	-49°	36th	0.1%	-114°
37th	1.0%	67°	38th		
39th	0.2%	153°	40th		
41st	0.5%	96°	42nd	0.1%	-1°
43rd	0.8%	-147°	44th	0.1%	134°
45th	0.2%	-59°	46th		
47th	0.4%	-112°	48th		
49th	0.7%	-5°	50th		
ODD	45.1%		EVEN	1.6%	
THD:	45.1%				

Example 4 - Switched mode power supply currents

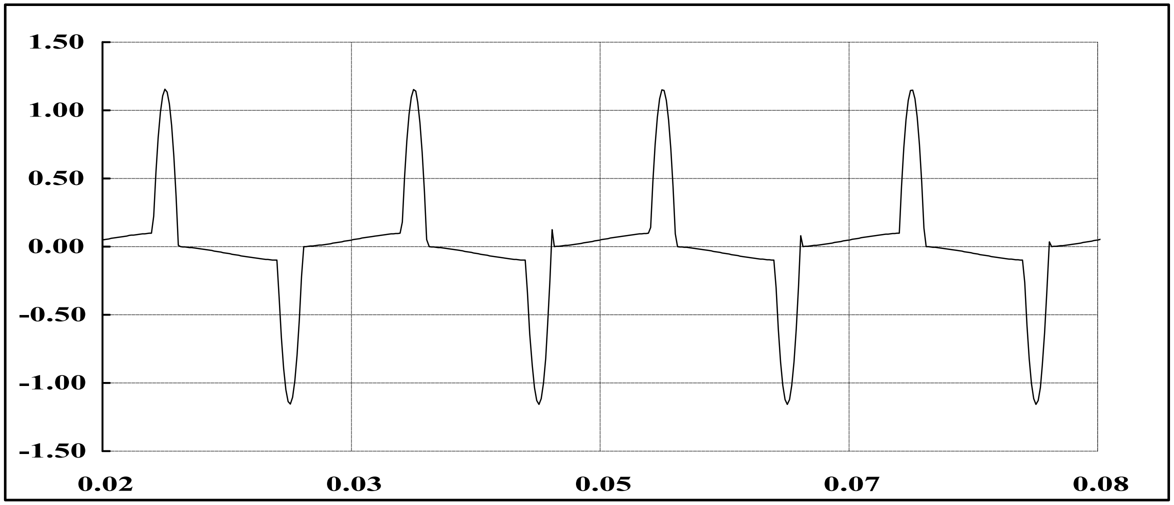


Example 5 - electronic ballast



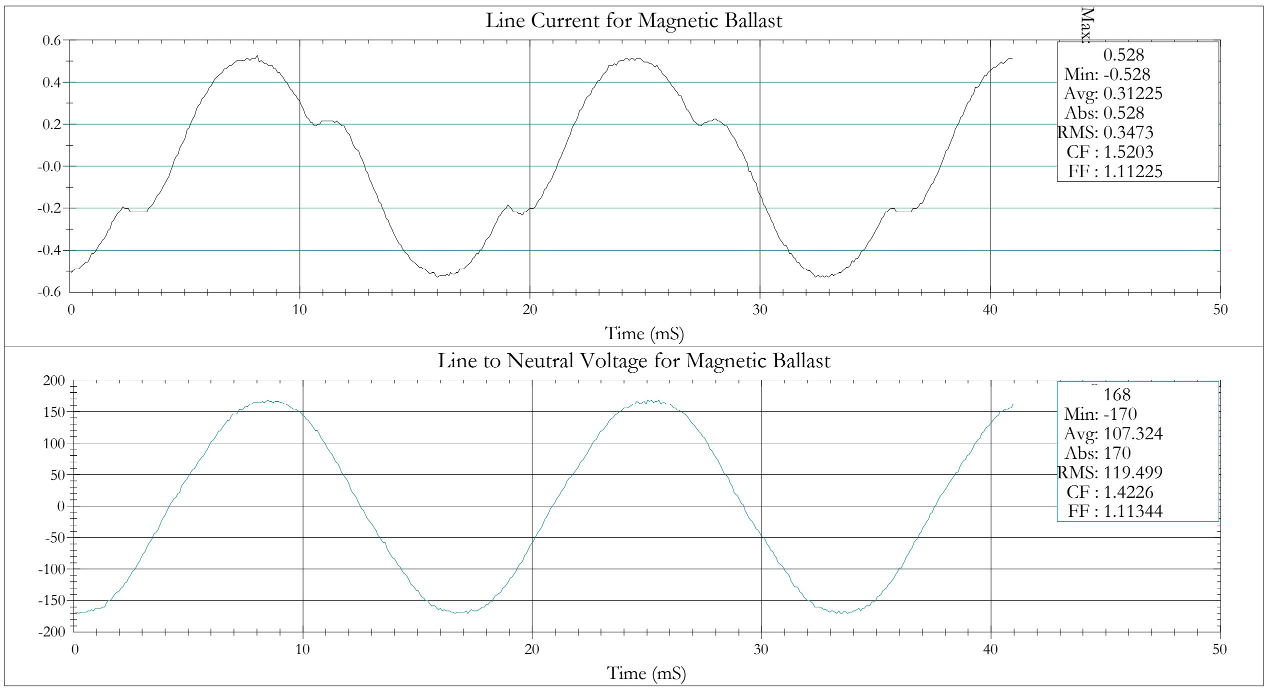
Saturable Loads

- Transformers and Reactors
- Small, harmonic rich magnetizing currents from normal operation are usually not a problem, but will contribute to background voltage distortion.



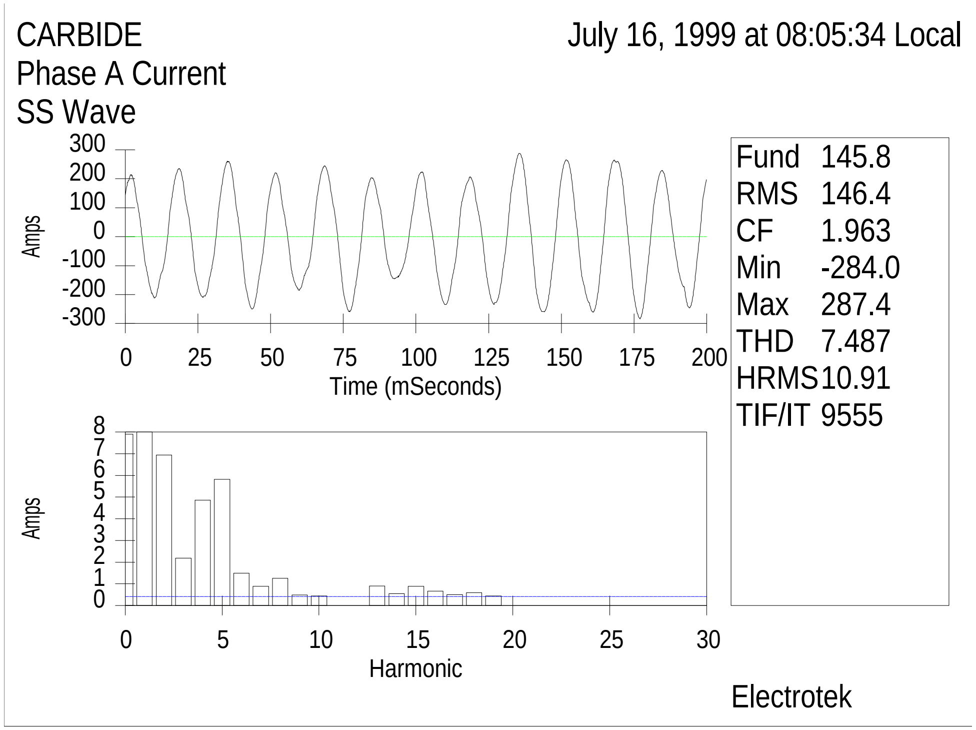
Arcing Loads

- Welding Loads, Arc Furnaces, Fluorescent Lighting
- Distorted voltage, current due to non-linear nature of electric arc



Arc Furnaces

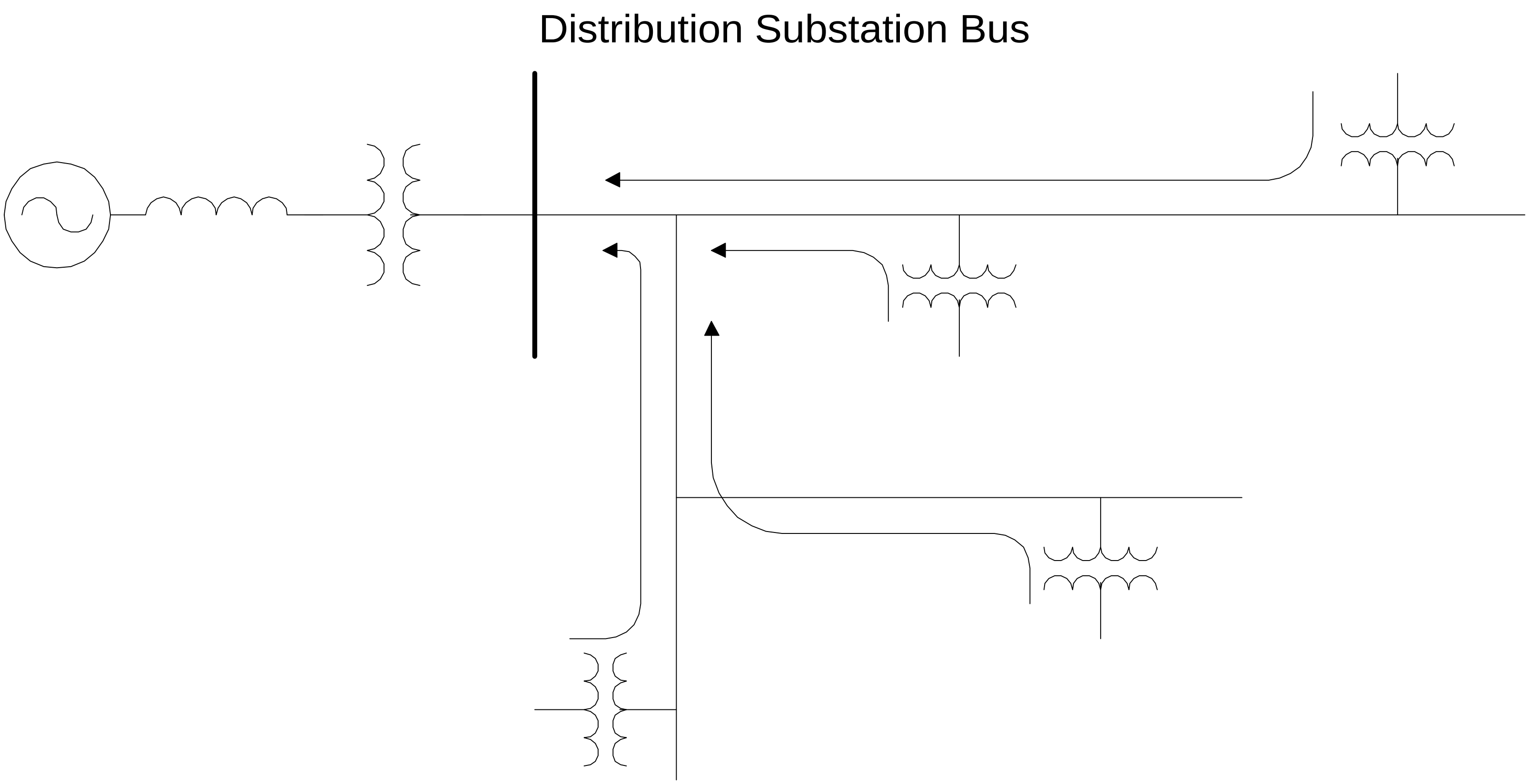
- Harmonics are variable (statistics are important)
- Even harmonics
- Interharmonics



System Response to Harmonics

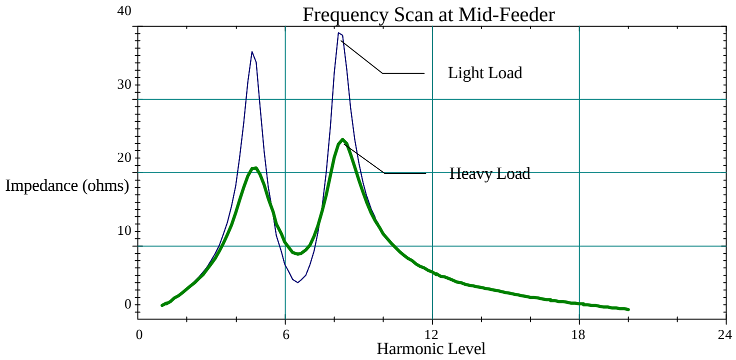
- As important as the size of harmonic sources
- Dictates the voltage distortion
- Resonance of system is a key problem

Where do harmonics go?



What are the Problems?

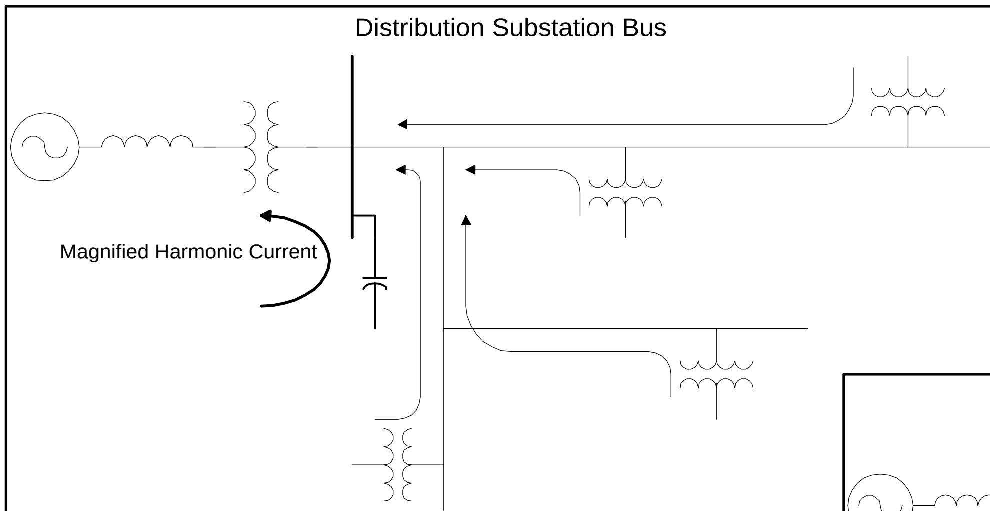
- Almost all harmonic problems relate to resonance conditions where harmonic levels are magnified by capacitor applications.
  - capacitor failures
  - fuse blowing
  - transformer overheating
  - electronic equipment malfunction
  - clocks running fast
  - motor heating



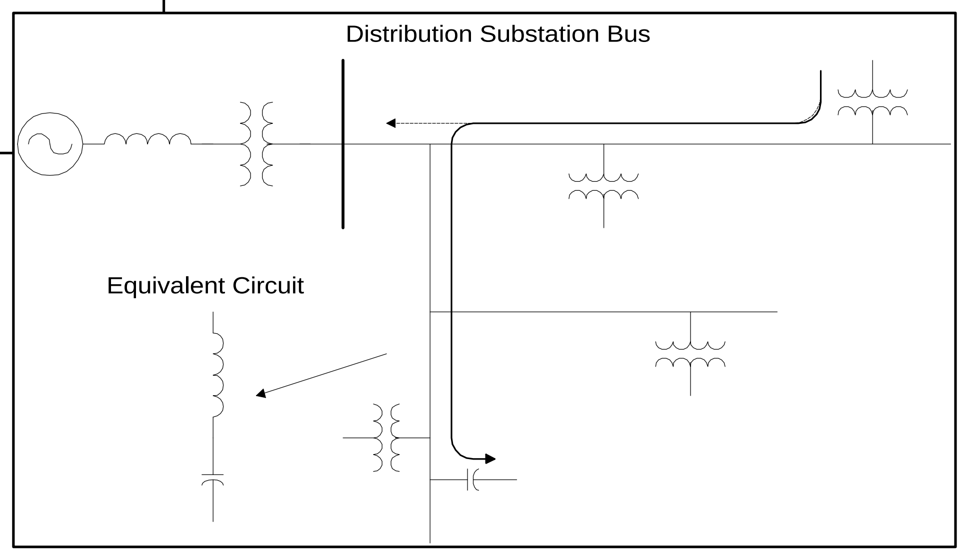
- There are also concerns for the penetration of single phase nonlinear loads causing harmonic losses and unacceptable voltage distortion.

Resonance Concerns

Parallel Resonance



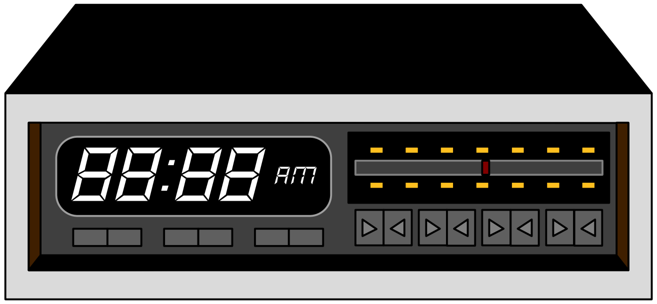
Series Resonance



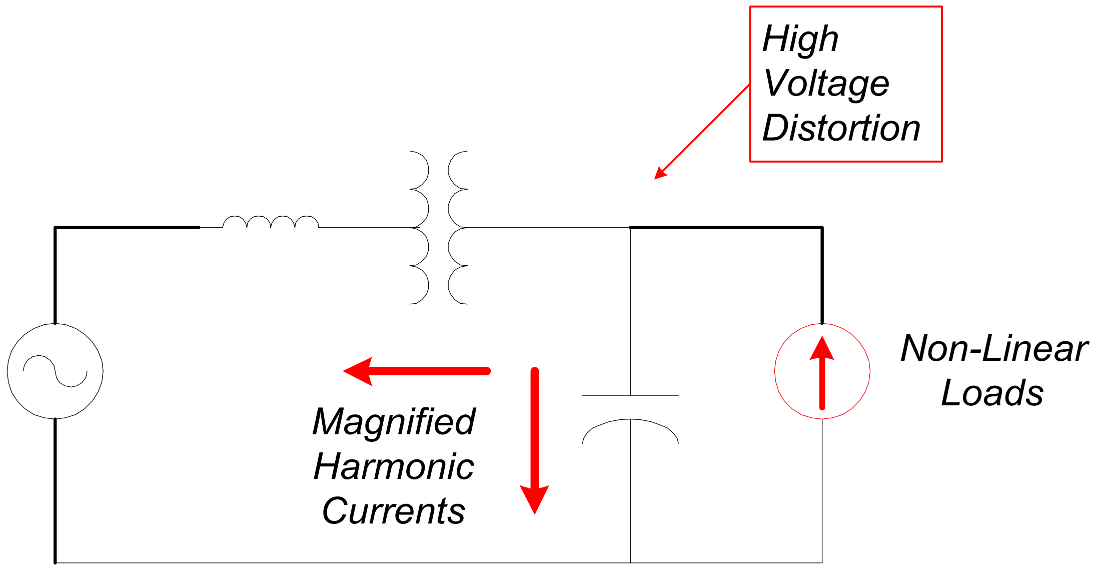
Impacts of Harmonics

Symptoms of Harmonic Problems

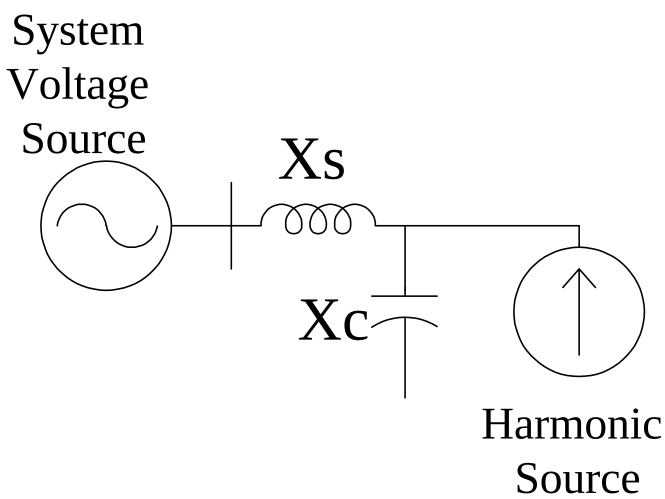
- Telephone interference
- Customer capacitor or transformer failure
- Capacitor fuse blowing (harmonic resonance)
- Transformer overheating at less than full load
- Motor overheating
- Clocks running fast / controls misoperating (voltage notching)
- High neutral currents

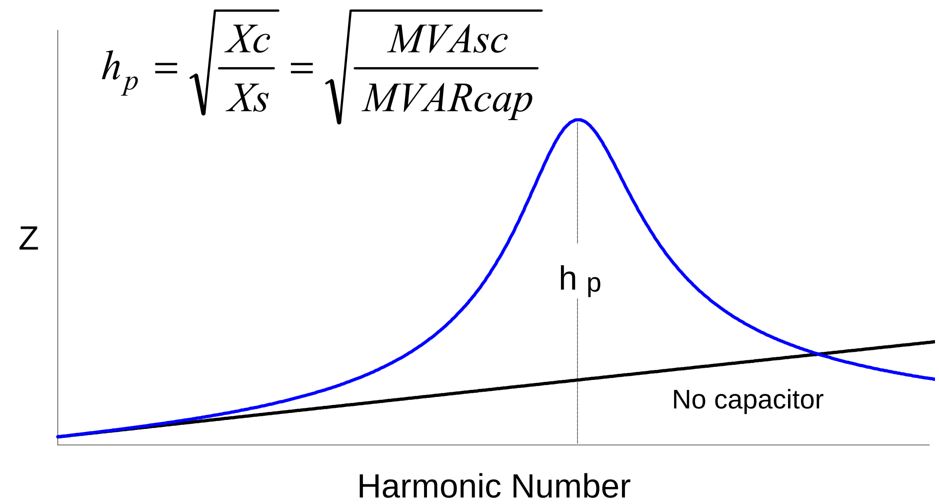


Parallel Resonance



Calculating the resonance frequency

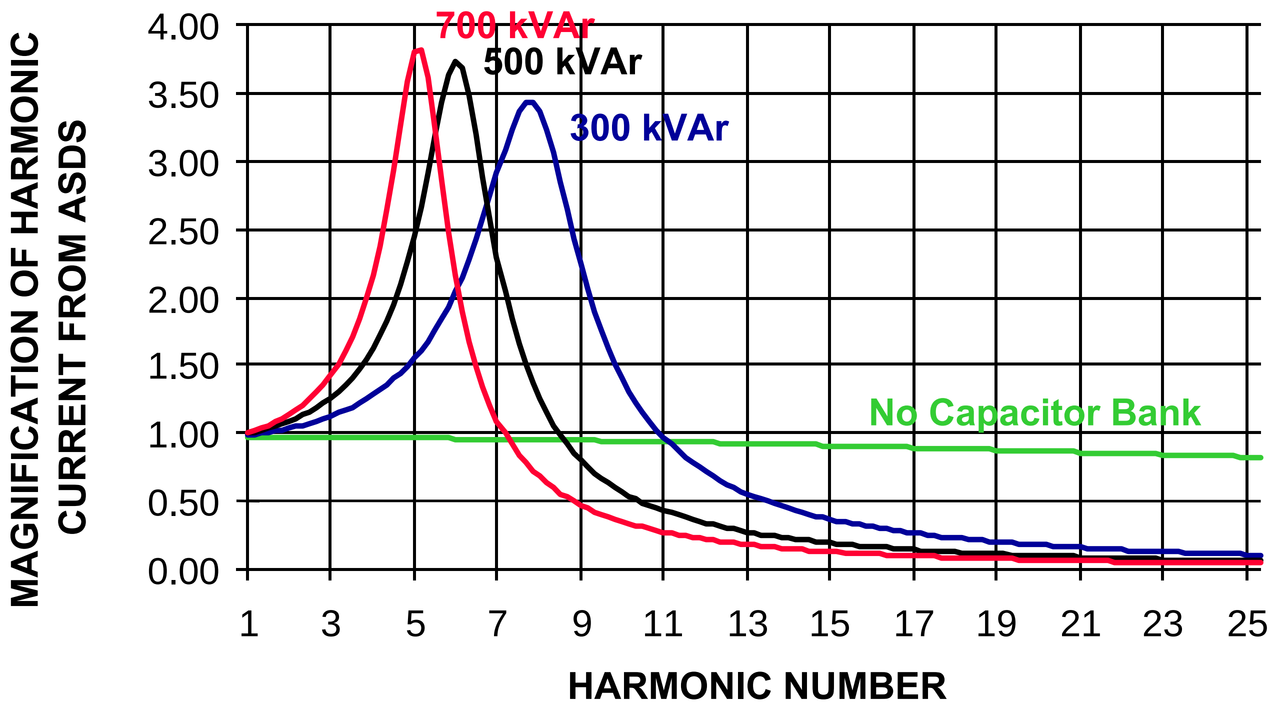




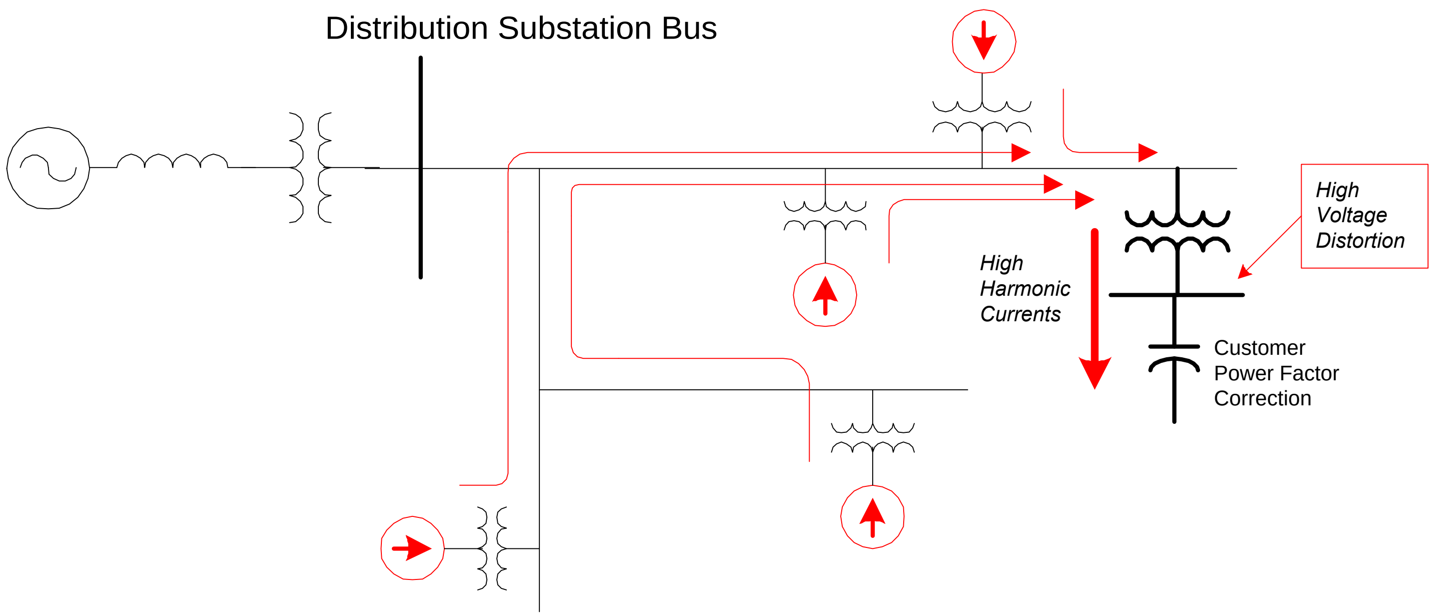
If the calculated frequency corresponds to one of the characteristic harmonic frequencies of a nonlinear load, high distortion can occur.

Resonance frequency, cont.

Resonance vs. capacitor size for a typical customer supplied with a 1500 kVA, 6% transformer.

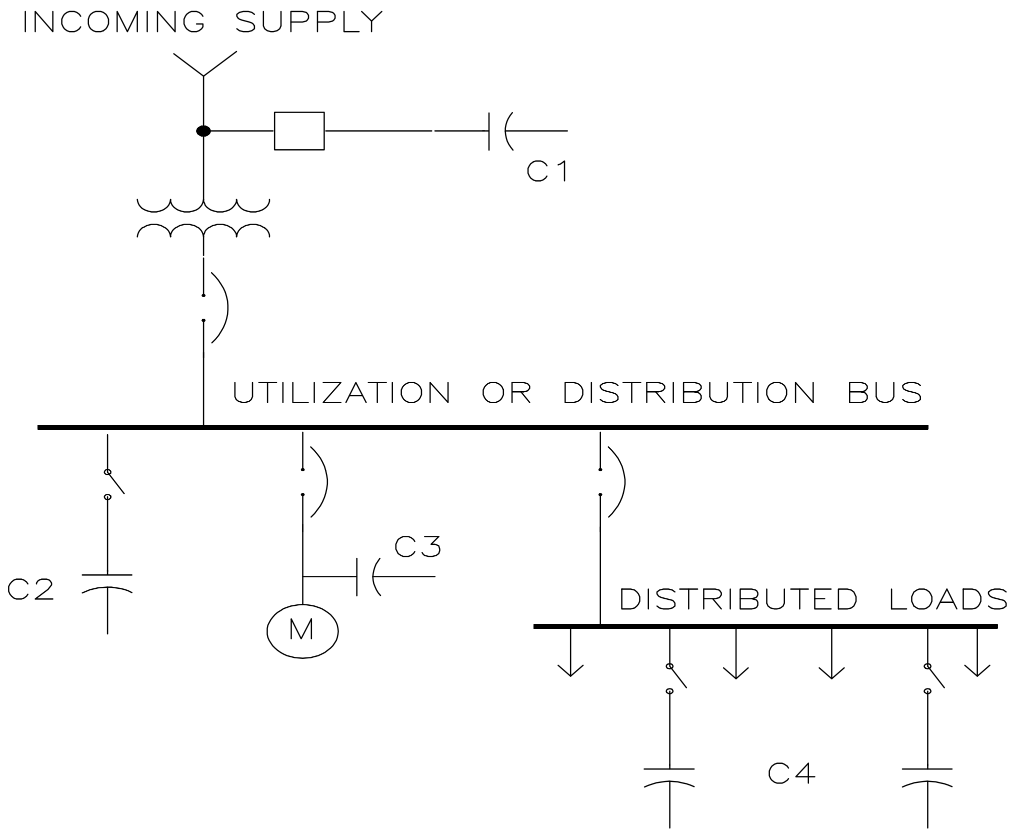


Series Resonance



Location for Power Factor Correction

- Capacitors can be installed in a variety of locations to provide reactive (VAr) power.



Impacts of parallel or series resonance problem

- Capacitor failures
- Fuse blowing
- High voltage distortion can impact other loads - e.g. motor heating
- High currents in supply transformer - overheating concerns.

Impact on Capacitors

- Higher harmonics: overcurrent
- High peak voltage
- Frequently first element to fail
- First place to look for harmonics problems

Note !

Solutions for resonance problems

- Don't use power factor correction capacitors.
- Apply power factor correction as tuned banks (harmonic filters).
- Keep parallel resonance frequency above the 8th harmonic (still could have problems at the 11th or 13th but less likely).

Motor Overheating

- Harmonic voltage distortion results in harmonic components in the motor current.
  - $I_h = V_h/X_s$
- Harmonic currents cause negative sequence heating in the motor.
- Harmonic currents combine to cause oscillatory torque components (mechanical resonance concern)
- Generally not a problem for voltage distortion levels less than about 8%.
- May be a concern for higher harmonic currents in high efficiency motors (lower negative sequence reactance).

Transformer Derating

- ANSI C57.110 provides guidelines for calculating the equivalent transformer duty for currents with more than 5% harmonic current content.
- Harmonic losses are dependent on the transformer eddy current losses.
- K-Factor transformers are designed to supply loads with nonlinear currents without being derated.

The transformer derating calculation

Transformer Load Losses

$$P_{LL} = \sum I_h^{\,2} + \left(\sum (I_h^{\,2} * h^2)\right) P_{EC-R}$$

where
I_h are individual harmonic current components
h is the associated harmonic order
P_{EC-R} is the per unit eddy current losses (from manufacturer)

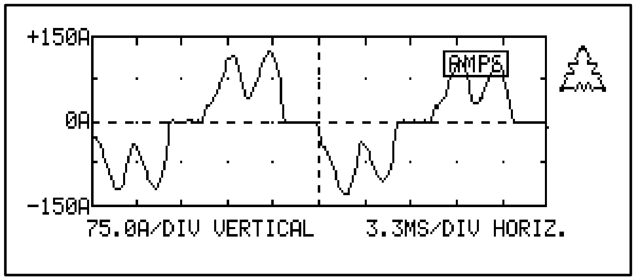
Define a K-factor

$$K = \frac{\sum \left(I_h^{\,2} * h^2\right)}{\sum I_h^{\,2}}$$

Convert to an Equivalent rms Current Capability for the transformer in per unit of the transformer rated current

$$\sqrt{\sum I_h^{\,2}} = \sqrt{\frac{1 + P_{EC-R}}{1 + K * P_{EC-R}}} (pu)$$

Example transformer derating calculation



Site: **Example Supply Transformer**
Load Dominated by ASD

Harmonic Distribution of Transformer Load Current:

Harmonic	Current (%)	Freq (Hz)	Current (pu)	I^2	I^2 * h^2
1	100.000	60	1.000	1.000	1.000
3	3.900	180	0.039	0.002	0.014
5	39.700	300	0.397	0.158	3.940
7	18.900	420	0.189	0.036	1.750
9	0.800	540	0.008	0.000	0.005
11	6.800	660	0.068	0.005	0.560
13	3.800	780	0.038	0.001	0.244
15	0.400	900	0.004	0.000	0.004
17	3.200	1020	0.032	0.001	0.296
19	2.300	1140	0.023	0.001	0.191
21	0.300	1260	0.003	0.000	0.004
23	1.800	1380	0.018	0.000	0.171
25	1.700	1500	0.017	0.000	0.181
			Totals:	1.203	8.359

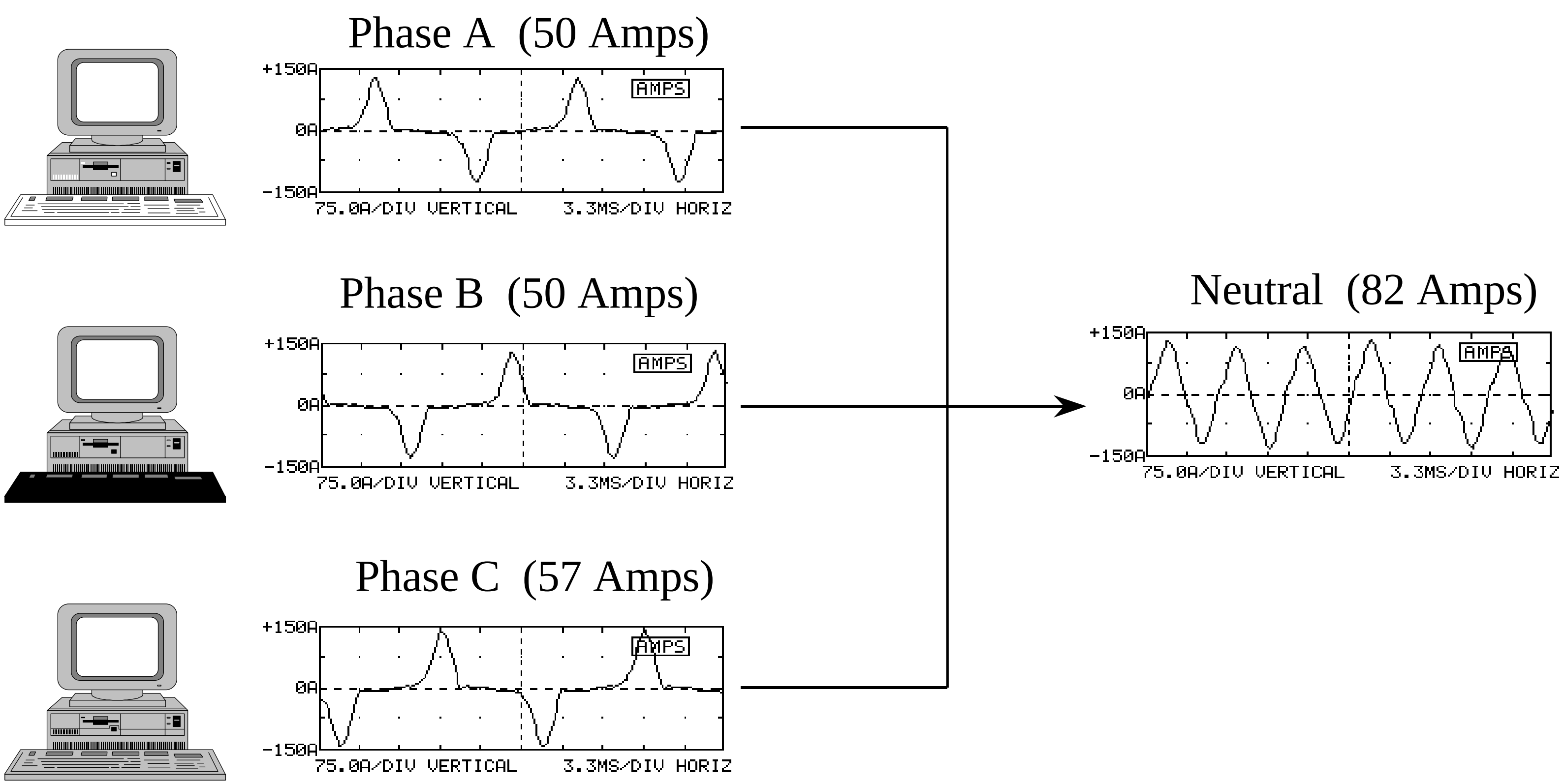
K Factor: 6.9

Standard Derating(ANSI/IEEE C57.110-1986): 0.88 pu

Assumed Eddy-Current Loss Factor (Pec-r) 8%

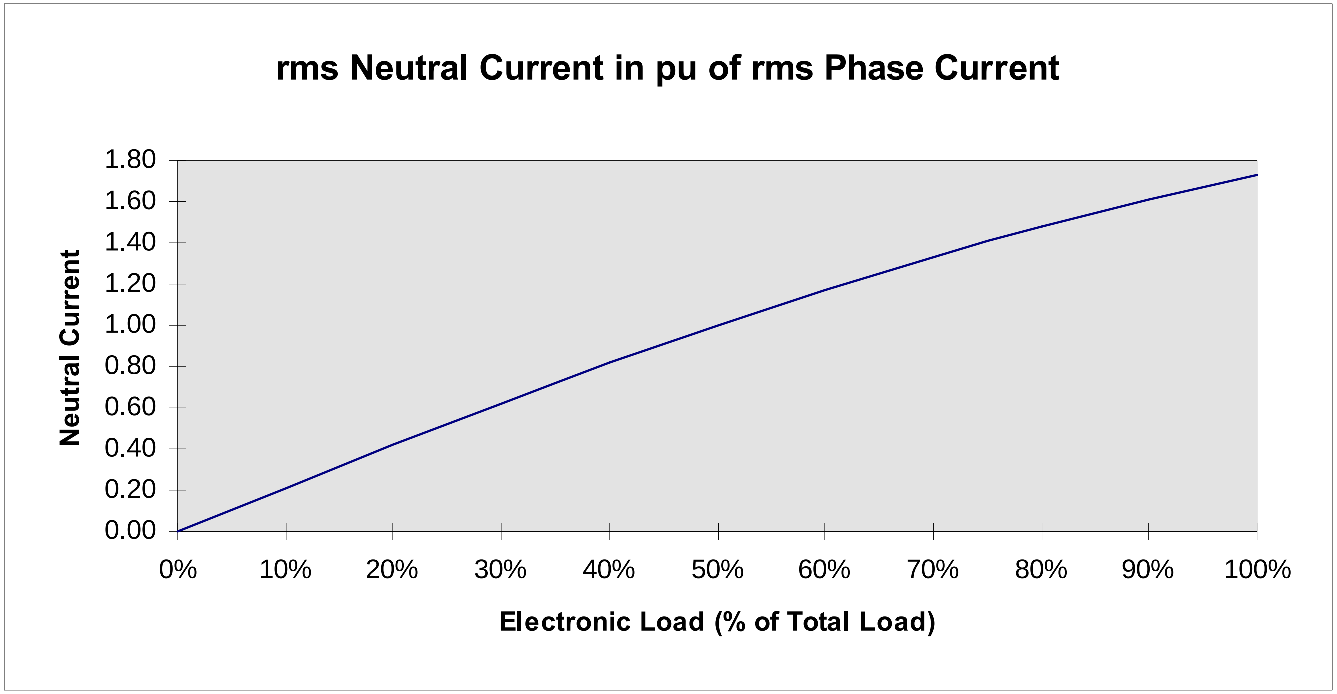
High Neutral Current

- Three phase and neutral currents for typical office computer circuit:

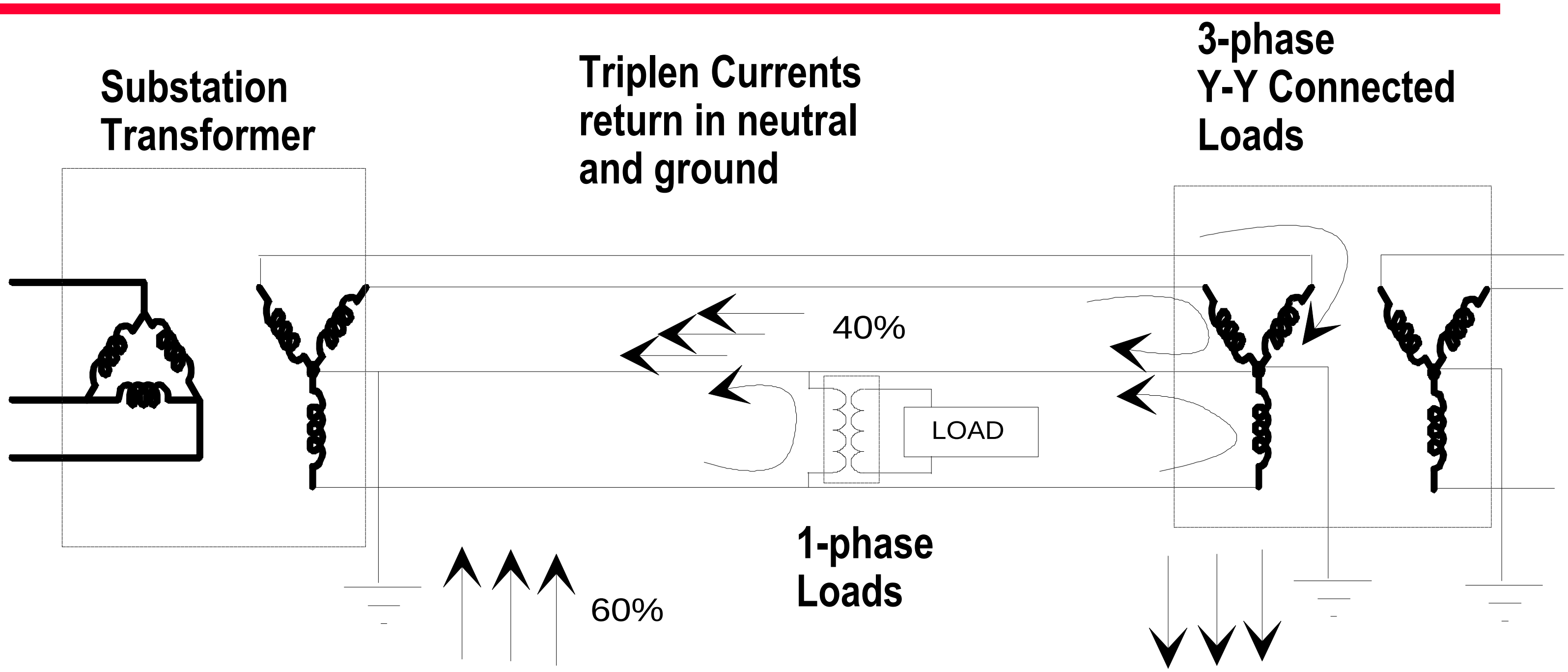


Estimating Neutral Currents

- This curve can be used to estimate neutral currents in per unit of the rms phase currents based on the portion of the circuit load that is electronic equipment.



Triplen Harmonic Currents

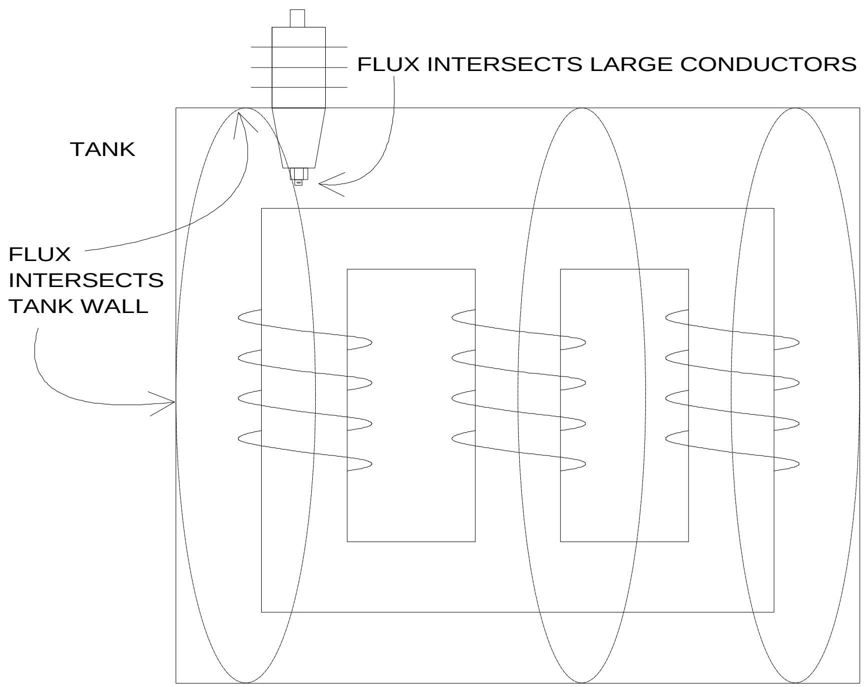


Sources of Triplen Harmonics:

Transformers
Lighting
Variable-Speed Heat Pumps
Computers, etc.

Adverse Effects of Triplen Harmonics

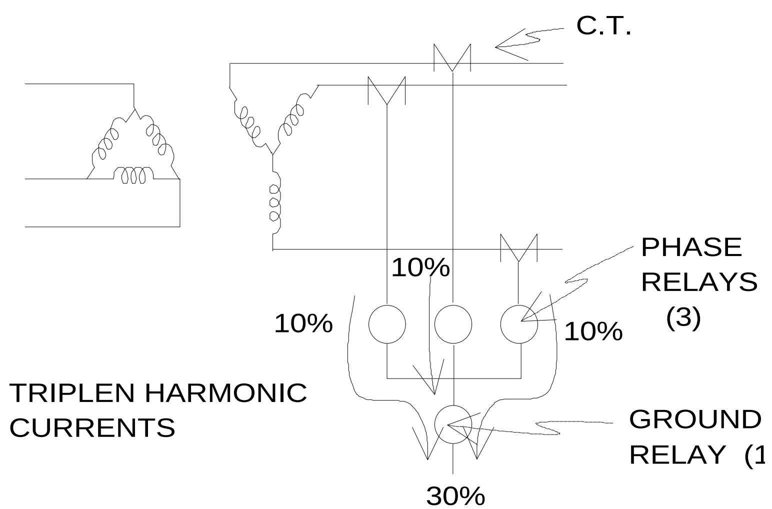
- Triplen Harmonics can cause substation transformer overheating
  - The zero-sequence flux does not stay in the core in 3-legged core transformers (most substation transformers)



Causes eddy currents in tank walls and other large conducting elements that are not normally in the flux field

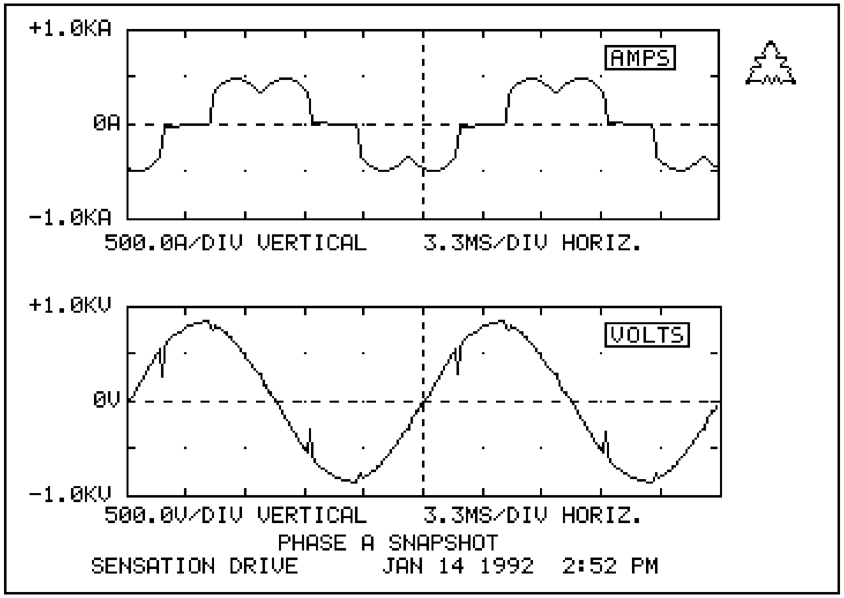
Adverse Effect of Triplen Harmonics

- Can cause ground relaying to false trip

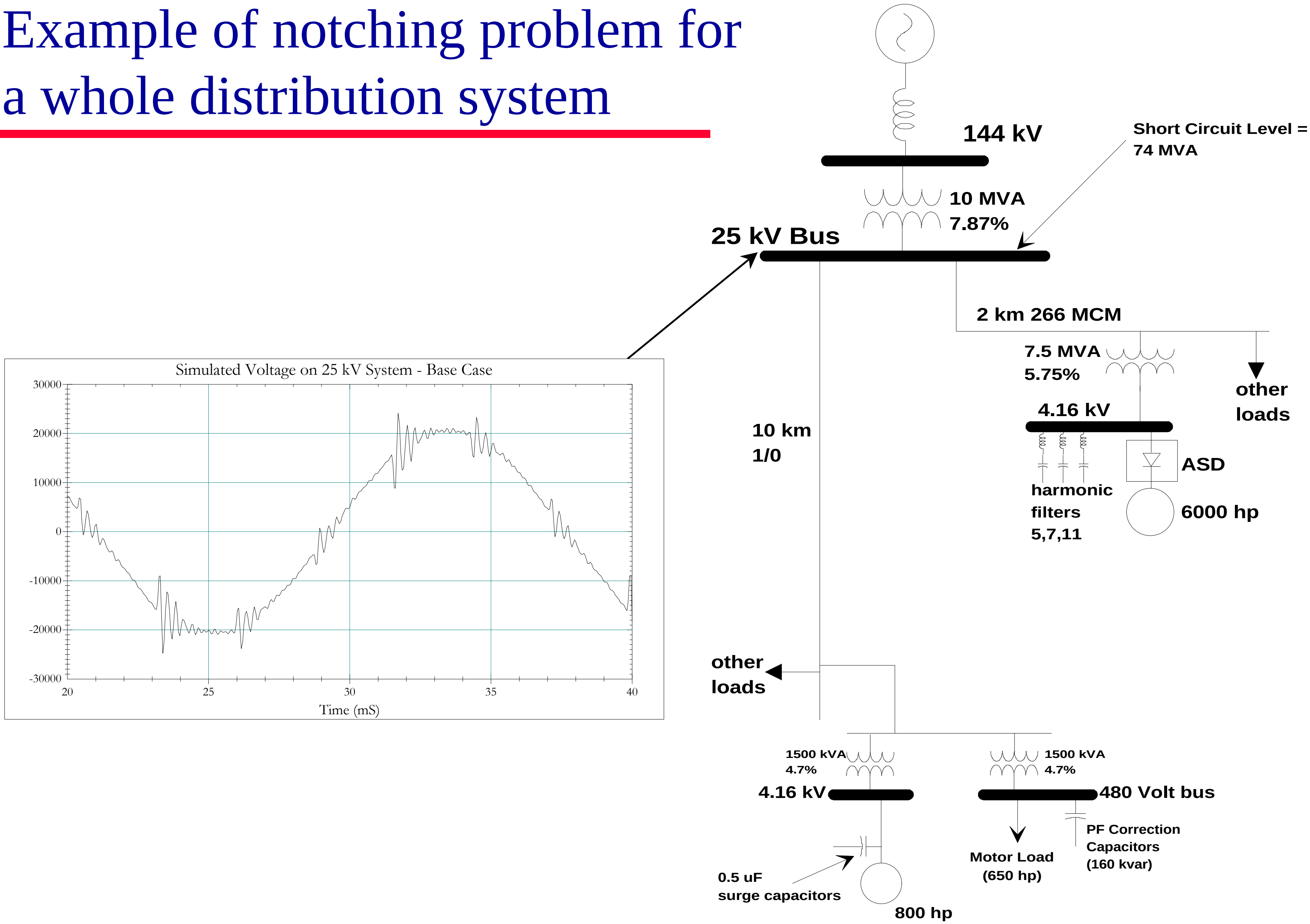


Timing Problems caused by Voltage Notching

- Caused by converter commutation.
- Dependent on firing angle and amount of commutating inductance.
- Can be controlled by the isolation inductance in series with the converter.
- Extra zero crossings cause clocks to run fast and other timing problems

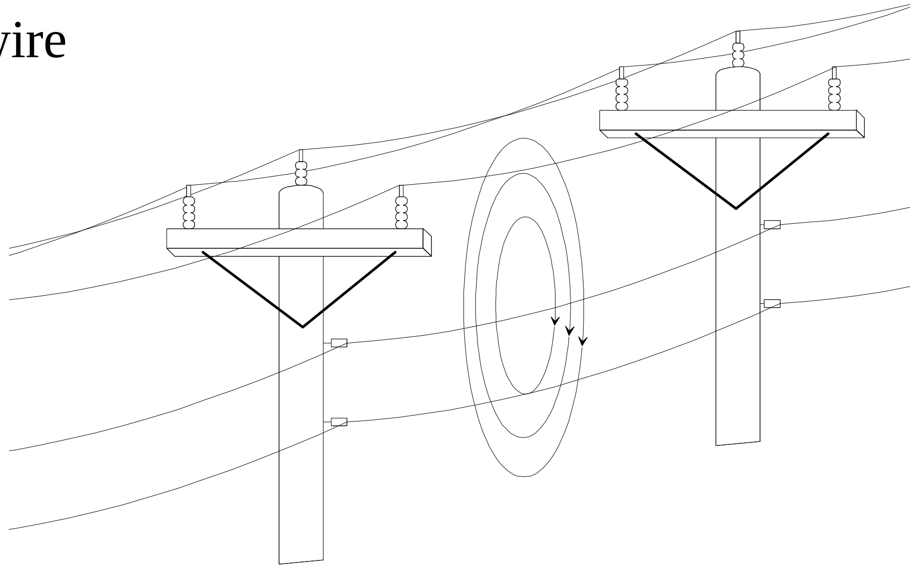


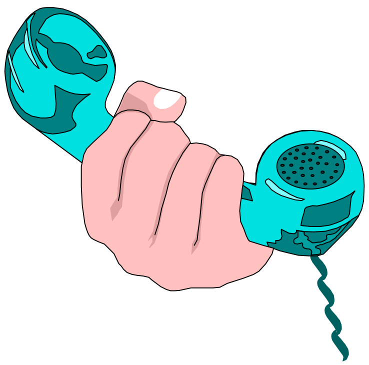
Example of notching problem for a whole distribution system



Telephone Interference

- Harmonic currents coupled into communication circuits.
- Mainly a problem with open-wire telephone circuits.
- Much less of a problem with twisted pair and shielded cables.



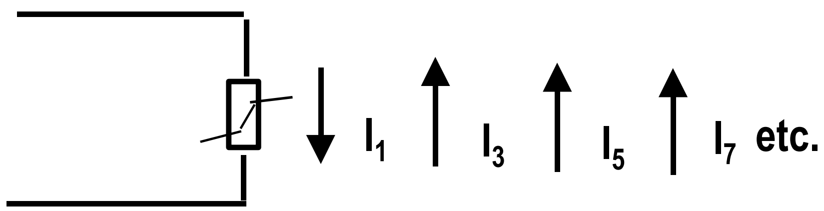


$$I*T = \sqrt{\left[\sum_{h=1}^{\infty} \left(I_h T_h\right)^2\right]}$$

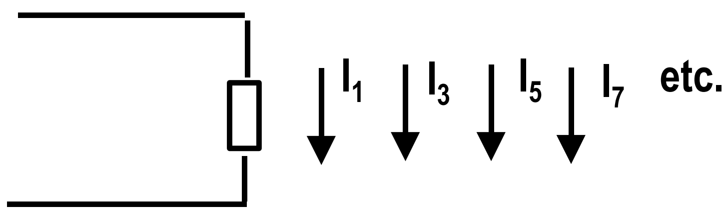
Effect of Harmonics on Metering

- Harmonic currents and powers typically flow out of nonlinear loads into the utility system
- Harmonic powers flow into linear loads if the voltage is distorted

Typical Nonlinear Load Case



Typical Linear Load Case Where Voltage is Distorted



Effect of Harmonics on Metering

- Watt-hour meters typically have a negative error at harmonic frequencies

Nonlinear Load

$P_{Measured} = P_1 - a_3P_3 - a_5P_5 - \ldots$ **> Actual Power consumed in load**

$(a_i < 1)$ **But harmonic powers mainly feed losses**

Linear Load

$P_{Measured} = P_1 + a_3P_3 + a_5P_5 + \ldots$ **< Actual Power consumed in load**

But extra power may be unwanted

In most practical cases, net metering of energy (KWH) has small error < 1%.

Effect of Harmonics on Metering

- Demand Metering

  Greatest metering errors are in demand metering

  Error is generally in the favor of the customer, when there is a significant error.

  Metering error is the result of ignoring reactive power due to harmonics.

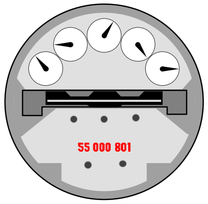
When Harmonics are present:

$$S = \text{Apparent Power} = \sqrt{P^2 + Q^2 + D^2}$$

"D" represents the reactive power due to the harmonics, which some metering schemes will neglect.

Harmonics and Metering

- Usually, there is not much real power (Watts) at harmonic frequencies (e.g. because voltage distortion is low).
- Conventional watt-hour meters under-register at harmonic frequencies.
- Electronic meters can accurately calculate watts in the presence of harmonics but it is not clear whether or not this is desirable.
- Meters that are measuring vars or power factor can be significantly impacted by distortion levels. In fact, there are no universally accepted definition for these quantities when harmonic distortion is present.



Harmonic Standards - Applying IEEE 519

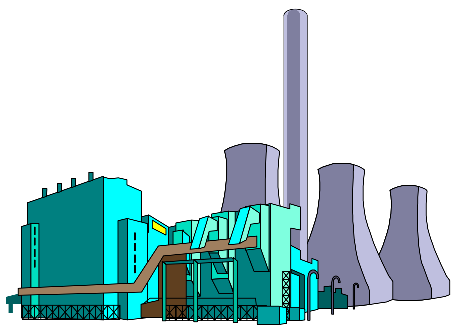
Standards for Harmonic Distortion Levels

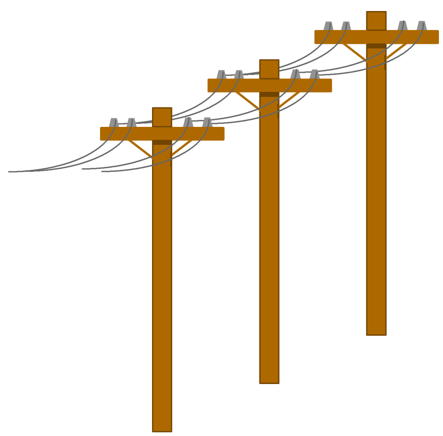
- Customer/System Limits:
  - IEEE 519-1992
  - IEC 1000-2-2 (Compatibility Levels)
  - IEC 1000-3-6
  - G5/3 (United Kingdom)
- Equipment Limits:
  - IEC 1000-3-2 (Formerly IEC 555-2) *up to 16 amps*
  - IEC 1000-3-4 *16-75 amps*
  - New Task Force in IEEE (Harmonic Limits for Single Phase Loads)
- How to Measure Harmonics:
  - IEC 1000-4-7

Scope of IEEE 519-1992

- Provide methodology for preventing harmonic voltage and current distortion problems on the power system through utility and customer cooperation.

Basic Philosophy of IEEE 519

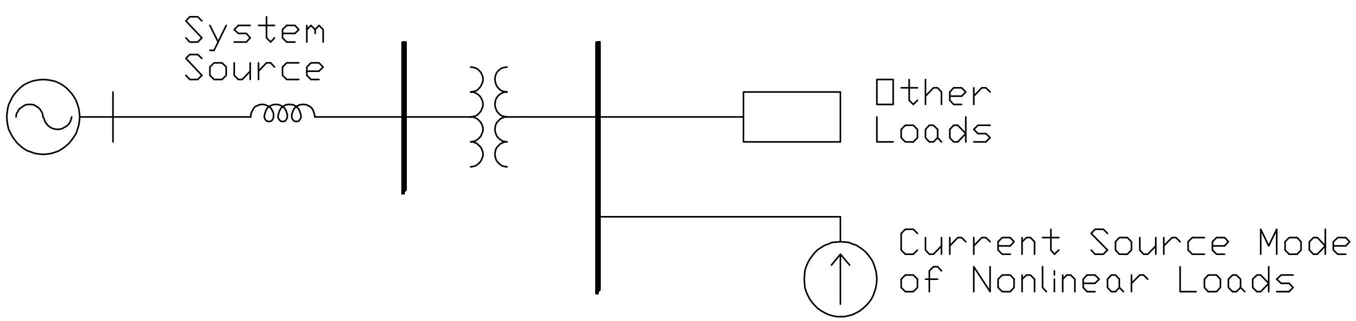




- The customer is responsible for limiting harmonic currents injected onto the power system.
- The utility is responsible for maintaining quality of voltage waveform.

Assumptions - Harmonic Sources

- Harmonics generated by nonlinear device characteristics
- Most devices look like sources of harmonic currents
- Voltage distortion caused by system response characteristics



Assumptions - System Response

- The normal flow of harmonics is from the source toward the utility supply.
- The most basic system characteristic is a simple inductance.
- The harmonic current limits for individual customers are based on this assumption.
- Capacitors can significantly affect the impedance vs. frequency characteristic - resonance.

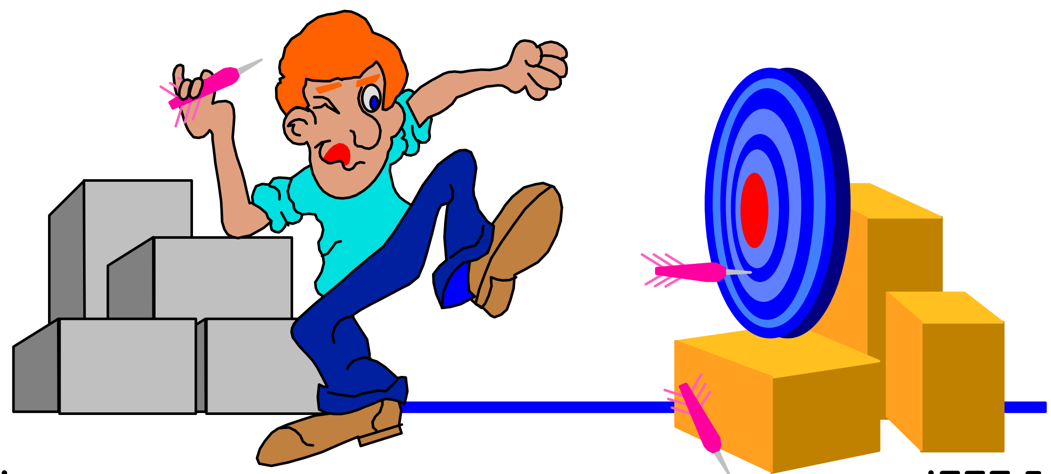
Harmonic Voltage Limits

Harmonic Voltage Limits - Utility Responsibility

Bus Voltage	Maximum Individual Harmonic Component (%)	Maximum THD (%)
69 kV and below	3.0%	5.0%
115 kV to 161 kV	1.5%	2.5%
Above 161 kV	1.0%	1.5%

Meeting Voltage Distortion Limits

- Limit the harmonic currents from nonlinear devices on the system (*customer harmonic current limits*).
- Make sure that system resonances do not result in excessive magnification of the customer harmonic currents (*utility control of system response)*.



How are Current Limits Developed?

- Assume the system can be represented by a short circuit inductance.
- Derive current distortion limits so that voltage distortion limits will not be exceeded.
- With diversity and cancellation, smaller customers can inject higher levels of harmonic currents.
- Higher harmonic current levels are permitted at lower order harmonic frequencies
  - Lower system impedance means lower voltage distortion
  - Lower frequencies have less impact on communication and transformers

Harmonic Current Limits

Harmonic Current Limits - Customer Responsibility

SCR = I_{sc}/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20 - 50	7.0	3.5	2.5	1.0	0.5	8.0
50 - 100	10.0	4.5	4.0	1.5	0.7	12.0
100 - 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Values shown are in percent of "*average maximum demand load current*"

SCR = short circuit ratio (utility short circuit current at point of common coupling divided by customer average maximum demand load current)

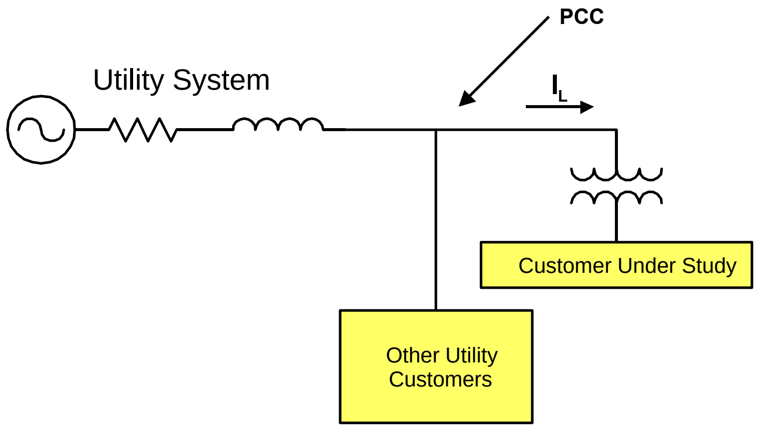
TDD = Total Demand Distortion (uses maximum demand load current as the base, rather than the fundamental current)

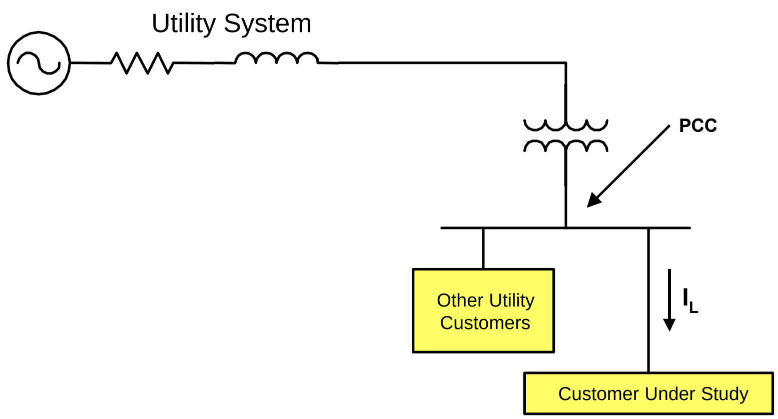
Important Concepts

- Point of Common Coupling:
  - Interface between the utility and the customer
  - This is where limits are applied (NOT AT INDIVIDUAL PIECES OF EQUIPMENT)
- Average Maximum Demand Load Current:
  - Maximum monthly demand load current averaged over 12 months
  - All percentages in the table are based on this current (NOT THE FUNDAMENTAL)
- SCR - Short Circuit Ratio:
  - Ratio of the short circuit current at the point of common coupling to the “average maximum demand load current”

Point of Common Coupling

- Usually high side of customer transformer
- Measurements can be performed on low side and referred to high side





Some Important Questions

- Where is the Point of Common Coupling?
  - Interface with other customer
  - Metering location
  - Equipment location

- What is the "average maximum demand load current"?
  - What about new facilities?
  - New equipment, system changes

- How can we estimate compliance?
  - Source characteristics
  - Cancellation, how they combine

More Questions

- How do we measure compliance?
  - Where to measure, what quantities?
  - When? For how long?
  - Statistics of harmonic levels
- What about non-integer harmonics?
  - arc furnaces
  - cycloconverters
- How do we handle interaction between customer and the system?
  - Filters and capacitors absorb harmonic currents from system
  - Need to know direction of harmonic current flow

Total Demand Distortion

Total Demand Distortion (*TDD*) is defined as:

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

where:

I_h = magnitude of individual harmonic components (rms amps)

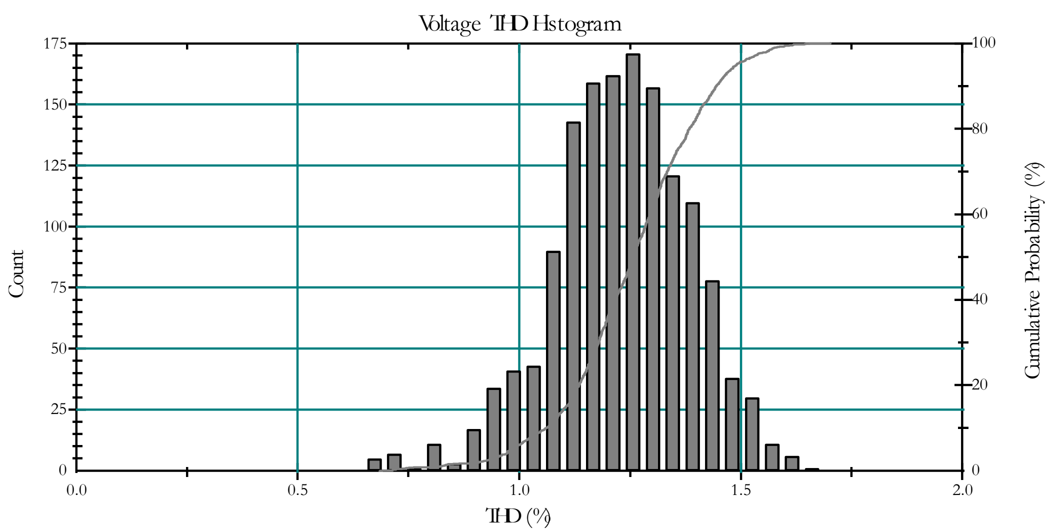
h = harmonic order

I_L = maximum demand load current (rms amps) defined above

Measurements

- Measure at the point of common coupling.
- Measure over a period of time. IEEE 519 allows up to 150% of the current limit for up to 1 hour. Another approach would be to use the 95% probability level (IEC approach)

NOT JUST A SNAPSHOT!

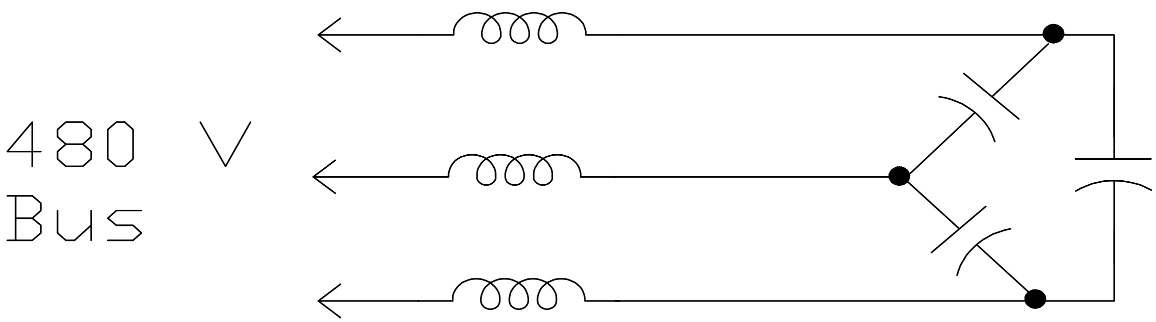


Evaluation Procedure

- Customer load characteristics from billing information, estimates of future loads.
- Measurements to characterize the customer harmonic current generation.
- Evaluate impact of power factor correction procedures.
- Evaluate levels with respect to standard.
- Joint development of solutions if there is a problem.

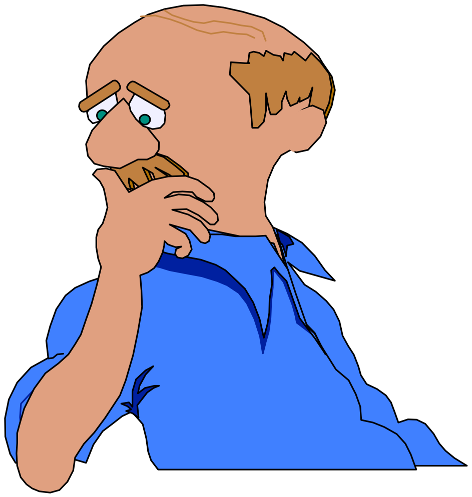
Developing Solutions

- Solutions must consider interaction between system and customer - COOPERATION needed.
- Analysis tools will often be required.
- Identify problems and solve them at design stage.



How to Use the Standard

- Use it to prevent distortion problems from occurring.
- Use it as a starting point for evaluation of problems.
- Use the numbers as guidelines.
- Engineering judgment needed!!!!!!



What’s the Next Step

- “Application Guide for Applying Harmonic Limits”
- Evaluate experience of utilities using the standard
- Better measurement tools, analytical tools
- Cooperation between utilities and customers to solve problems

IEC Approach

- Limit harmonic currents for individual equipment (type testing).
- IEC 1000-3-2 for equipment up to 16 amps.
- IEC 1000-3-4 for equipment up to 75 amps (under development).
- This should limit overall harmonic distortion levels to acceptable values.
- Procedure for evaluating customers supplied at medium voltage and high voltage (1000-3-6).

IEC Approach for MV/HV Customers

- IEC Approach for MV/HV Customers (1000-3-6):

Three stage approach:

- Stage 1: Automatic Acceptance.
- Stage 2: Acceptance Based on Customer and System Characteristics.
- Stage 3: Special Case Exceptions for Customers Exceeding Stage 2 Limits.

IEC 1000-3-2 (General Loads)

- Equipment current limits for equipment up to 16 amps.
- Designed for 380 volt systems (L-L).
- Class A equipment is general purpose loads.

Harmonic Order	Maximum Permissible Harmonic Current (in Amperes)
Odd Harmonics	
3	2.3
5	1.14
7	0.77
9	0.4
11	0.33
13	0.21
15-39	0.15 x (15/n)
Even Harmonics	
2	1.08
4	0.43
6	0.3
8-40	0.23 x (8/n)

IEC 1000-3-2 (Lighting Loads)

- Class C equipment:

Harmonic Order	Maximum value expressed as a percentage of the fundamental input current of luminaires
2	2%
3	30% x PF
5	10%
7	7%
9	5%
11-39	3%

IEC 1000-3-2 (Power Supply Loads)

- Class D equipment (special waveform).
- Note that relative limits only apply up to 300 watts. Absolute limit applies up to the 16 amp maximum.

Harmonic Order	Relative Limit (mA/W)	Maximum permissible harmonic current (A)
3	3.4	2.3
5	1.9	1.14
7	1	0.77
9	0.5	0.4
11	0.35	0.33
13-39	linear extrapolation: 3.85/n	see table for Class A equipment

IEC 1000-3-4 (Loads up to 75 Amps)

- Under development.
- Limits dependent on short circuit ratio.
- Initial draft set of limits under discussion.

	I1/Ic < 1/35	I1/Ic < 1/170
Harmonic Order	In/I1 (%)	In/I1 (%)
3	21.6	50.4
5	10.7	25
7	7.2	16.9
9	3.8	8.8
11	3.1	7.2
13	2	4.6
15	0.7	1.6
17	1.2	2.8
19	1.1	2.6

IEC 1000-2-2 Compatibility Levels

Harmonic Voltage COMPATIBILITY LEVELS (IEC 1000-2-2)

ODD HARMONICS						EVEN HARMONICS		
not multiple of 3			multiples of 3					
	Harmonic Voltage (%)			Harmonic Voltage (%)			Harmonic Voltage (%)	
Order h	LV-MV	HV	Order h	LV-MV	HV	Order h	LV-MV	HV
5	6	2	3	5	2	2	2	2
7	5	2	9	1.5	1	4	1	1
11	3.5	1.5	15	0.3	0.3	6	0.5	0.5
13	3	1.5	21	0.2	0.2	8	0.5	0.5
17	2	1				10	0.2	0.5
19	1.5	1	>21	0.2	0.2	12	0.2	0.2
23	1.5	0.7						
25	1.5	0.7				>12	0.2	0.2
>25	0.2+1.3(25/h)	0.2+0.5(25/h)						

THD Limit = 8% for LV-MV Systems

Characterizing Levels with Measurements

- IEC Approach - Harmonic levels are characterized statistically
  - **Un_{vs}** = mean rms value at harmonic n with a sliding "very short" (3 sec) window.
  - **Un_{sh}** = mean rms value at harmonic n with a sliding "short" (10 min) window
  - Important statistical values:
    - » maximum
    - » 95% probability level
      (most of compatibility levels are based on this)
    - » mean
- IEEE Approach - guidelines for measurements but no fixed characterization procedure.

Controlling Harmonic Problems

General Methods for Harmonic Control

- Control characteristics of the harmonic sources (IEC 555-2)
- Harmonic cancellation between nonlinear loads
- Passive harmonic filters
  - Individual loads
  - Filtering for groups of loads (e.g. service entrance)
  - Filtering on the power system
- Active filters
  - End user system
  - Distribution system

Controlling Harmonic Distortion

- Harmonic Characteristics of the Nonlinear Loads
- Cancellation of Harmonics from Different Loads
- Avoiding Resonance Problems
- Designing Harmonic Filters
- Active Filters

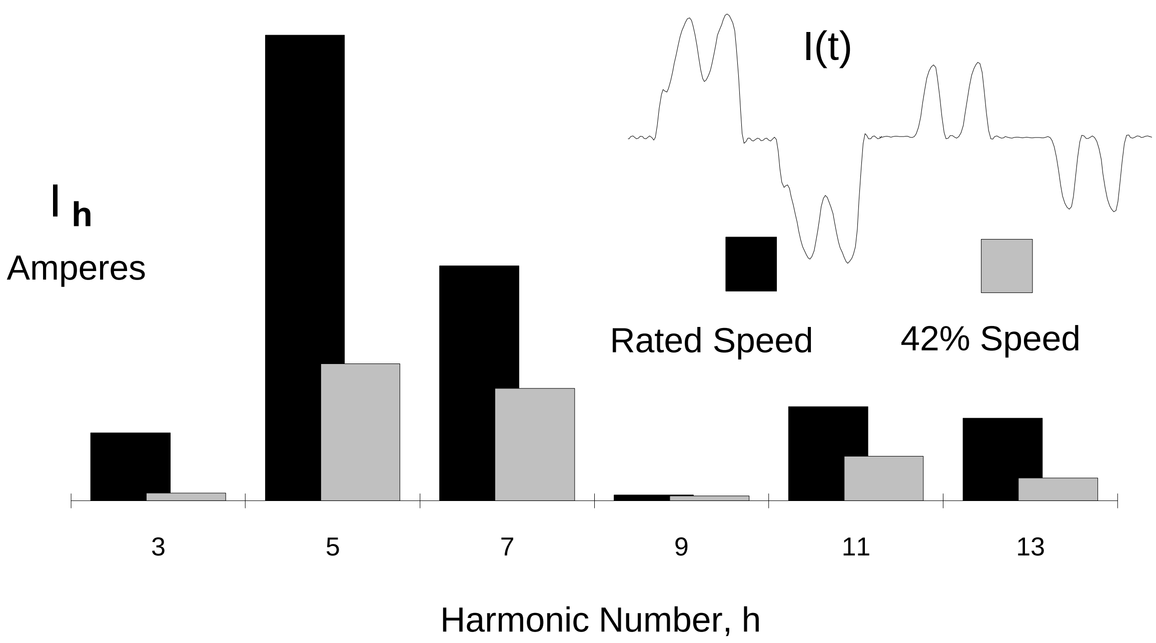
Harmonic Characteristics of Nonlinear Loads

- Best place to solve harmonic problems is at the source.
- Nonlinear loads can be designed to minimize the generation of harmonic currents.
- May involve some increased cost - therefore, economic evaluation of different options may be needed

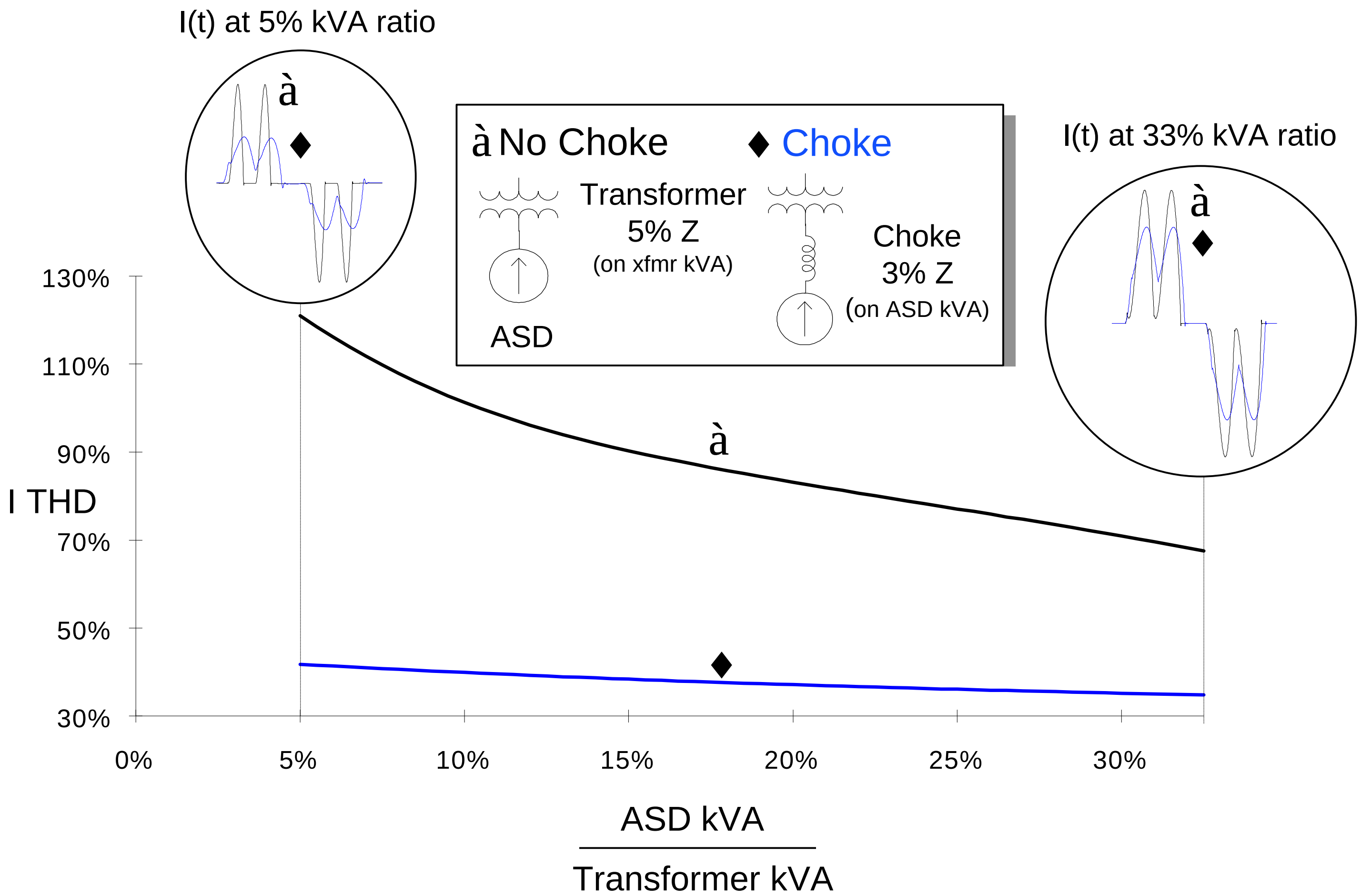
PWM Type Adjustable Speed Drives

Harmonic currents are a function of the motor load (speed).

Can be fooled by expressing the harmonic currents as a percent of the fundamental.



Effect of ac side line choke



Other equipment design issues

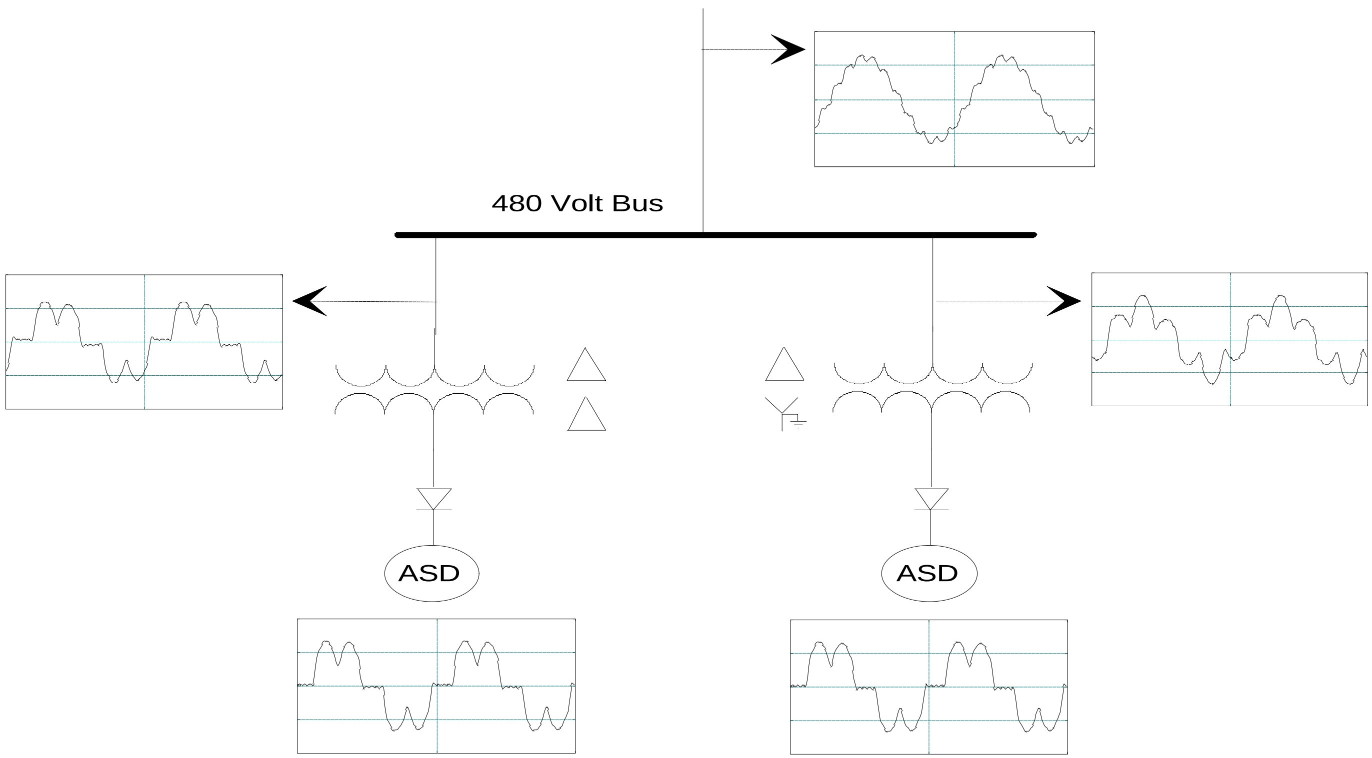
- Choke can be part of the dc link in PWM type drives or on the ac input.
- Active front ends for smaller drives significantly increase the cost (almost double).
- Different design options are possible for larger drives to control harmonics - information from manufacturers about harmonic generation characteristics.
- Current source drives and induction furnace converters - be careful about interharmonics (output frequency coupling to the input).

Harmonic Cancellation Techniques

- 12-pulse converters and ASDs
- Supplying different loads with different transformer connections

Transformer configuration for 12 pulse operation

60% of the plant load could be ASDs without exceeding 519 guidelines if they are in a 12 pulse configuration



Normal cancellation from different loads in an industrial facility

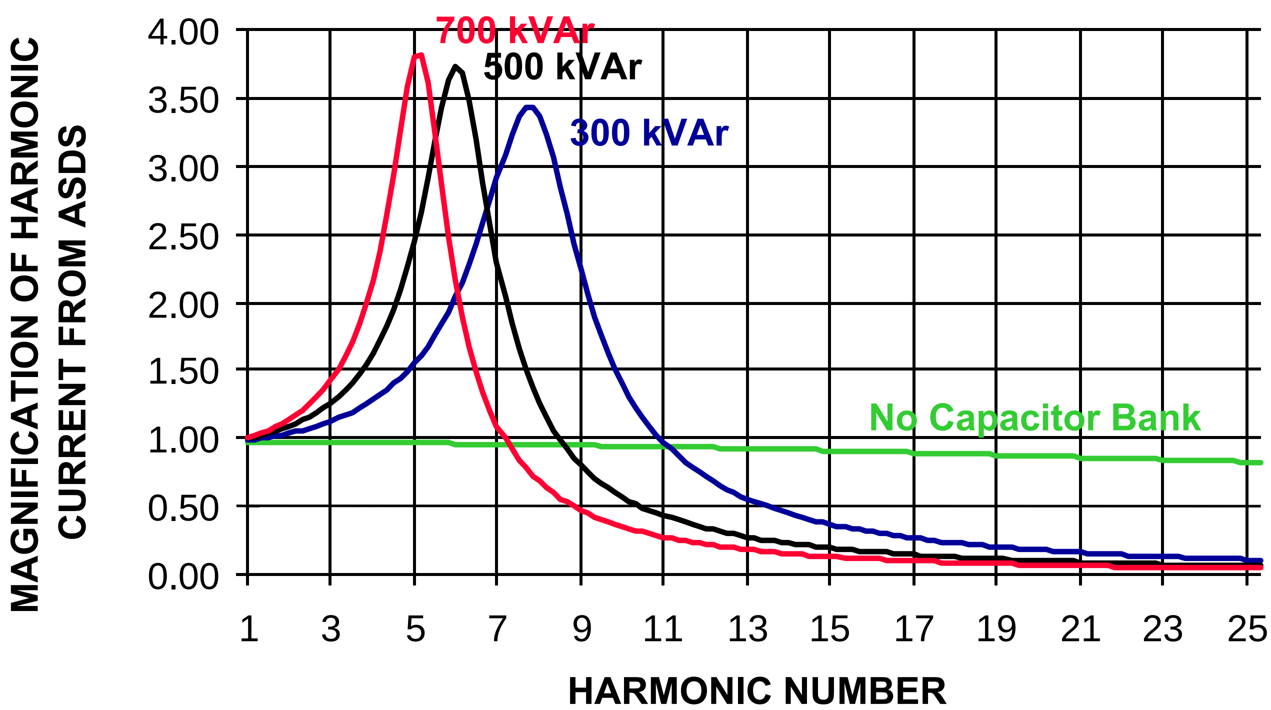
- PWM-type ASDs will not tend to have much cancellation of lower order harmonic components (rectifiers are not phase-controlled)
- DC Drives could have 30-50% cancellation from multiple drives, depending on the number of drives.
- The cancellation will be much better if some drives are supplied through delta-wye transformers and some drives through delta-delta transformers.

Avoiding Resonance Problems

- Power factor correction capacitors can cause resonance problems
- Most problems can be avoided by choosing a capacitor size that will not result in a resonance near the fifth or seventh harmonic component
- Typically, this means a capacitor that is less than 25% of the transformer kVA
- If more kvar is needed for power factor correction, filters (tuned banks) may be needed

Resonance Frequency

Resonance vs. capacitor size for a typical customer supplied with a 1500 kVA, 6% transformer.

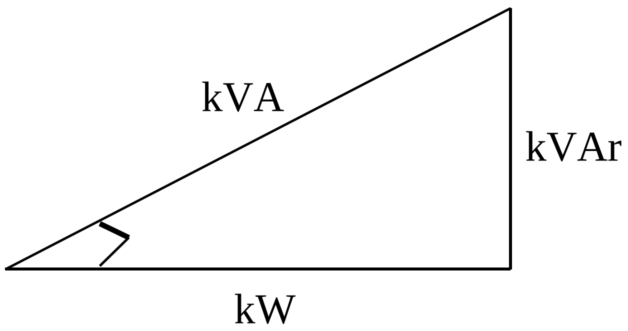


Filter Design

- Size the filters for power factor correction requirements.
- Make sure they can handle worst case harmonics from nonlinear loads in the facility and from background harmonics on the power system.
- Filters used to avoid resonance problems - don't necessarily need to be tuned right on a harmonic.
- Always tune the filter at or below the lowest characteristic harmonic of the nonlinear loads.

Determine power factor correction requirements

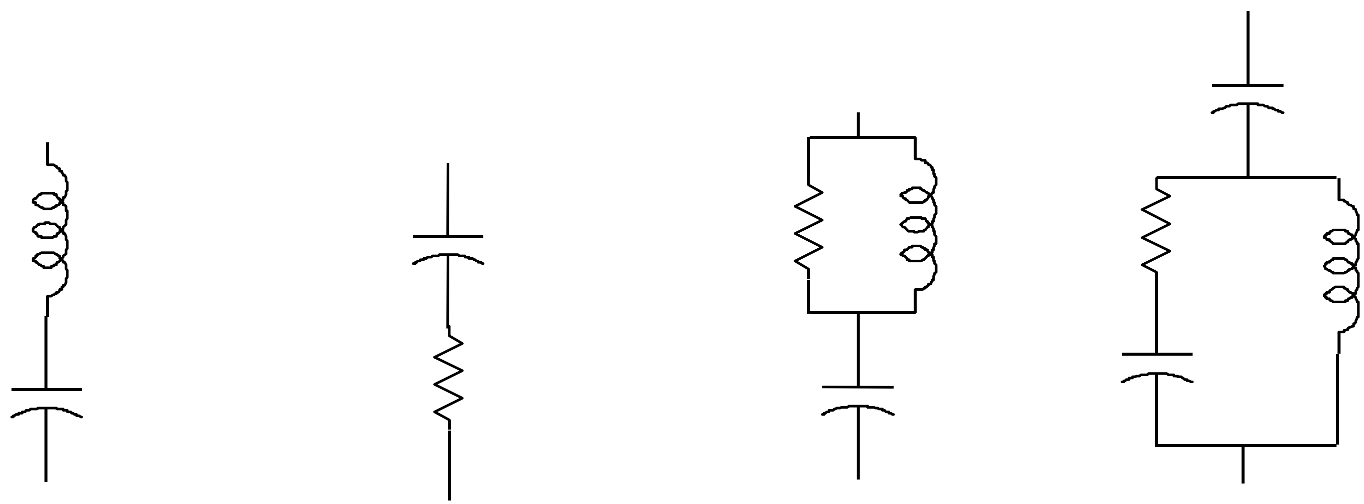
Power factor correction requirements determined from displacement power factor (dPF), not True Power Factor.



$$\mathrm{DPF} = \cos\theta$$

$$\mathrm{kVA} = \sqrt{\mathrm{kW}^2 + \mathrm{kVAr}^2}$$

Filter Configurations



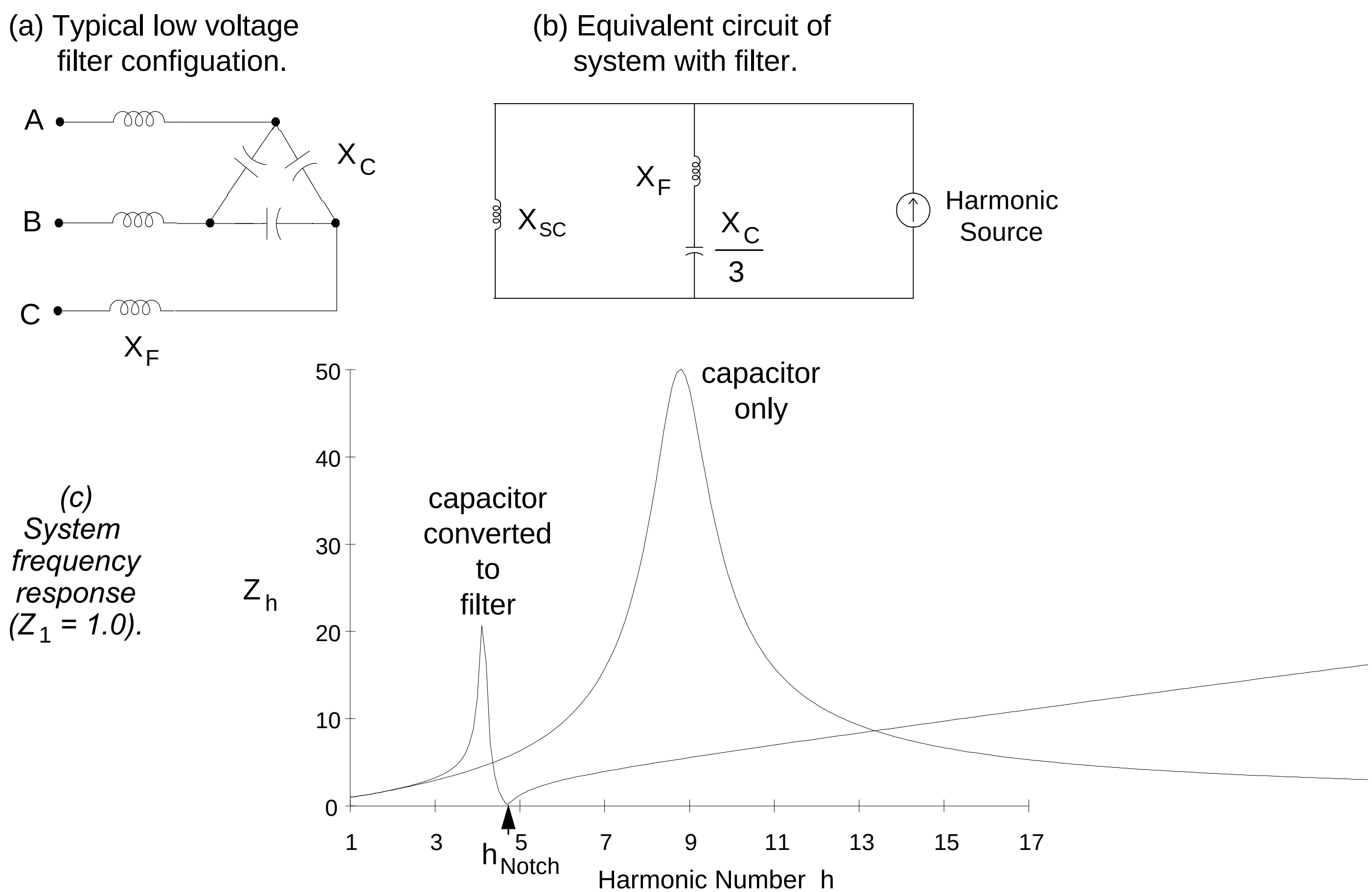
SINGLE-TUNED

FIRST ORDER HIGH-PASS

2ND ORDER HIGH-PASS

3RD ORDER HIGH-PASS

Effect of filter on the frequency response characteristics



Example Filter Design Spreadsheet

Low Voltage Filter Calculations: **Example Filter Specification**

SYSTEM INFORMATION:

Filter Specification:	5	th	Power System Frequency:	60	Hz
Capacitor Bank Rating:	500	kVAr	Capacitor Rating:	480 60	Volts Hz
Nominal Bus Voltage:	480	Volts	Derated Capacitor:	500	kVAr
Capacitor Rated Current:	601.4	Amps	Total Harmonic Load:	500	kVA
Filter Tuning Harmonic:	4.7	th	Filter Tuning Frequency:	282	Hz
Cap Impedance (wye):	0.4608	W	Cap Value (wye):	5756.5	uF
Reactor Impedance:	0.0209	W	Reactor Rating:	0.0553	mH
Filter Full Load Current:	629.9	Amps	Supplied Compensation:	524	kVAr
Transformer Nameplate: *(Rating and Impedance)*	1500 6.00	kVA %	Utility Side Vh: *(Utility Harmonic Voltage Source)*	1.00	% THD
Load Harmonic Current:	30.00	% Fund	Load Harmonic Current:	180.4	Amps
Utility Harmonic Current:	47.7	Amps	Max Total Harm. Current:	228.1	Amps

CAPACITOR DUTY CALCULATIONS:

Filter RMS Current:	669.9	Amps	Fundamental Cap Voltage:	502.8	Volts
Harmonic Cap Voltage:	36.4	Volts	Maximum Peak Voltage:	539.2	Volts
RMS Capacitor Voltage:	504.1	Volts	Maximum Peak Current:	858.0	Amps

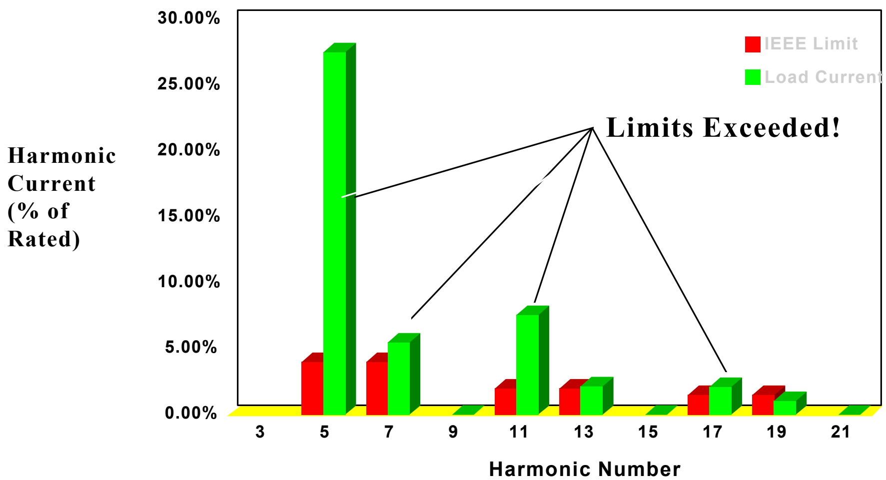
Important Parameters:

- Capacitor Size and Voltage
- Tuning Frequency
- Reactor Impedance
- Capacitor Limits
- Reactor Current Rating (60 Hz and Harmonic)

CAPACITOR LIMITS: (IEEE Std 18-1980)

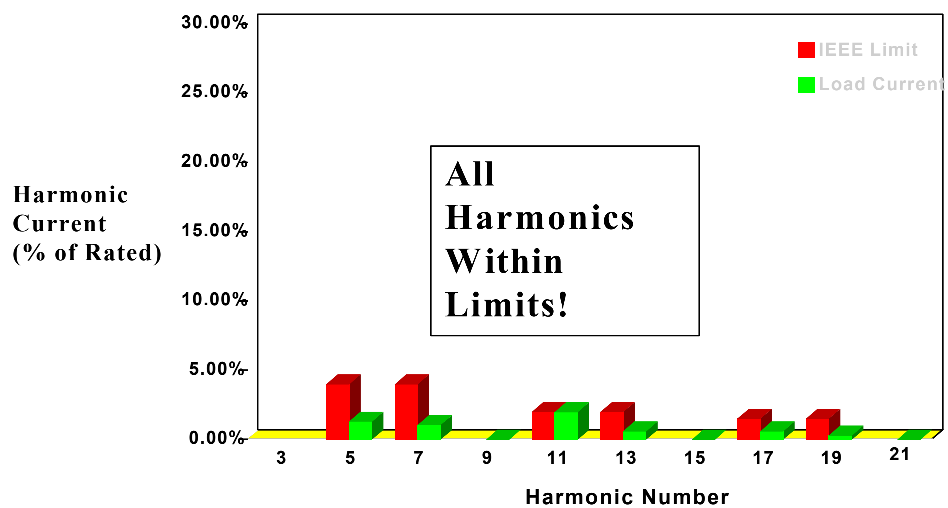
	Limit		Actual
Peak Voltage:	120%	⟷	112%
Current:	180%	⟷	111%
KVAr:	135%	⟷	117%
RMS Voltage:	110%	⟷	105%

Simple Filter Works for Most Cases



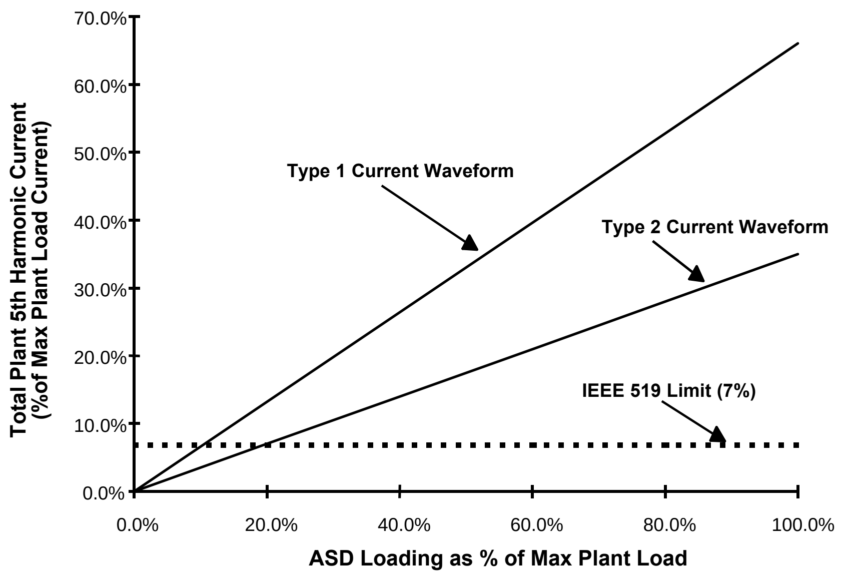
Plant with dc drives - no filters or power factor correction

Plant with dc drives - power factor correction applied as filters tuned to the 4.7th harmonic

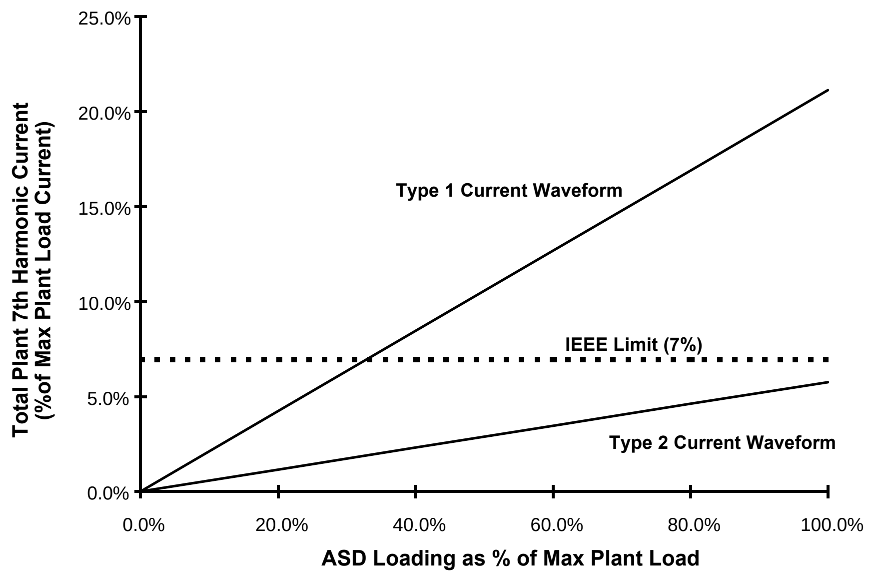


Effect of 4.7th Filter in General Case with ASDs

No filters or power factor correction



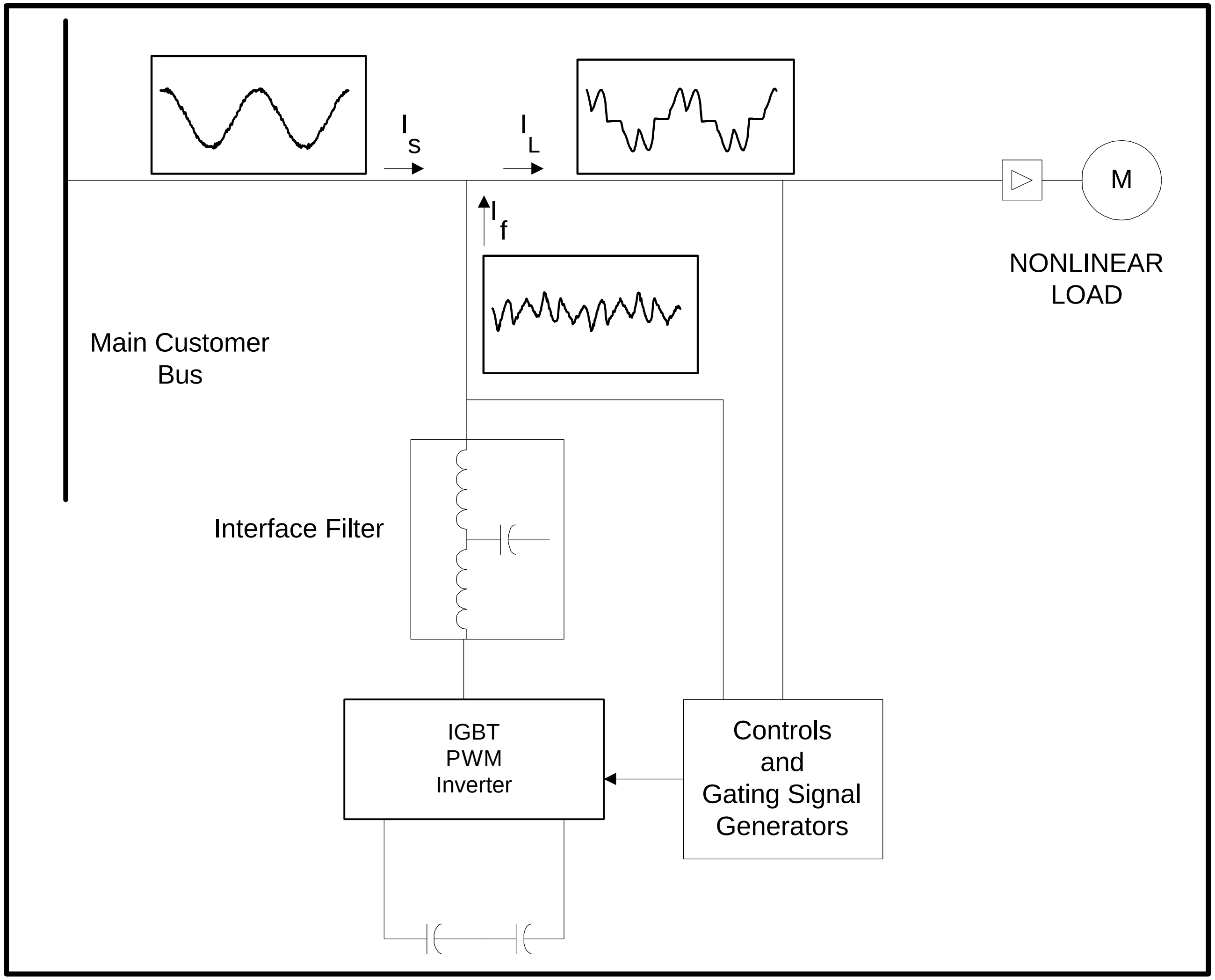
Power factor correction applied as filters tuned to the 4.7th



Active Filters

- Active power line conditioners are becoming available in sizes up to 150 kVA
- APLCs negate the harmonic currents injected by the non-linear loads connected to them
- The combination of the APLC and non-linear loads looks like a resistive load to the power system with low distortion and unity power factor

Active Filter Components

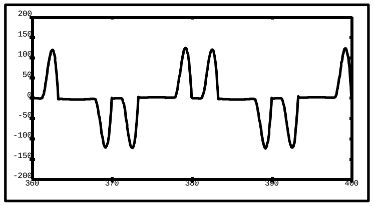


Active filter effectiveness for ASD Loads

Drive with no choke:

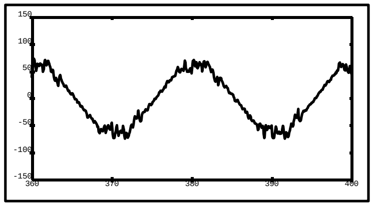
Required rating = 0.88 amps/kVA of load

Load current



THD = 109%

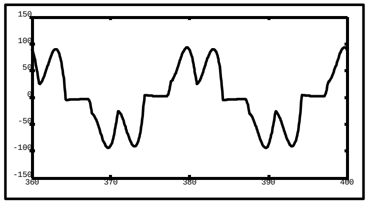
Source current



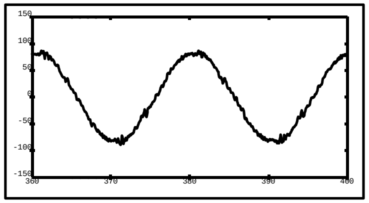
THD = 13.2%

Drive with 3% choke:

Required rating = 0.49 amps/kVA of load



THD = 45%



THD = 5.0%

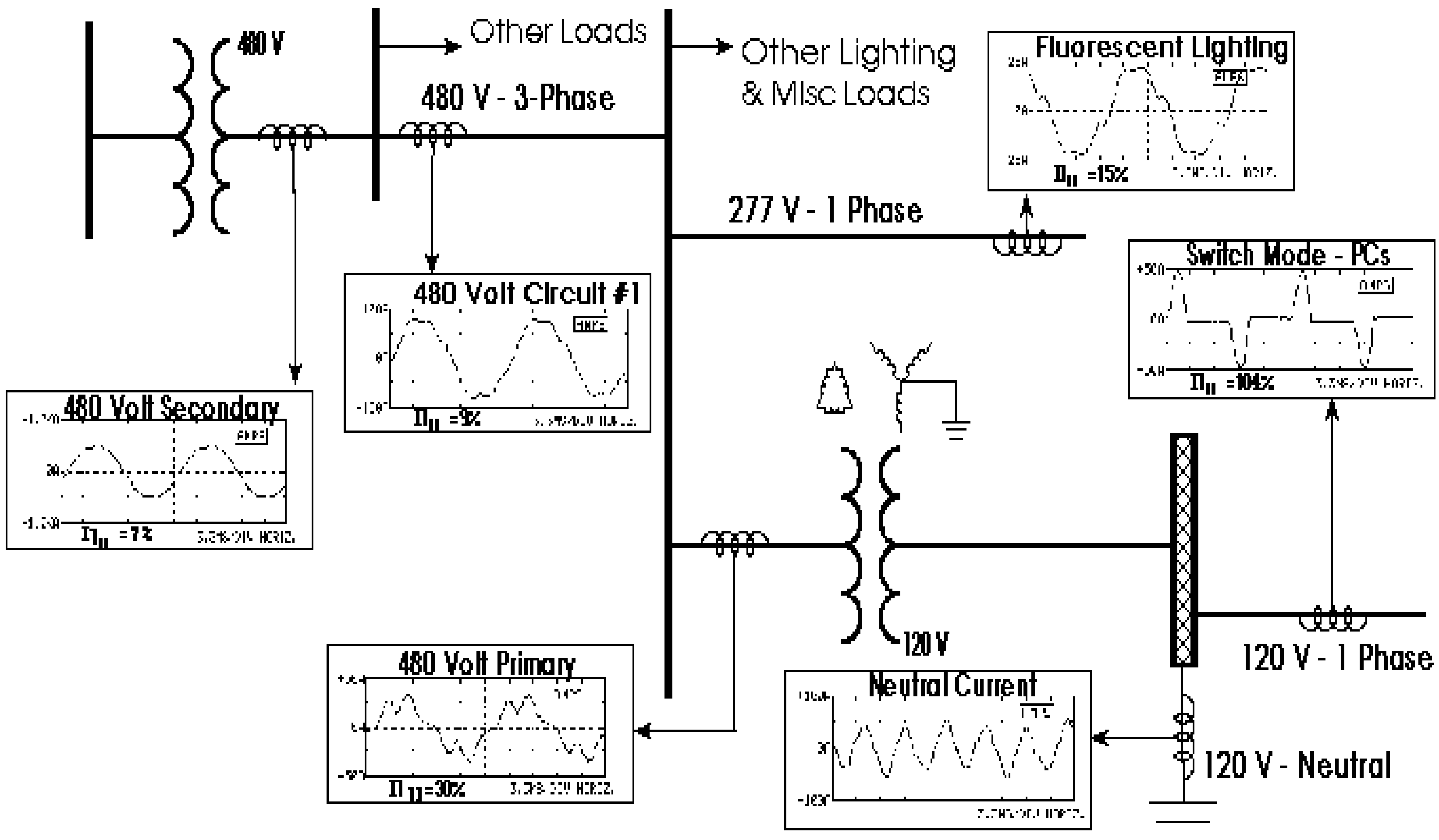
Good applications for active filters

- Nonlinear loads that do not require fundamental frequency reactive compensation (e.g. switch mode power supplies, PWM ASDs).
- Hybrid configuration with passive filters for improved harmonic control.
- 12 pulse converters where additional harmonic control still needed.
- The technology can be built into the converters for UPS systems or other energy storage devices.

Commercial Facility Concerns

- Proliferation of electronic loads
- Harmonic cancellation from multiple sources
- Distortion levels within facility vs. service entrance
  - transformer derating
  - neutral currents
- Impact of ASDs for HVAC systems

Harmonic Cancellation



Problem - Excessive Neutral Currents

- Usually Caused by Office Equipment
  - Printers, PCs
  - Switch Mode Power Supplies
- Neutral Current May be 173% Larger than Phase Conductor Currents
  - No Overcurrent Protection on Neutral Conductors
  - Transformer Neutrals also Affected

Solutions to Overloaded Neutrals and Transformer Derating

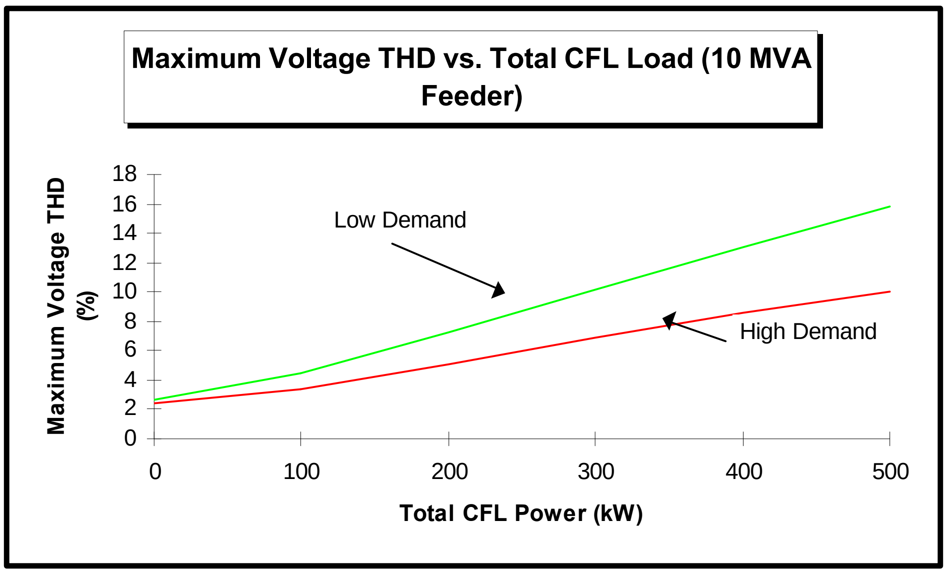
- Increase the neutral conductor size
- Neutral for each phase
- Double neutral
- Third harmonic filter at each load
- Zig Zag transformer close to loads
- Active filters

Residential Circuit Concerns

- Electronic equipment
- Compact fluorescents
- ASDs for heat pumps and air conditioners
- EV battery chargers?
- Where to control harmonics (equipment, customer, system)

Compact Fluorescents

- Current distortion typically 100-135%
- Harmonics tend to add on the distribution system
- Preliminary studies indicate a potential problem at relatively low penetration levels.

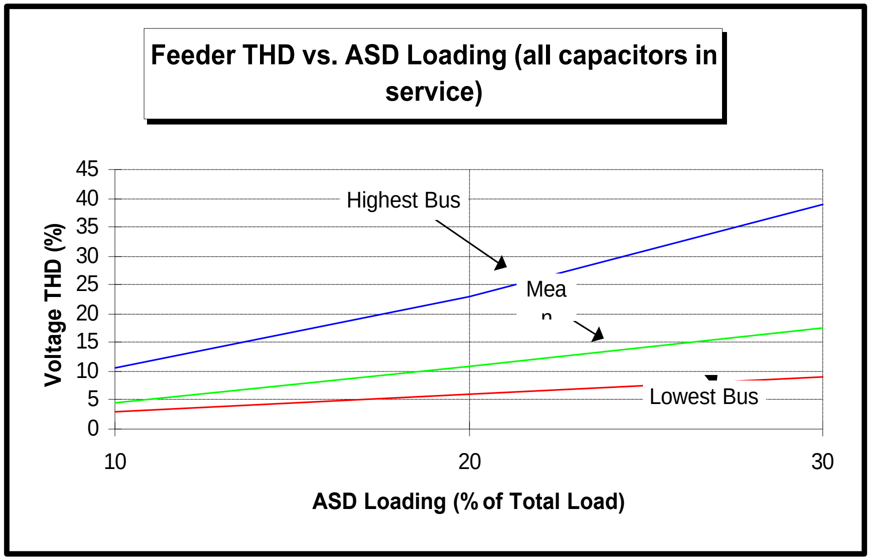


"The Effect of Modern Compact Fluorescent Lights on Voltage Distortion," D.J. Pileggi et al, 1992 Summer Power Meeting.

ASDs for Heat Pumps, Air Conditioners

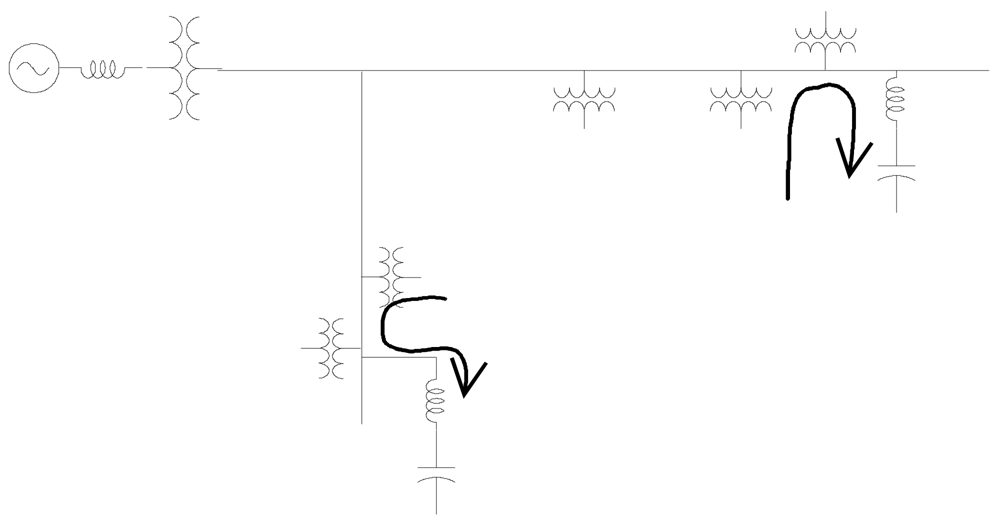
- Similar concerns to compact fluorescents, except much larger load.
- Typical current distortion at full load without choke = 70%
- Choke can reduce input current distortion to approximately 35%

"Field Measurements and Preliminary Study of Harmonic Distortion Caused by Distributed Single Phase ASD Heat Pumps," W.M. Grady et al, PQA 92.



Harmonic Control on the Distribution System

- General Filtering Principles
  - Shorten path for critical harmonics
  - “Nail down” the voltage distortion at the ends of the feeder



Summary/Conclusions

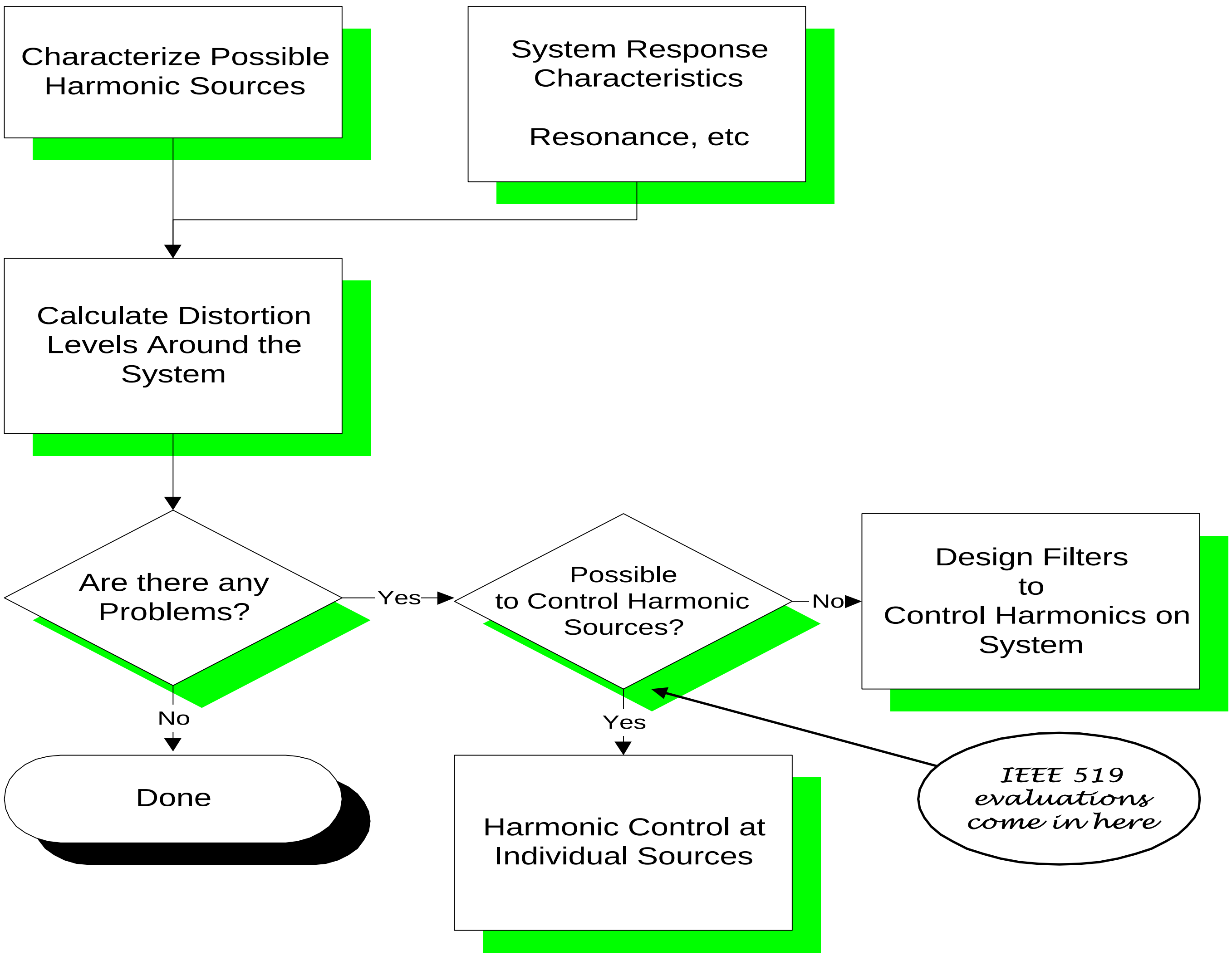
- Best place to solve harmonic problems is at the source (equipment specifications, equipment design).
- Always make sure ASDs have a choke inductance built in or added to the front end.
- Harmonic problems come up when power factor correction capacitors are added - consider tuned banks to avoid problems
- Active filters may play a more significant role in the future, especially if they are part of UPS systems or other energy storage systems

Power System Analysis and Modeling

Harmonic Analysis Methods

- Preliminary assessment:
  - hand calculations to determine system resonant frequencies
- Harmonic measurements:
  - characterize the behavior of harmonic sources
- Computer simulations:
  - investigate different conditions and system configurations
- Solution development:
  - changing capacitor sizes and/or locations installing harmonic filters or active filters

Methodology



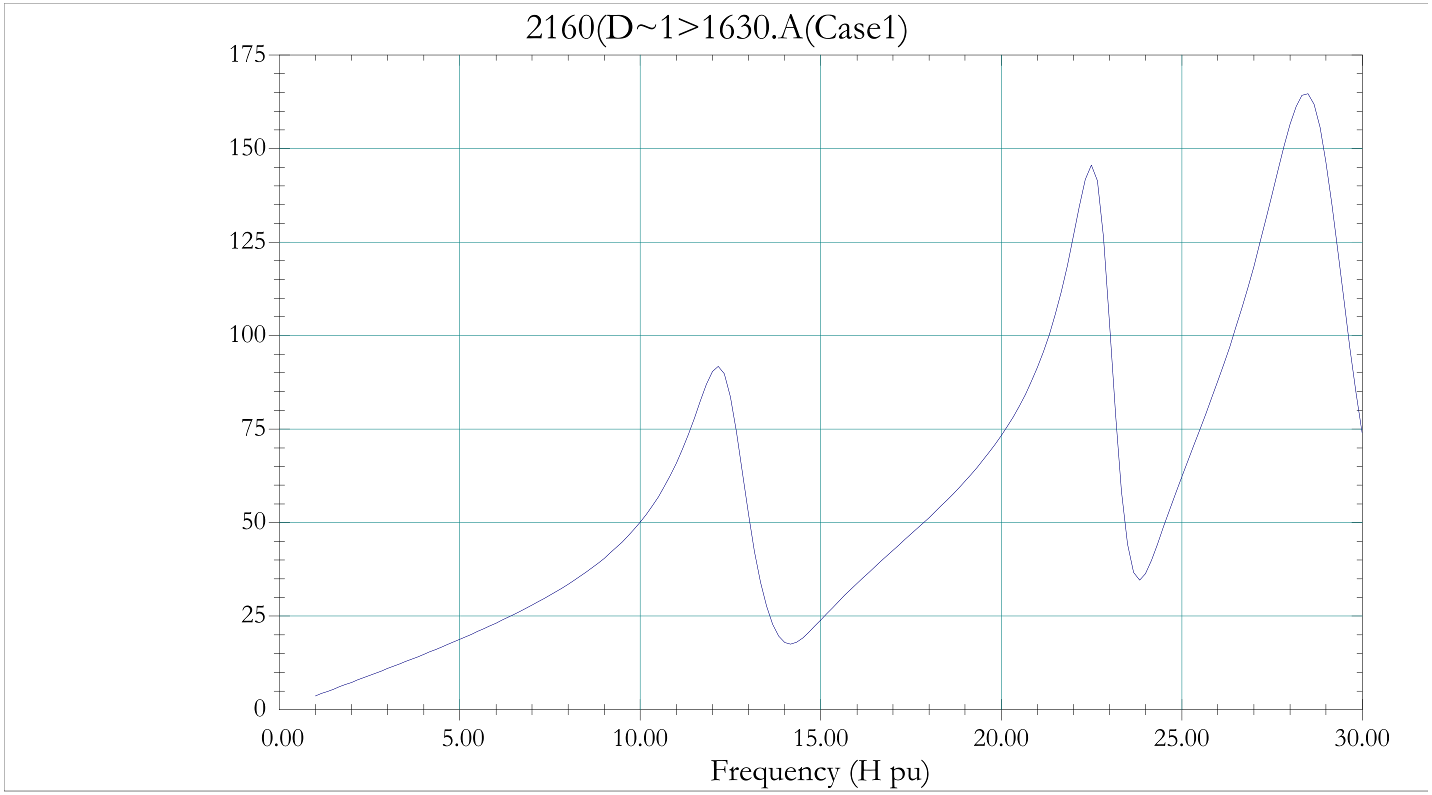
Computer Techniques

- Time Domain Simulations
  - Electromagnetic Transients Program - EMTP
- Harmonic Load Flow
  - HARMFLO, etc.
- Linear Admittance Matrix Solution
  - V-HARM, SuperHarm, etc.
- Hybrid Approach

System Response Characteristics

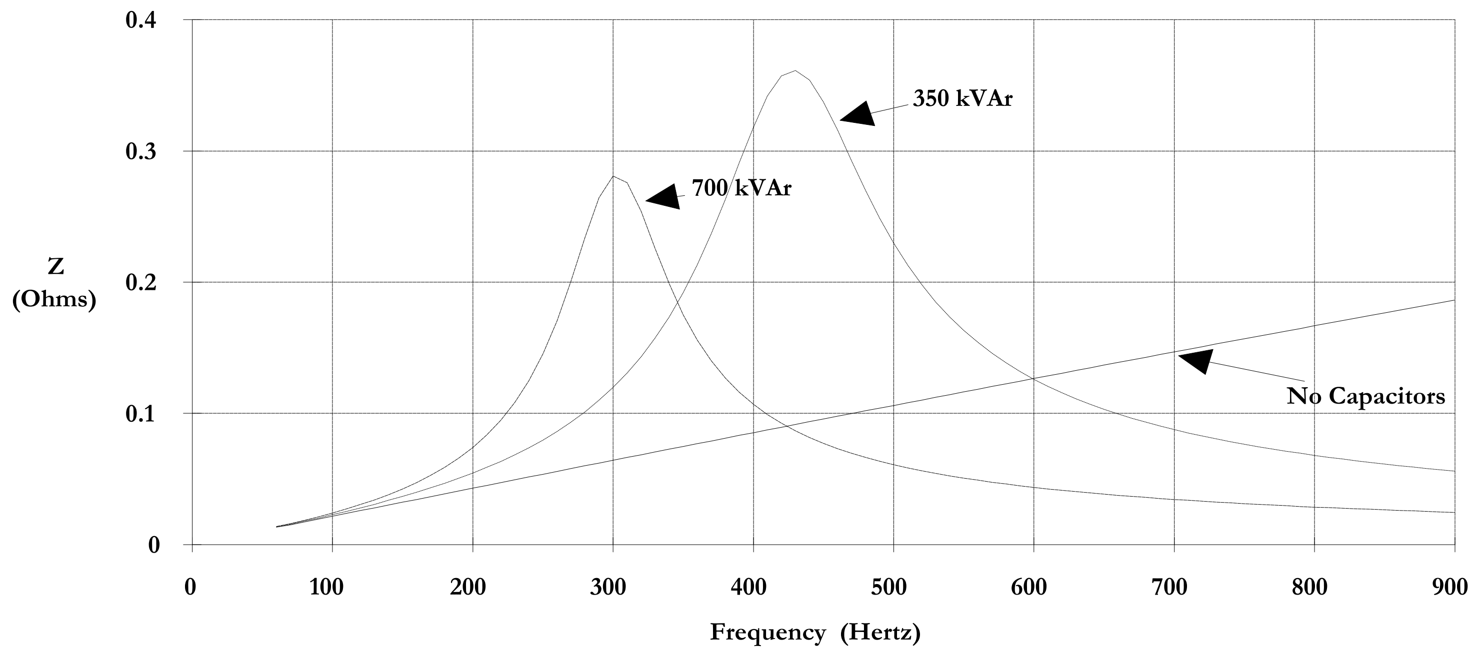
- Short circuit strength
- Transmission lines and cables
- Capacitor banks
- System contingencies
- Series resonance at lower voltage capacitors
- System load characteristics (damping)
- Filters

Impedance vs. Frequency



Effect of Shunt Capacitors

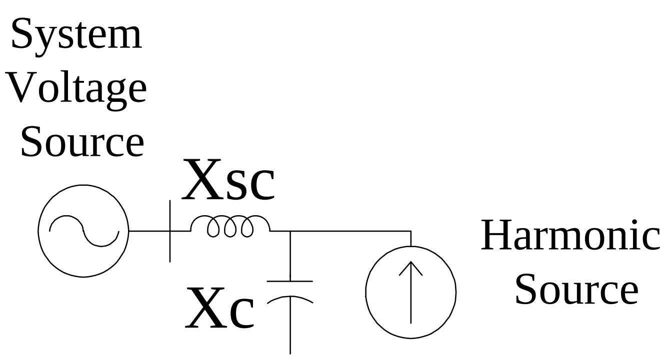
- Shunt capacitors dramatically alter the system frequency response. They create a parallel resonance that can magnify harmonic currents and cause increased voltage distortion levels.



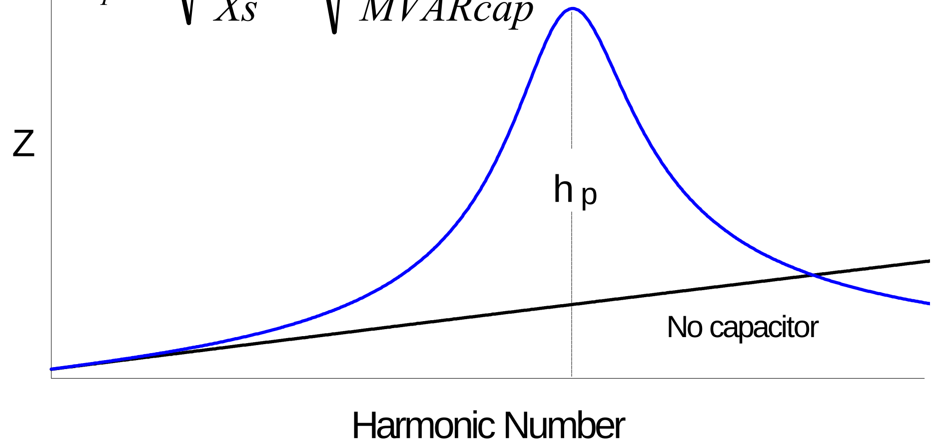
What Factors Affect System Response?

Parallel Resonance

- When, from the perspective of a harmonic source, a capacitor appears to be in parallel with the system source reactance, the impedance seen by the source becomes very high at harmonic number:



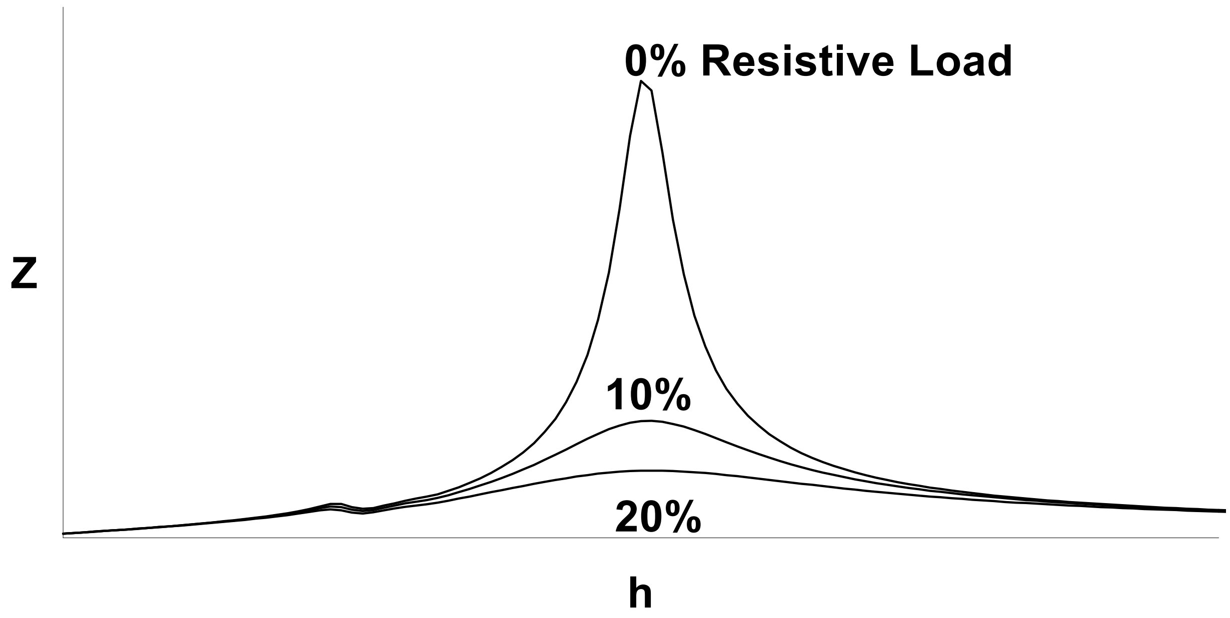
$$h_p = \sqrt{\frac{Xc}{Xs}} = \sqrt{\frac{MVAsc}{MVARcap}}$$



What Factors Affect System Response?

Damping

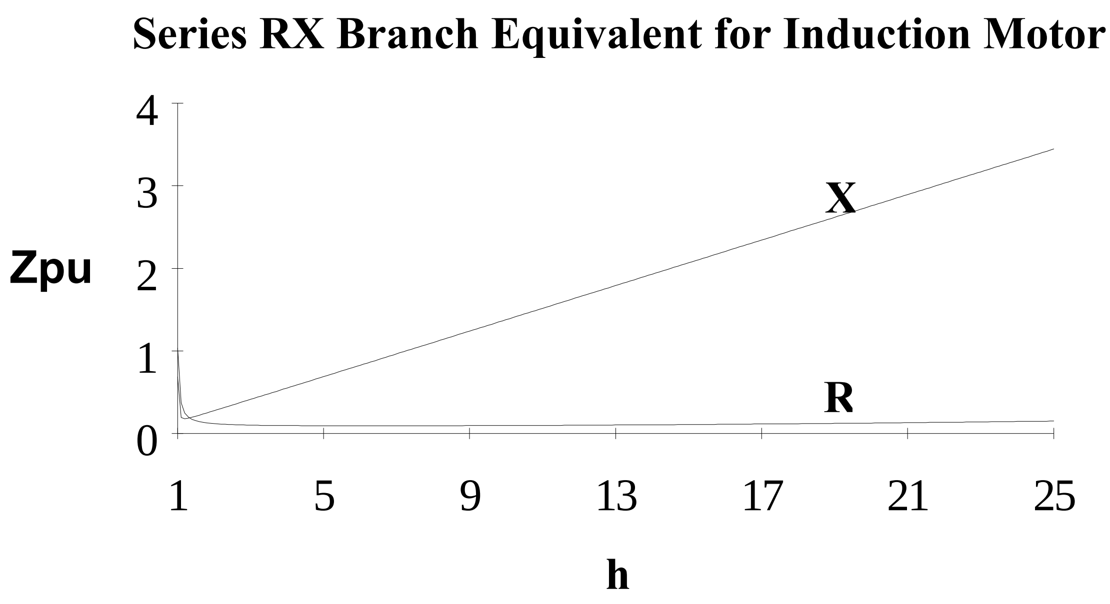
Resistive loads are very effective in damping resonant peaks.



What Factors Affect System Response?

Damping

Motor loads provide little damping. They may even increase distortion, by shifting resonance towards a frequency excited by a harmonic source.



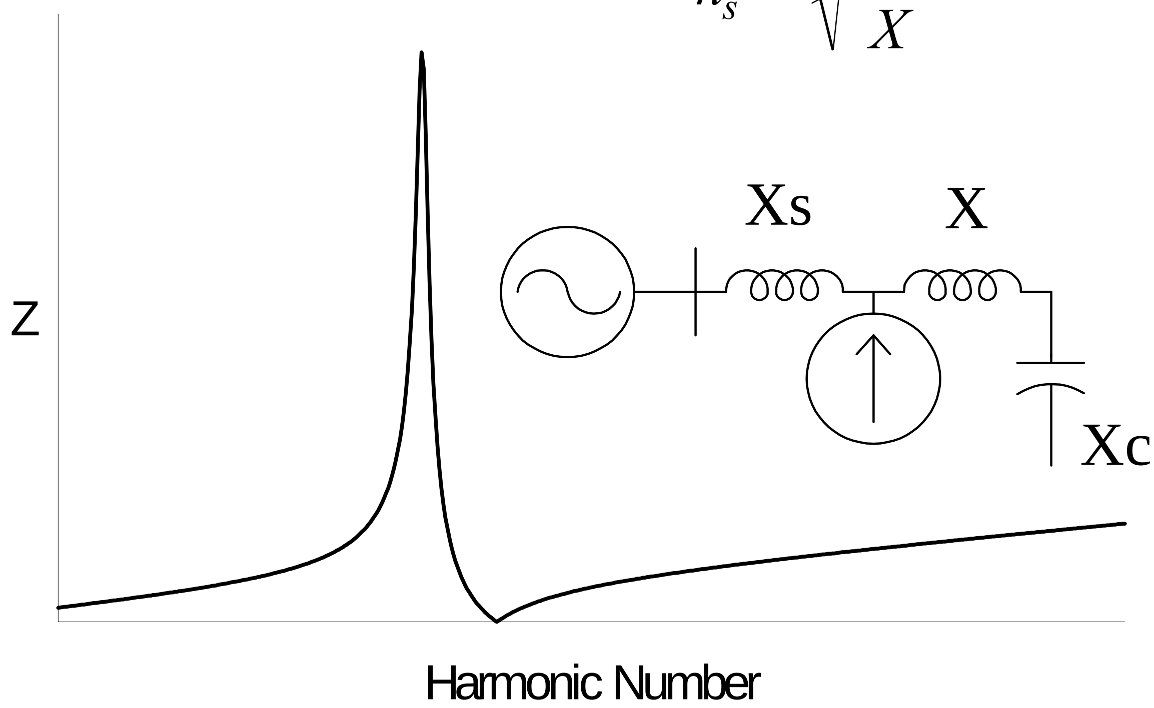
What Factors Affect System Response?

Series Resonance

When a capacitor and an inductive reactance appear as a series LC branch from the perspective of a harmonic source, the branch has zero reactance at harmonic number:

$$h_s = \sqrt{\frac{X_C}{X}}$$

Can be intentional (harmonic filter), or unintentional (customer capacitor drawing harmonic currents through service entrance transformer).

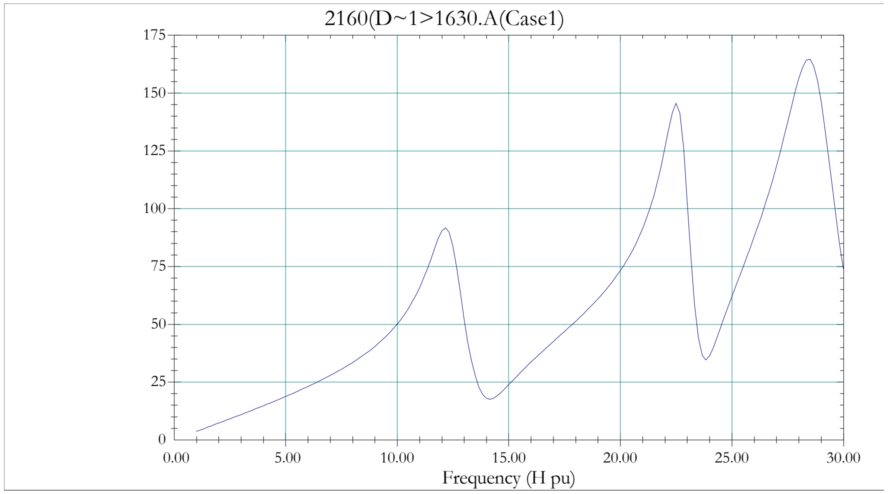


Some Modeling Guidelines

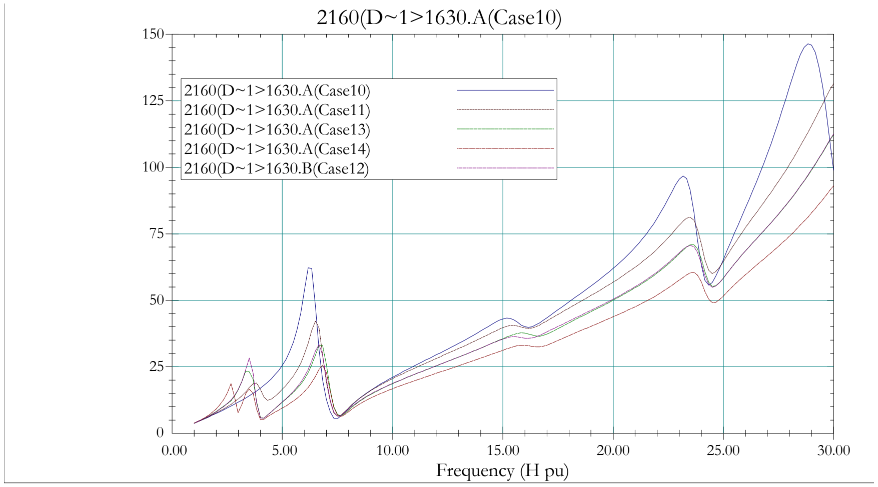
- Substation transformer with short circuit equivalent on the high side.
- Overhead distribution lines can be modeled with series impedances. Cables must include shunt capacitance.
- Include all capacitor bank locations in the model.
- Model transformers and low side buses for customers with low voltage power factor correction or filters.
- Include simple resistive representation for load or resistance with a series inductance to represent step down transformers.
- Three phase model is needed to evaluate positive and zero sequence harmonic components together. Otherwise, positive sequence representation usually adequate.

Example -
Effect of Lower Voltage Capacitors

Base case -
No low voltage caps

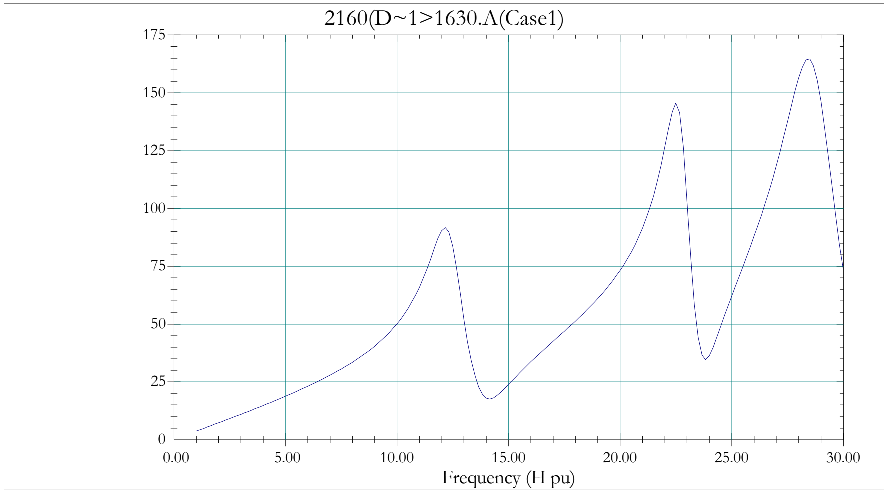


Different lower voltage cap cases

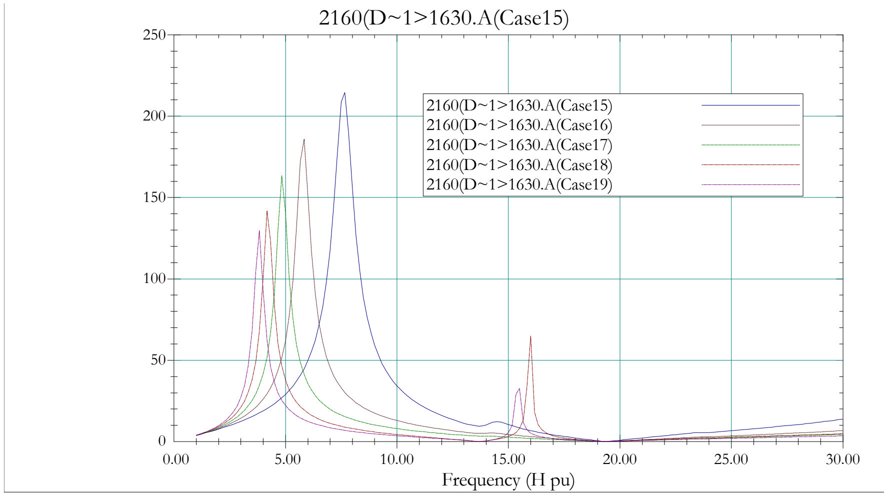


Example -
Effect of large cap banks

Base case -
No caps at source location (69 kV)

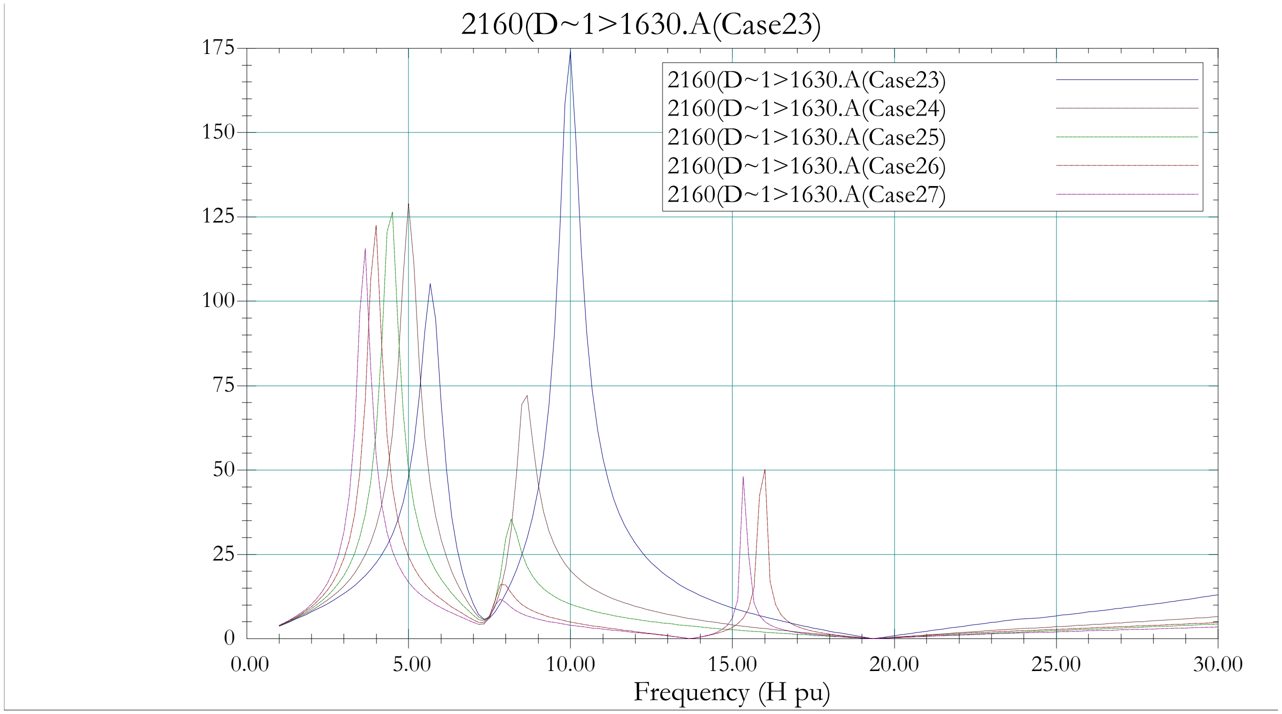


Effect of caps at 69 kV bus



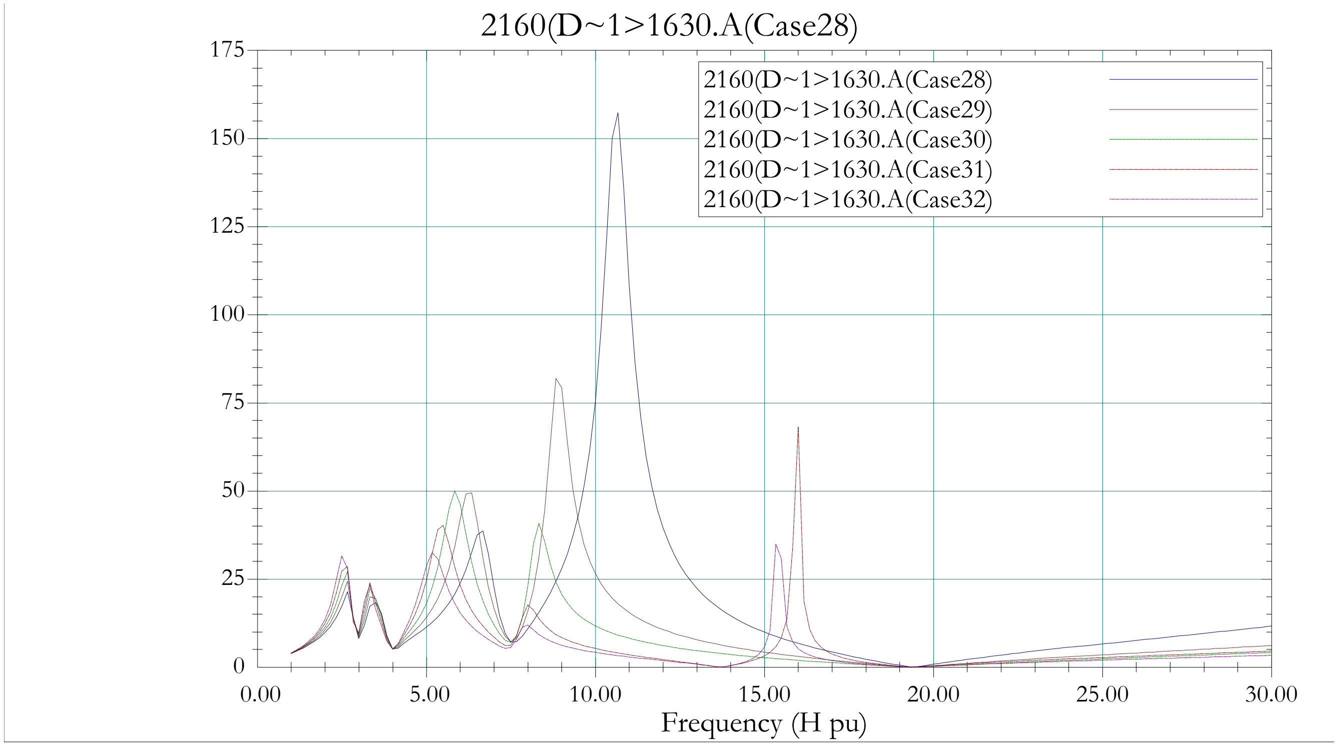
Example -
Other caps at 69 kV

Nearby 69 kV capacitor in service -
variation of caps at the source bus



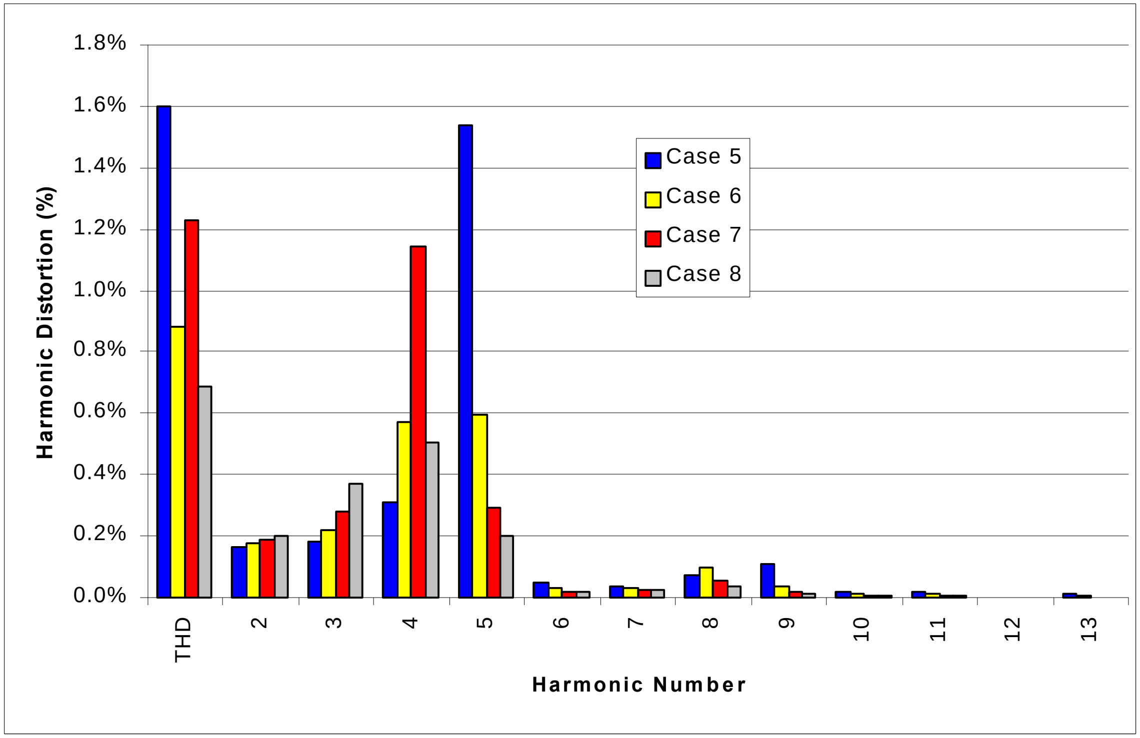
Example - Other caps at 69 kV and lower voltage caps

Effect of capacitors on 69 kV system and at lower voltage 13 kV buses.



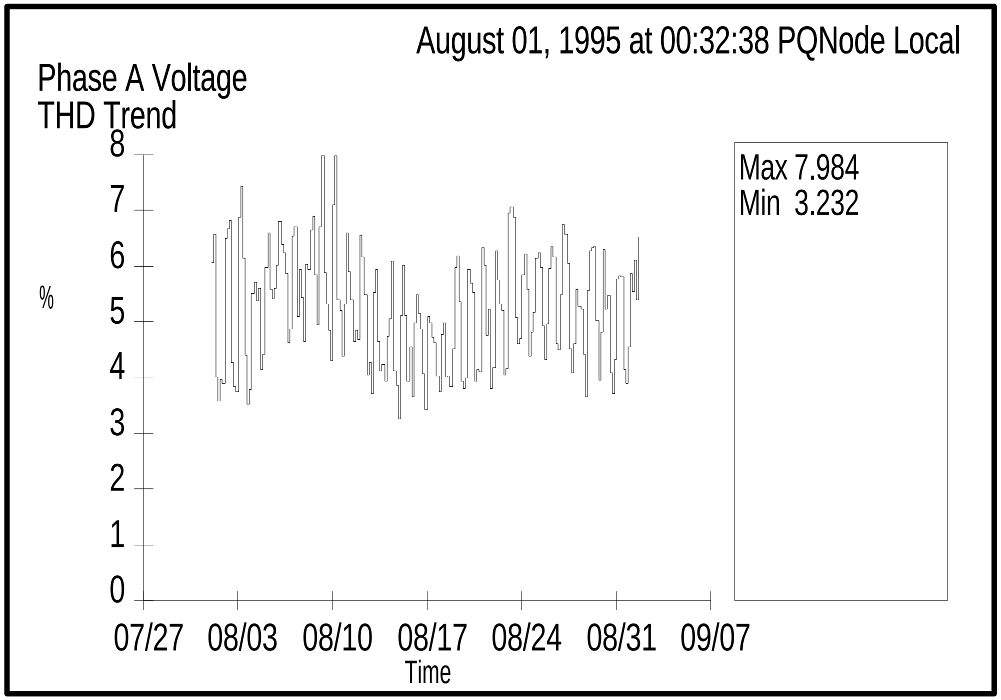
Estimate actual distortion levels

- Select some worst case harmonic characteristics for harmonic-producing loads and combine with the frequency response characteristics of the system.



Distribution System Considerations

- Increasing proliferation of harmonic producing loads can cause system voltage and current distortion levels to become unacceptable.



How Can Harmonics be Controlled?

- Control at the equipment level (IEC 1000-3-2).
- Control at the customer level (IEEE 519 - current).
- Control on the utility system (IEEE 519 - voltage).

Some combination of these will probably be necessary.

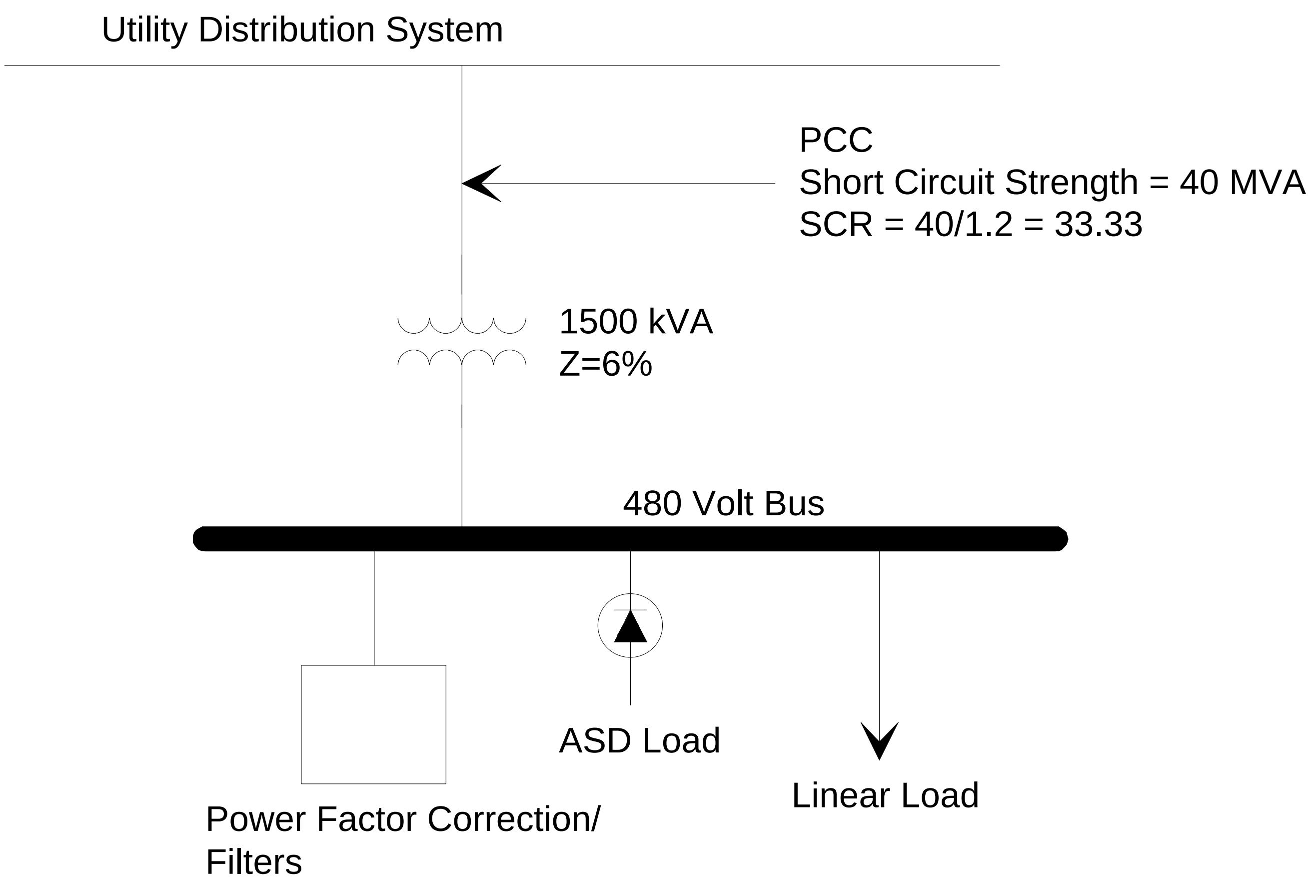
Future of Harmonic Control

- Harmonics will be controlled at individual nonlinear loads with better power supplies and active compensation.
- Harmonics will be controlled at the customer level with active devices that can provide var control, harmonic control, and some power conditioning (e.g. voltage sag ride through support).
- Harmonics will be controlled on the distribution system along with vars using active filter technology.

Harmonic Case Studies

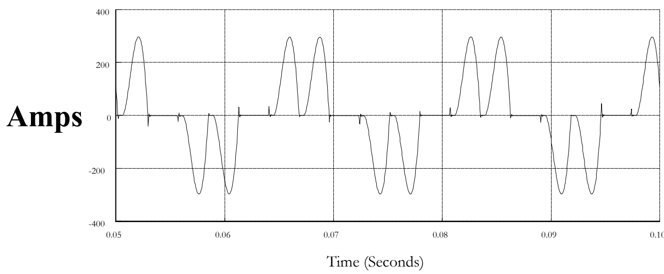
Case Study 1: Example Industrial Harmonics Evaluation

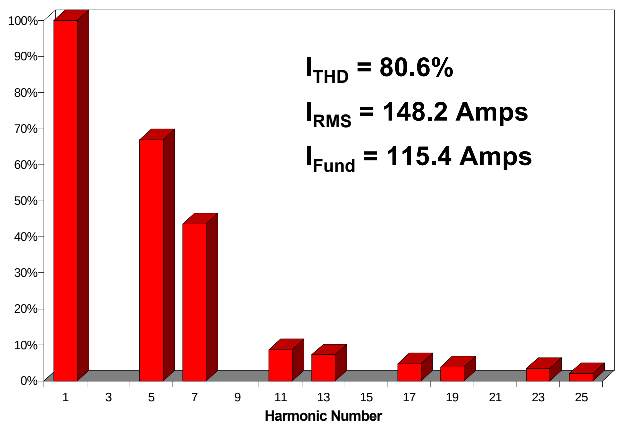
Example System for Analysis



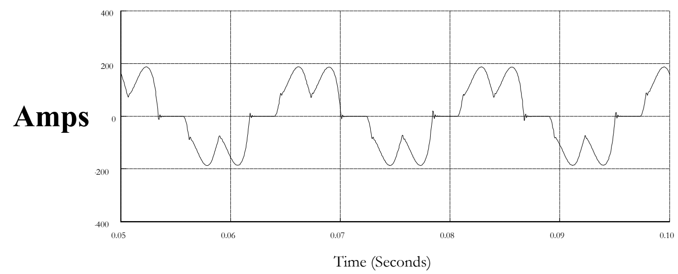
ASD Harmonic Currents

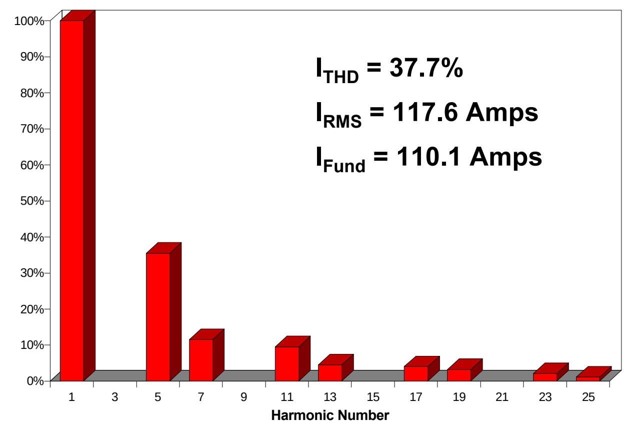
TYPE 1 Waveform
100 HP PWM ASD - No Choke





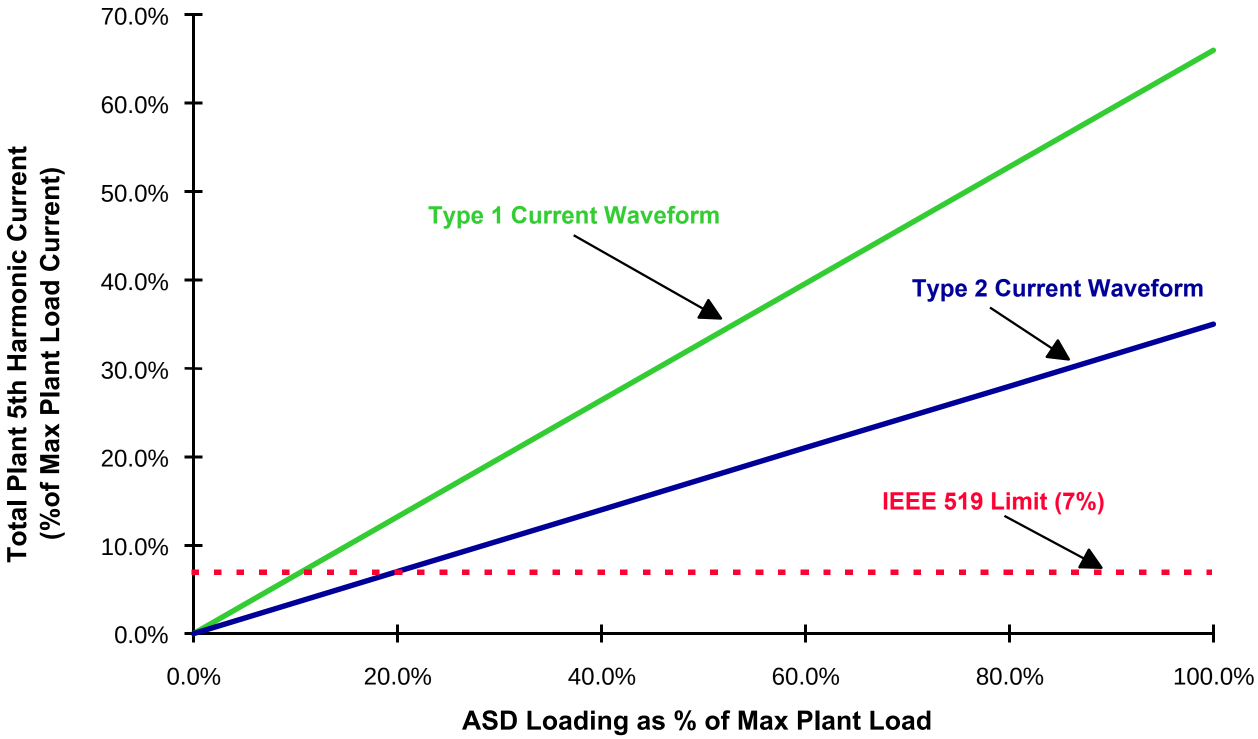
TYPE 2 Waveform
100 HP PWM ASD - 3% Choke





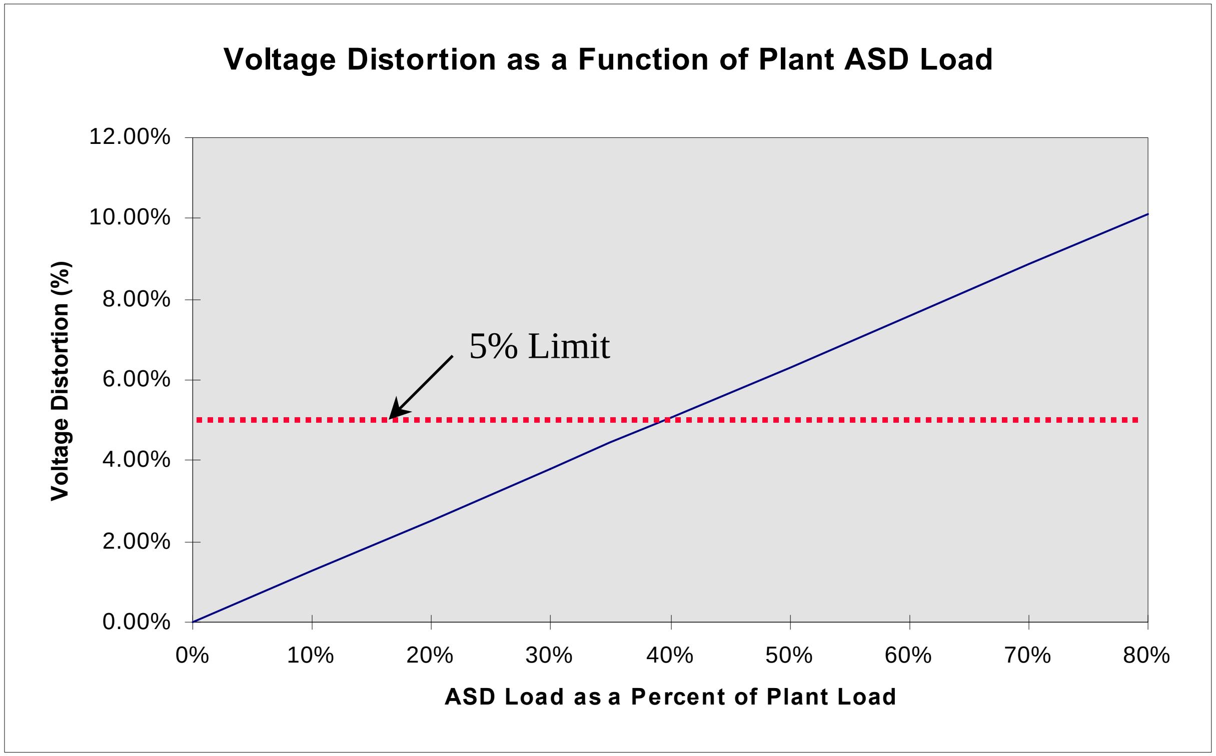
Rules of Thumb

- How much of the plant load can be ASDs without exceeding IEEE 519 guidelines?
- The limit is usually determined by 5th harmonic component.



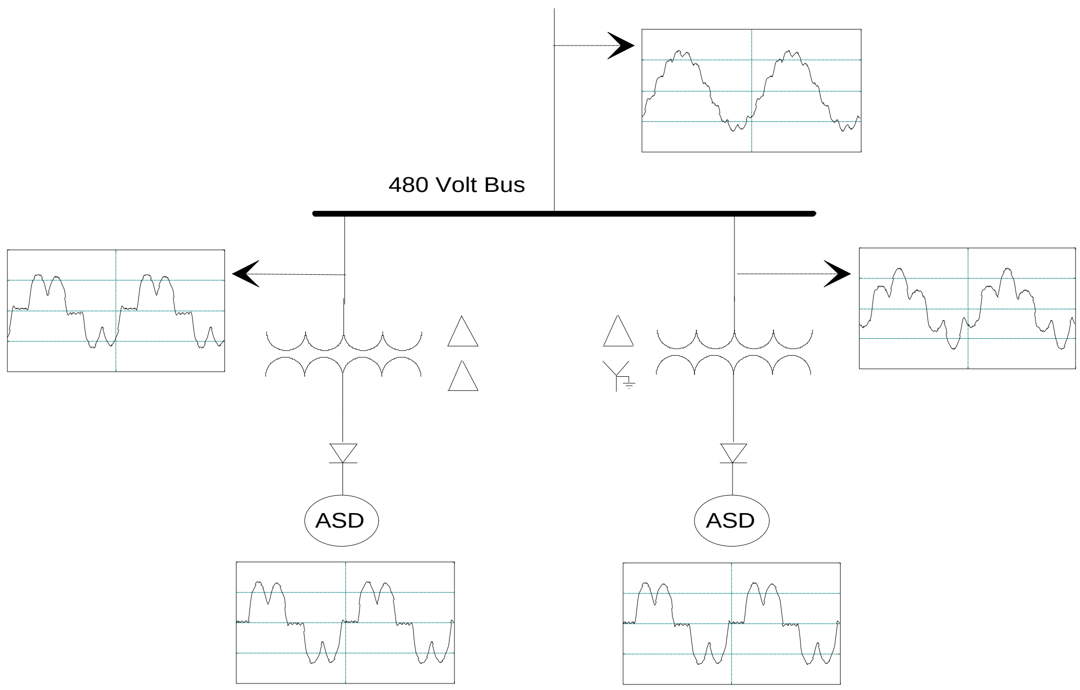
Rules of Thumb

- How much of the plant load can be ASDs without exceeding 5% voltage distortion?



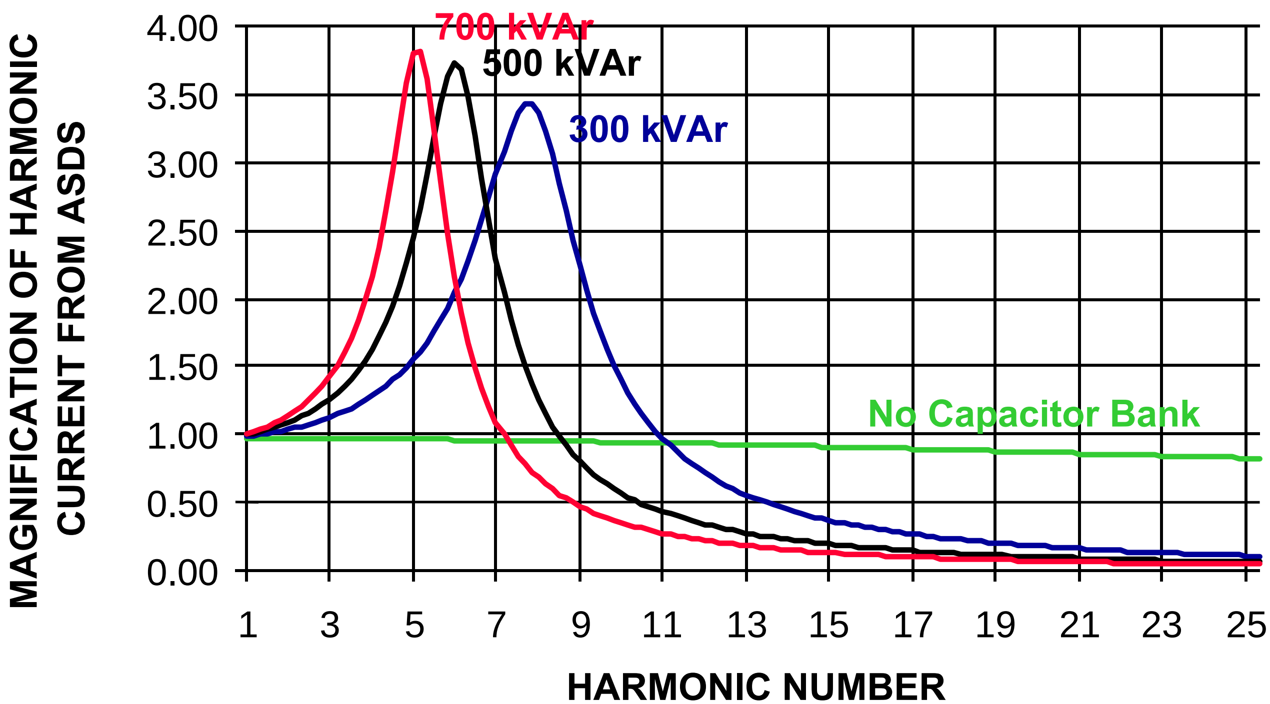
Designing for Cancellation

- Transformer connections can be used to get cancellation of harmonics from different drives.



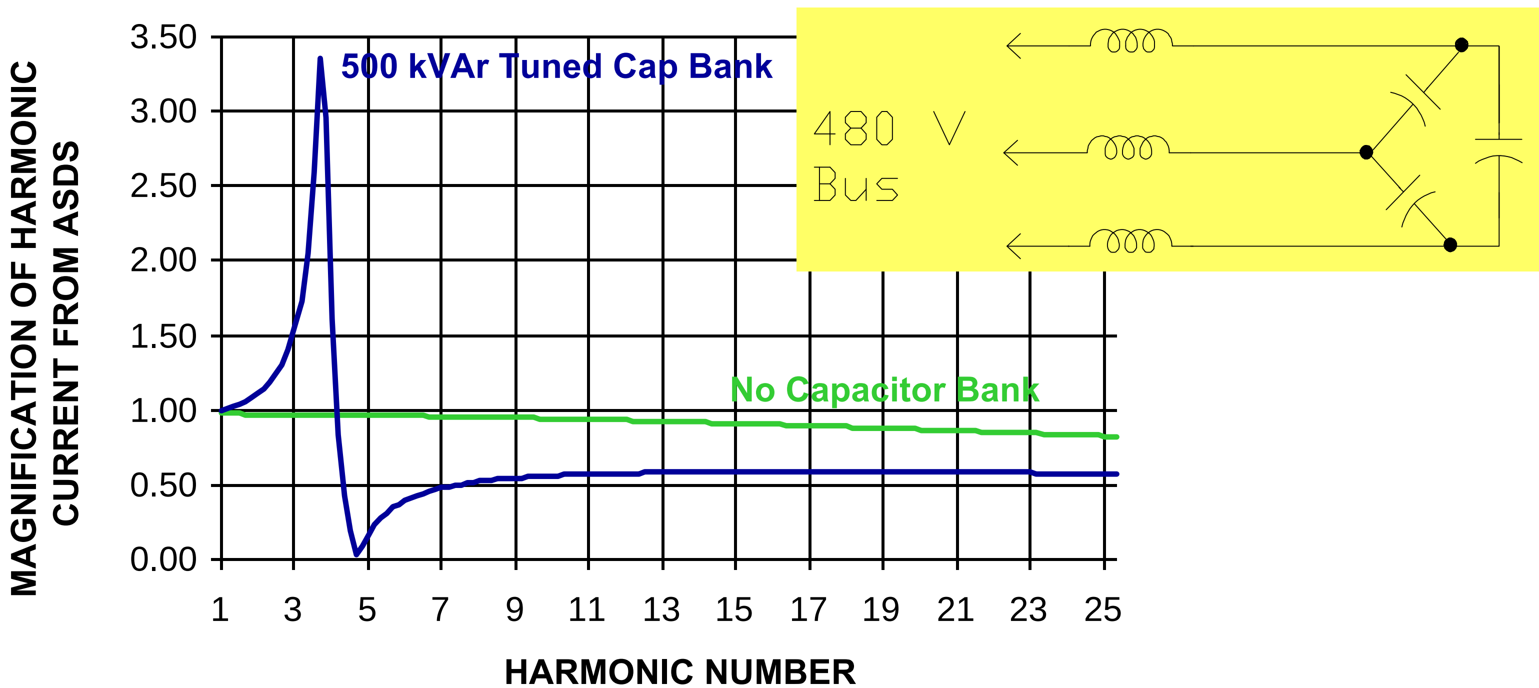
Effect of Power Factor Correction

- Rules of thumb only apply if there are no power factor correction capacitors.



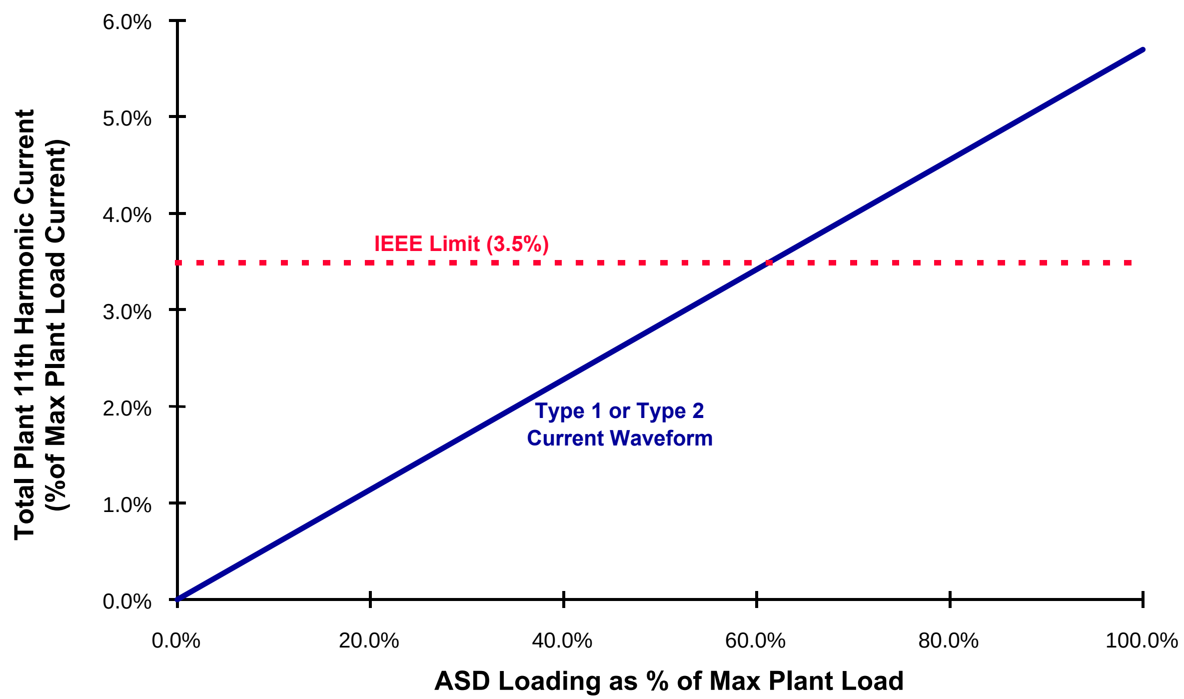
Power Factor Correction as Filters

- Power factor correction can be applied as harmonic filters to solve both the power factor problem and the harmonic problem.



How many filter branches are needed?

- With a fifth harmonic filter, the evaluation will typically be dominated by the 11th harmonic component.



Sizing the Filter - Example Spreadsheet

Low Voltage Filter Calculations:

SYSTEM INFORMATION:

Filter Specification:	5 th	Power System Frequency:	60 Hz
Capacitor Bank Rating:	500 kVAr	Capacitor Rating:	480 Volts 60 Hz
Nominal Bus Voltage:	480 Volts	Derated Capacitor:	500 kVAr
Capacitor Rated Current:	601.4 Amps	Total Harmonic Load:	750 kVA
Filter Tuning Harmonic:	4.7 th	Filter Tuning Frequency:	282 Hz
Cap Impedance (wye equivalent):	0.4608 W	Cap Value (wye equivalent):	5756.5 uF
Reactor Impedance:	0.0209 W	Reactor Rating:	0.0553 mH
Filter Full Load Current:	629.9 Amps	Supplied Compensation:	524 kVAr
Transformer Nameplate: *(Rating and Impedance)*	1500 kVA 6.00 %	Utility Side Vh: *(Utility Harmonic Voltage Source)*	2.50 % THD
Load Harmonic Current:	33.33 % Fund	Load Harmonic Current:	300.7 Amps
Utility Harmonic Current:	119.1 Amps	Max Total Harm. Current:	419.8 Amps

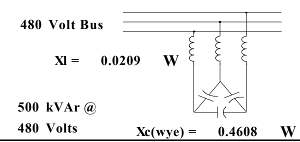
CAPACITOR DUTY CALCULATIONS:

Filter RMS Current:	757.0 Amps	Fundamental Cap Voltage:	502.8 Volts
Harmonic Cap Voltage:	67.0 Volts	Maximum Peak Voltage:	569.8 Volts
RMS Capacitor Voltage:	507.2 Volts	Maximum Peak Current:	1049.7 Amps

CAPACITOR LIMITS: (IEEE Std 18-1980)

	Limit		Actual
Peak Voltage:	120%		119%
Current:	180%		126%
KVAr:	135%		133%
RMS Voltage:	110%		106%

FILTER CONFIGURATION:



FILTER REACTOR DESIGN SPECIFICATIONS:

Reactor Impedance:	0.0209 W	Reactor Rating:	0.0553 mH
Fundamental Current:	629.9 Amps	Harmonic Current:	419.8 Amps

Summary - Rules of Thumb

Condition	TYPE 1 Characteristic (No Choke)	TYPE 2 Characteristic (3% Choke)
Simple System - No Caps, No Filters	10%	20%
480 Volt PF Correction Caps	<10% (Must be Analyzed)	<20%
480 Volt Tuned Caps to 4.7th Harmonic	35%	60%
480 Volt Filters - Multiple Steps	>35% (Must be Analyzed)	>60%

Case Study 2:
Impact of Dispersed Harmonic Sources

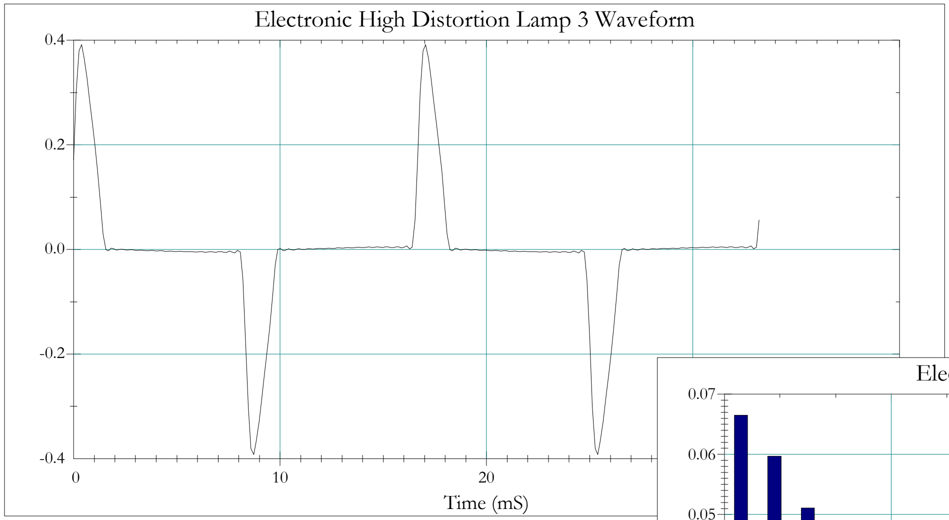
Introduction

- CFLs are being promoted as part of energy conservation programs at many electric utilities.
- A recent study has concluded that low CFL penetration levels can cause the feeder voltage distortion to exceed 5%.
- Previous studies have indicated that further investigation needs to be done.

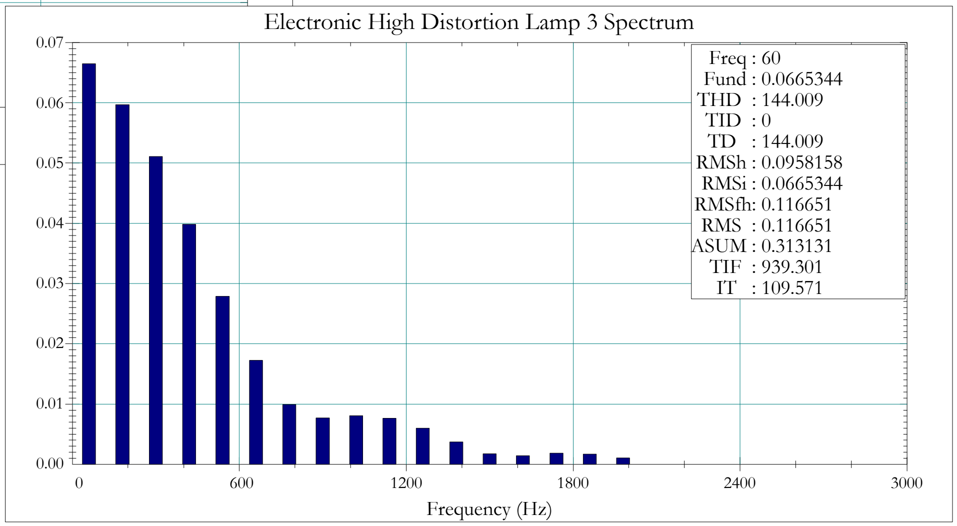
Introduction - cont.

- Measurements were performed to identify harmonic characteristics for different CFLs
- Transient models utilized to develop a detailed representation of typical loads.
- Harmonic simulations used to examine cumulative effect of CFLs.

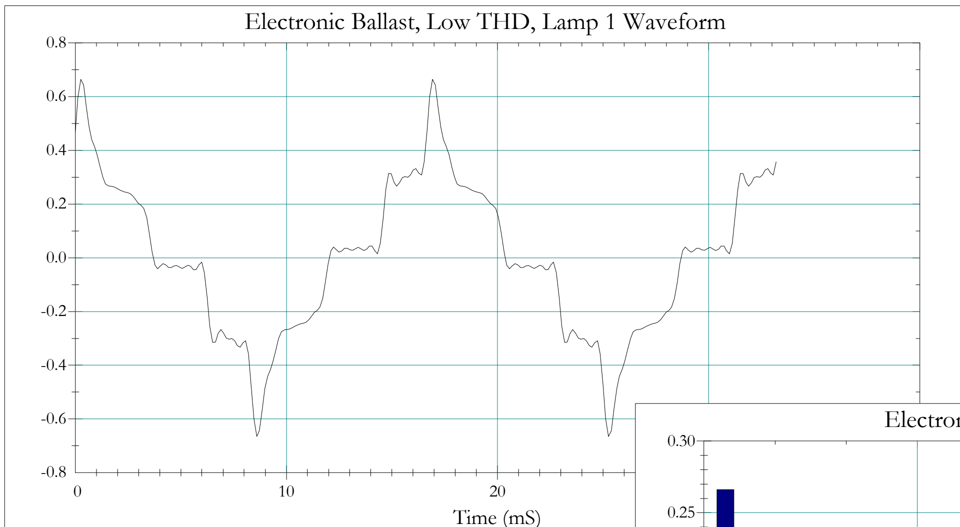
High Distortion Electronic Ballast CFLs

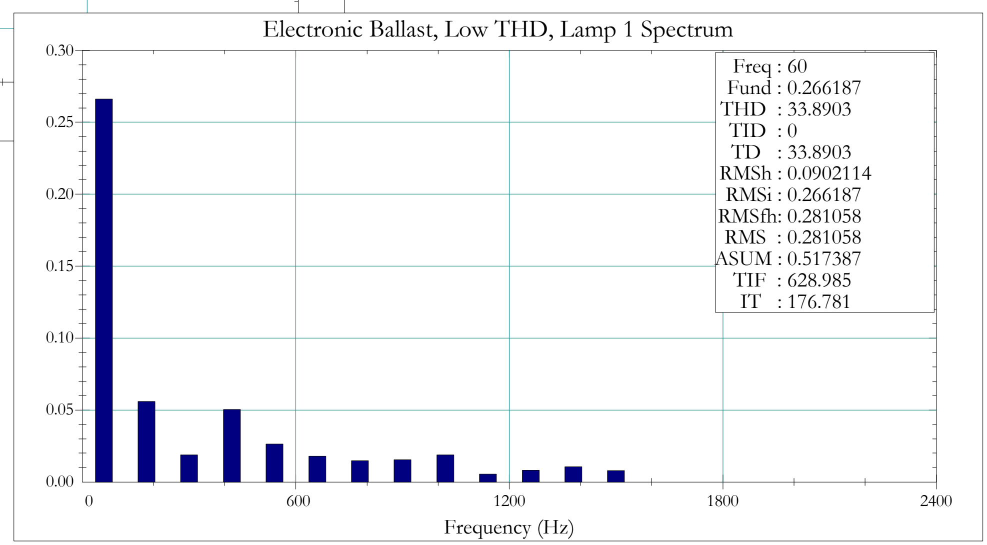


Harmonic Current Distortion of 140%



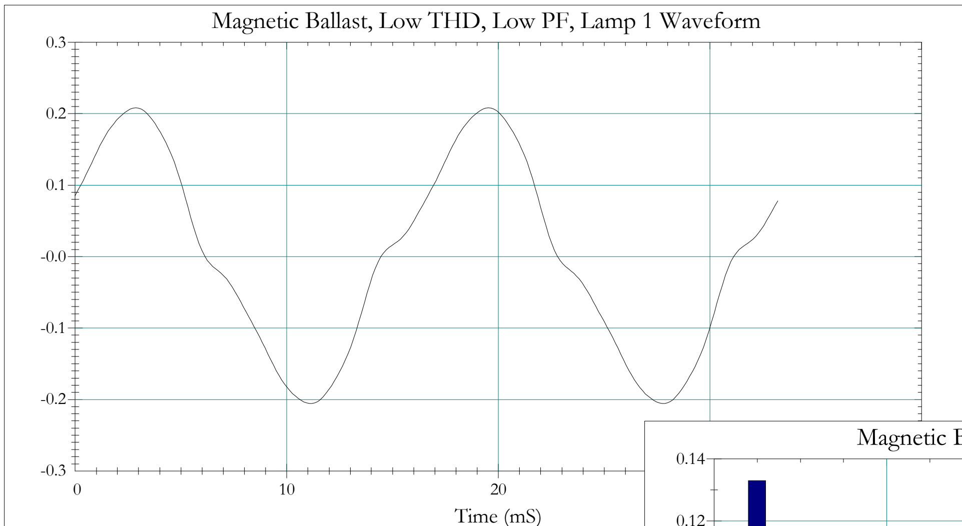
Low Distortion Electronic Ballast CFLs



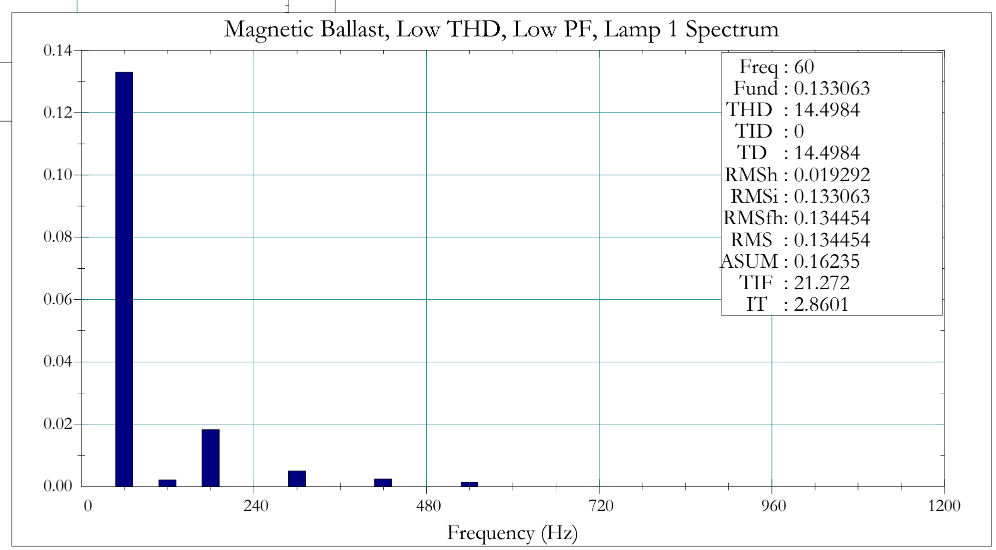


Harmonic Current Distortion of 30%

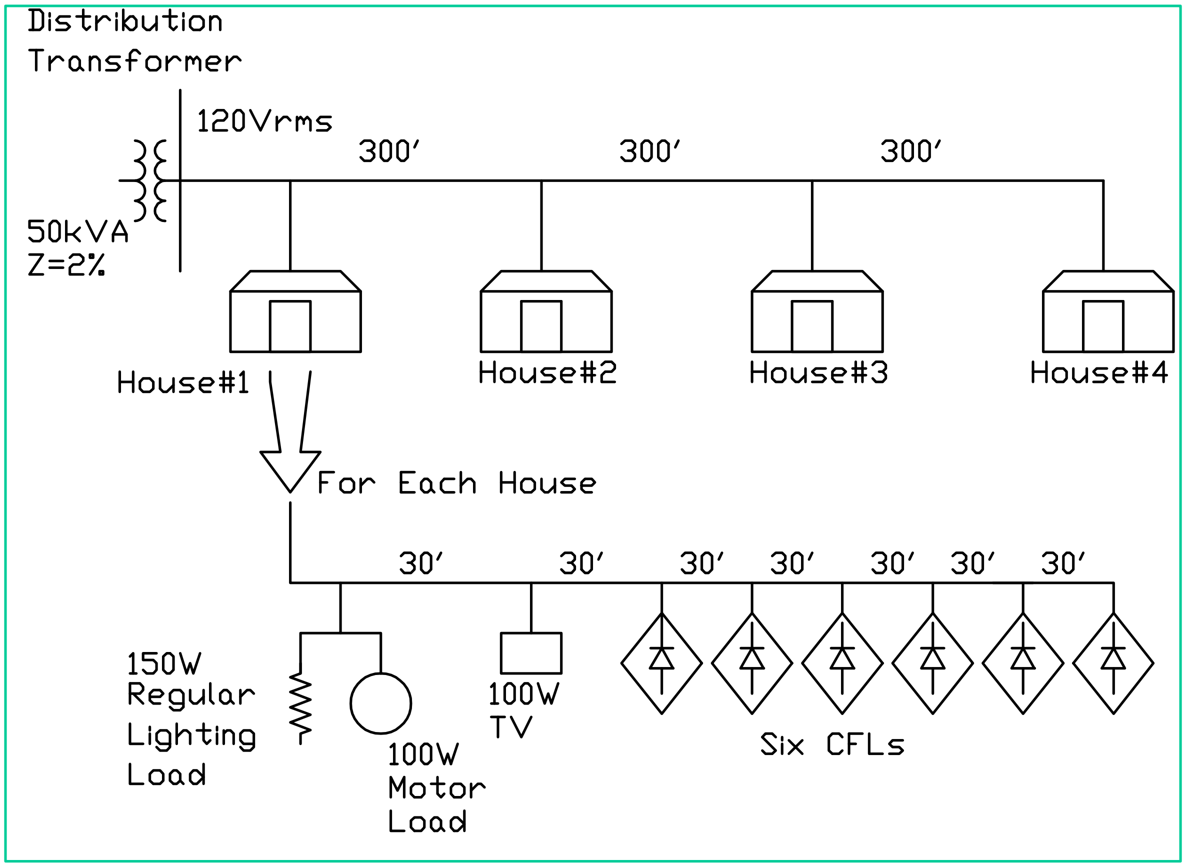
Magnetic Ballast CFLs



Harmonic Current Distortion of 20%



Residential Circuit Example

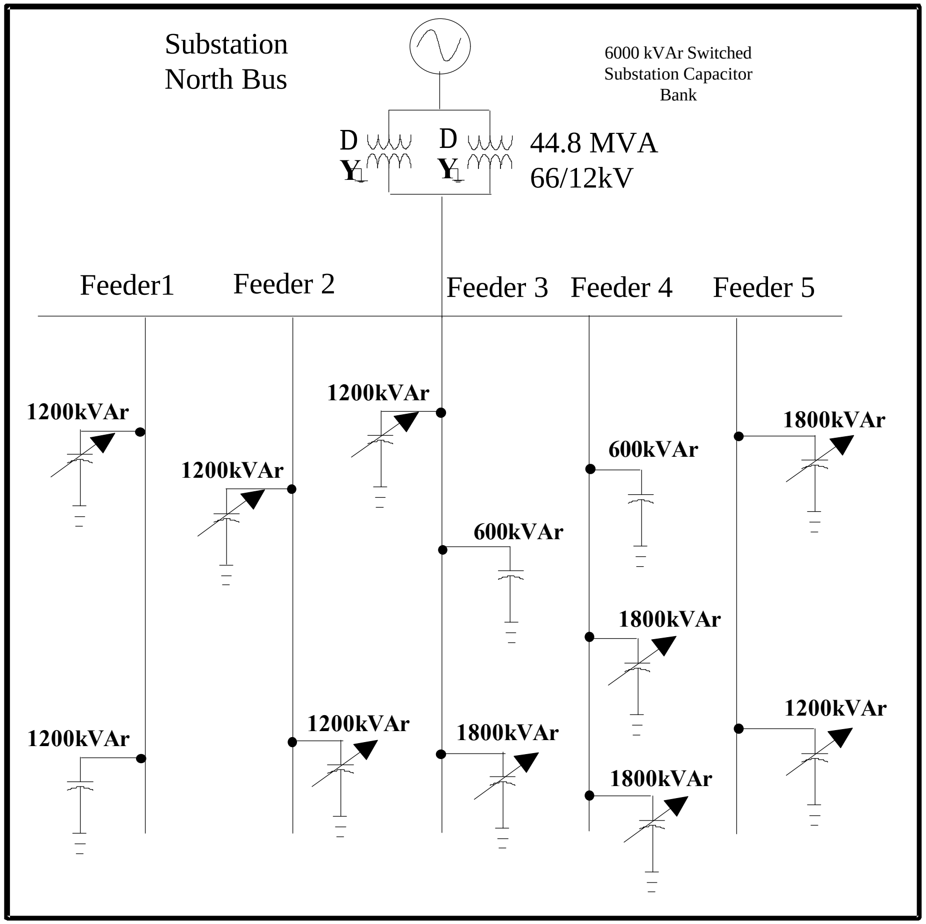


Assumed Harmonic Spectrum

Harmonic	Magnitude	Angle
1	100.0%	-11.5
3	82.0%	-38
5	53.4%	-62.5
7	31.6%	-85.1
9	16.6%	-103.3
11	8.2%	-111
13	1.5%	-99.1
15	1.0%	-88.4
17	0.6%	-95.5
19	0.5%	-109.5
21	0.3%	-120.5
23	0.1%	-107.5
25	0.1%	-67.4

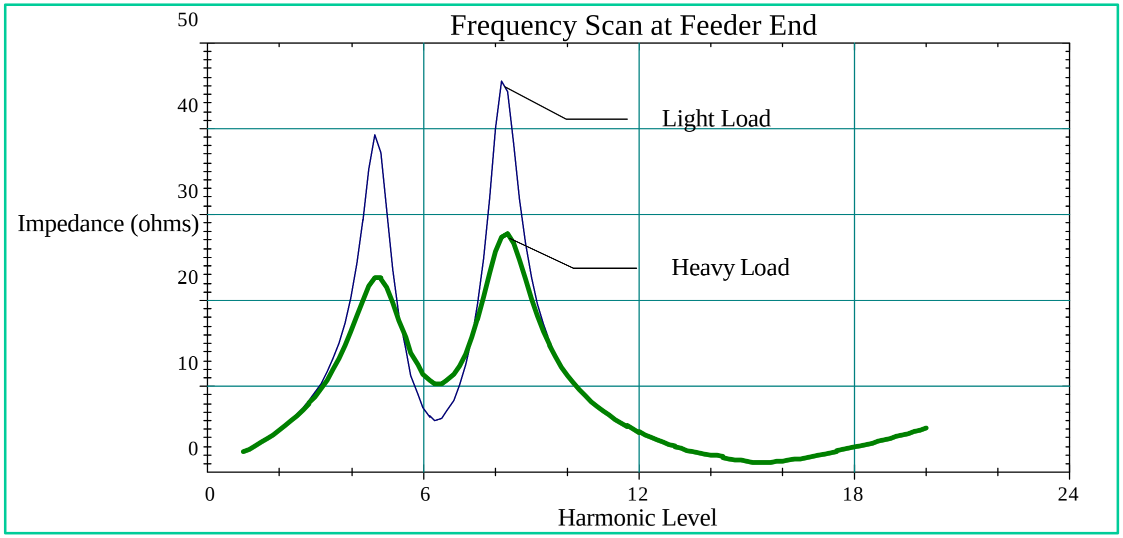
High Distortion Electronic Ballast CFLs Including Cancellation Effects

Distribution System Studied



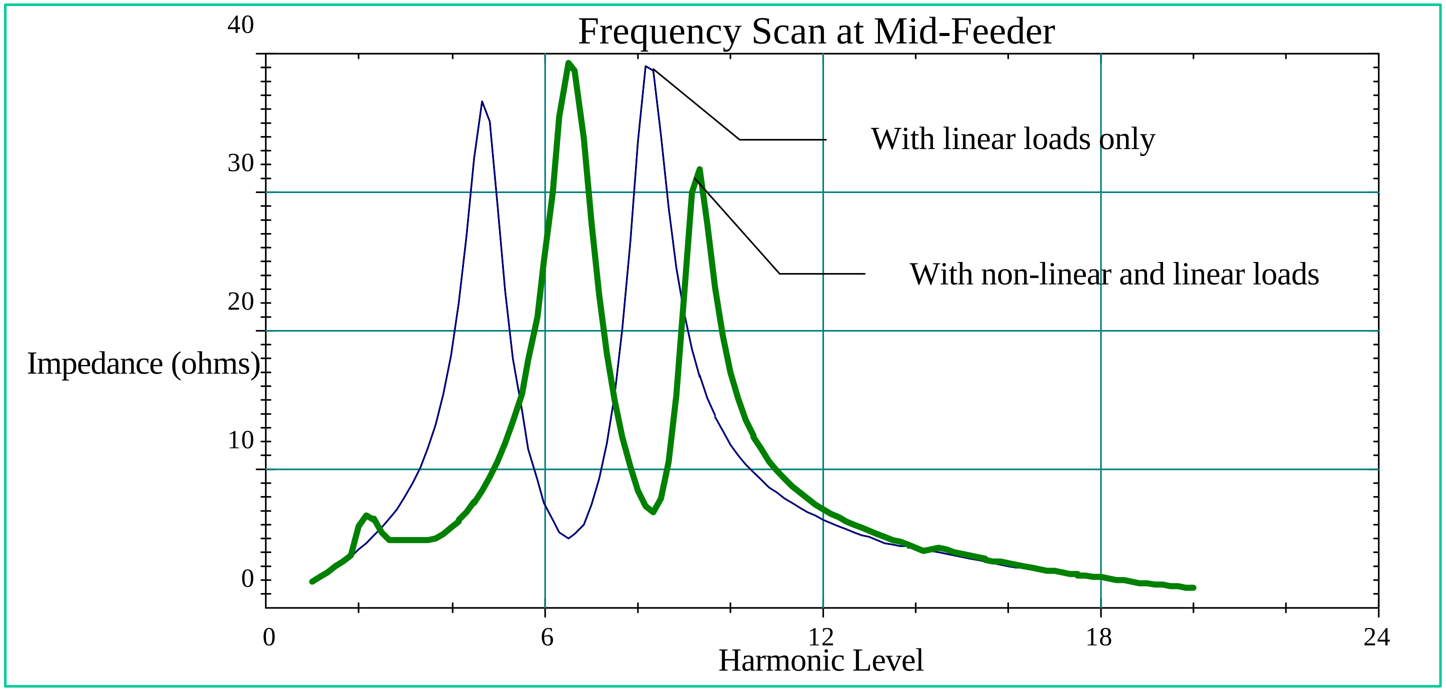
31% of loads are commercial

System Frequency Response



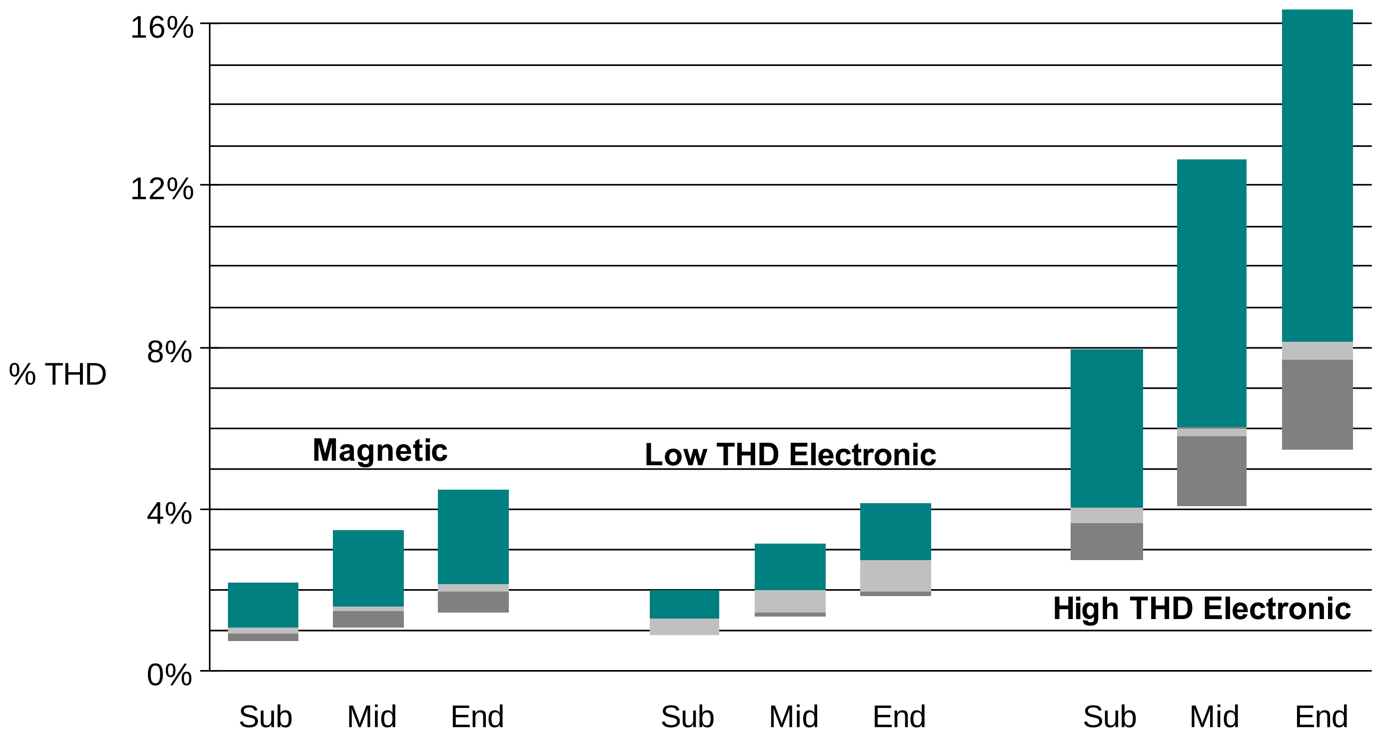
This case was selected to represent worst case realistic circuit conditions due to the system resonance at the fifth harmonic.

System Frequency Response Comparison



Effect of CFL Penetration

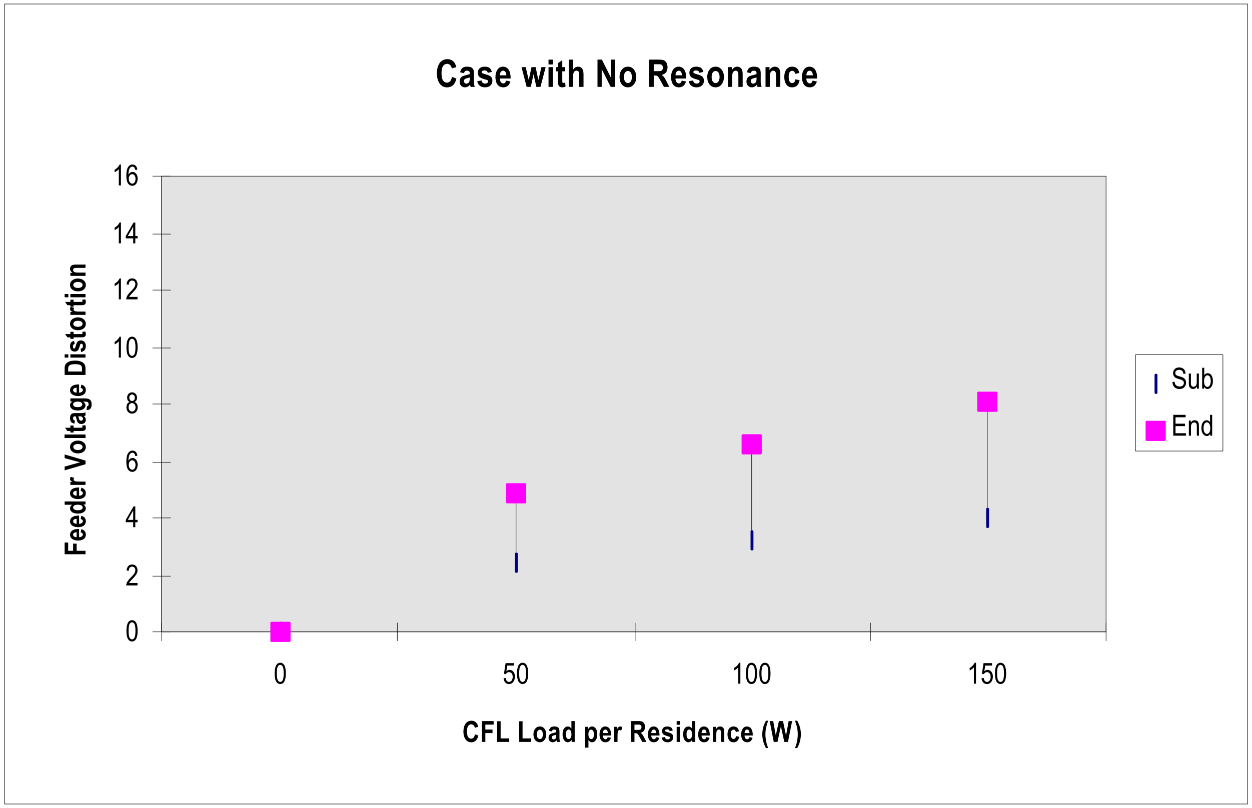
Effect of CFL Type



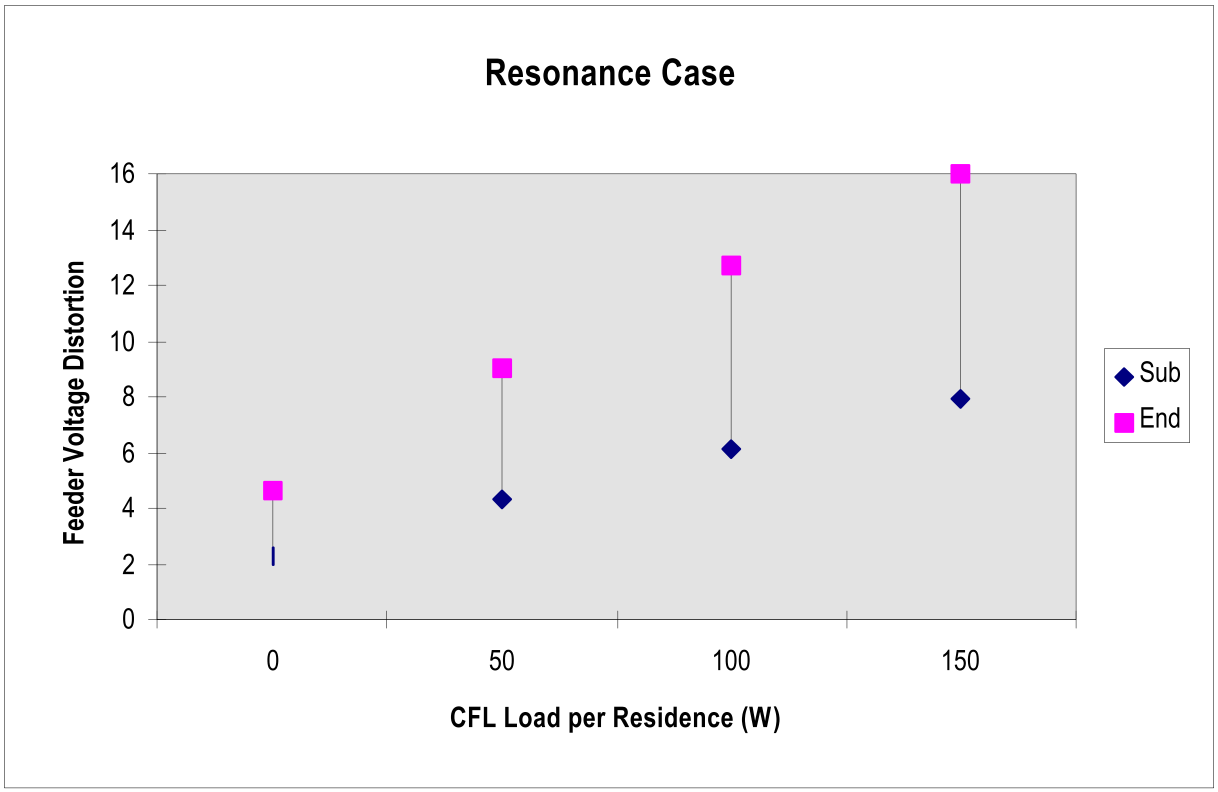
Summary

- High penetration levels of CFLs that use high distortion electronic ballasts can result in unacceptable voltage distortion levels.
- CFLs with lower current distortion levels (30% or less) should not cause problems on the feeder.
- Distortion levels are dependent on system conditions (capacitance, representation of electronic loads, etc.)

Summary of Voltage Distortion



Summary - cont.



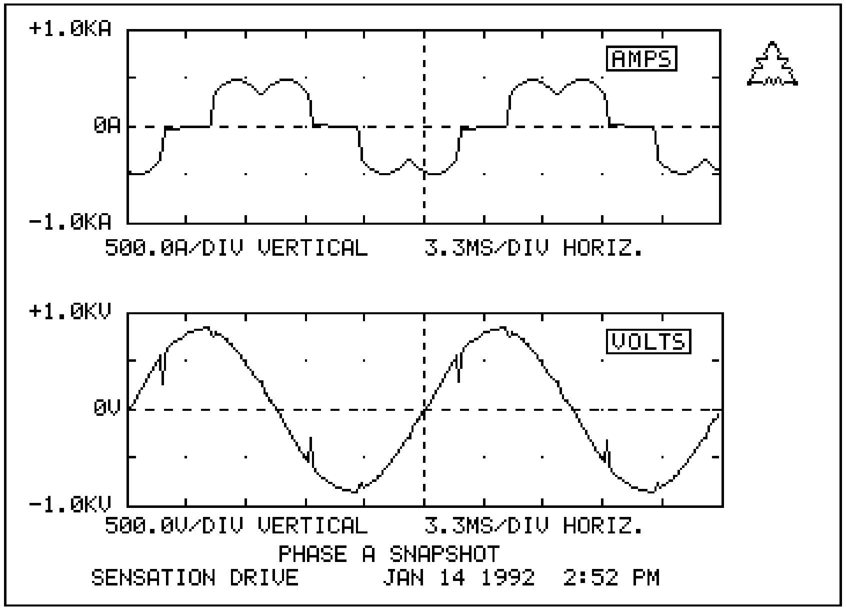
Case Study 3:
Voltage Notching Evaluation

Overview

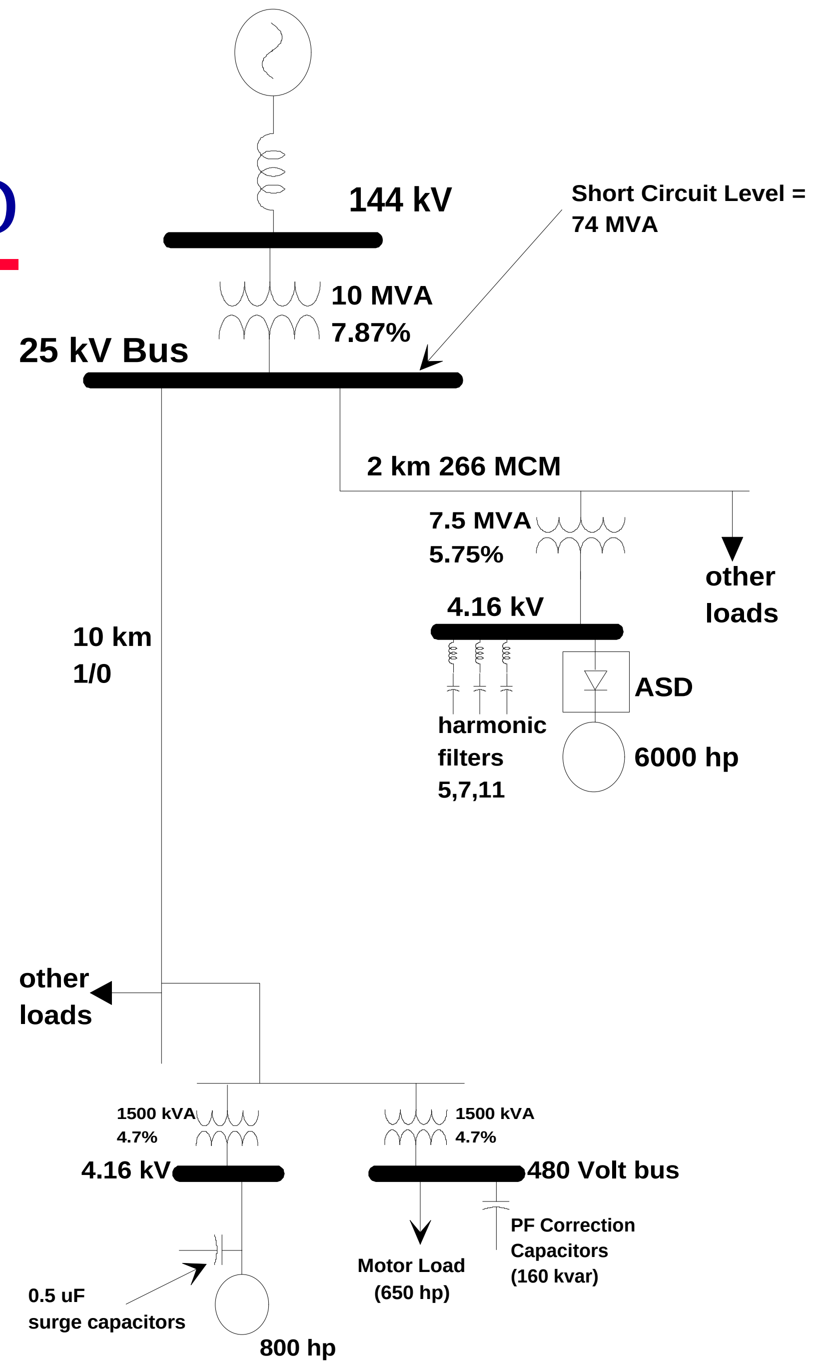
- Voltage Notching Concern
- Example Systems
- Problem Description
- Analysis
- Solutions
- Results

Voltage Notching

- Caused by converter commutation.
- Dependent on firing angle and amount of commutating inductance.
- Can be controlled by the isolation inductance in series with the converter.

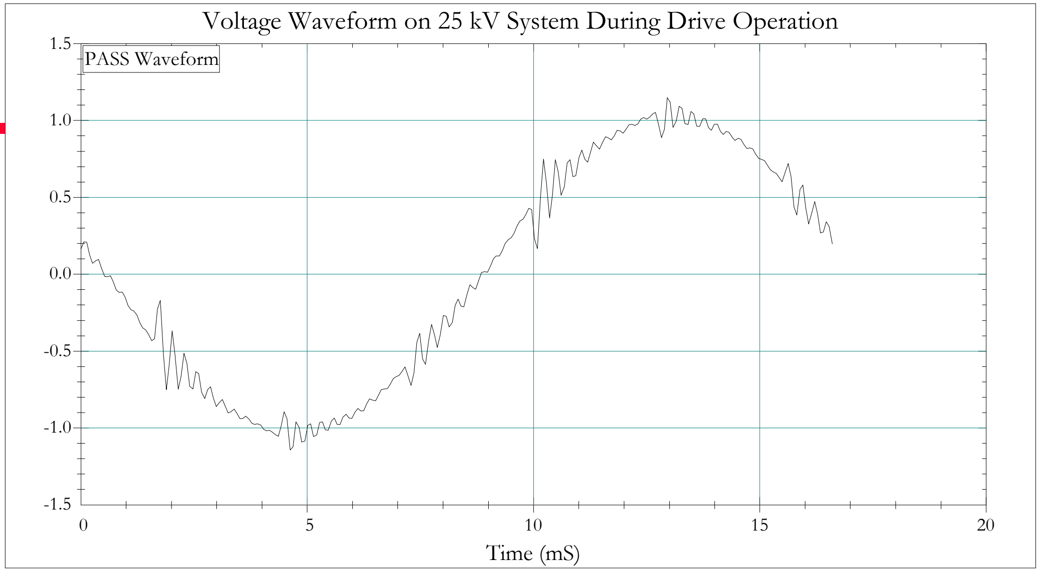


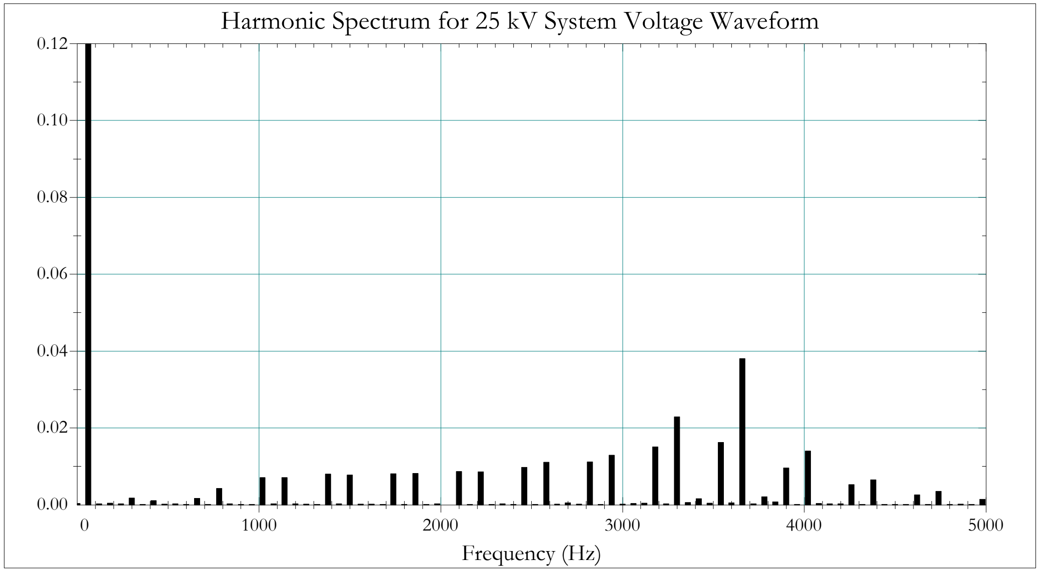
Example 1 - Large Induction Motor with ASD



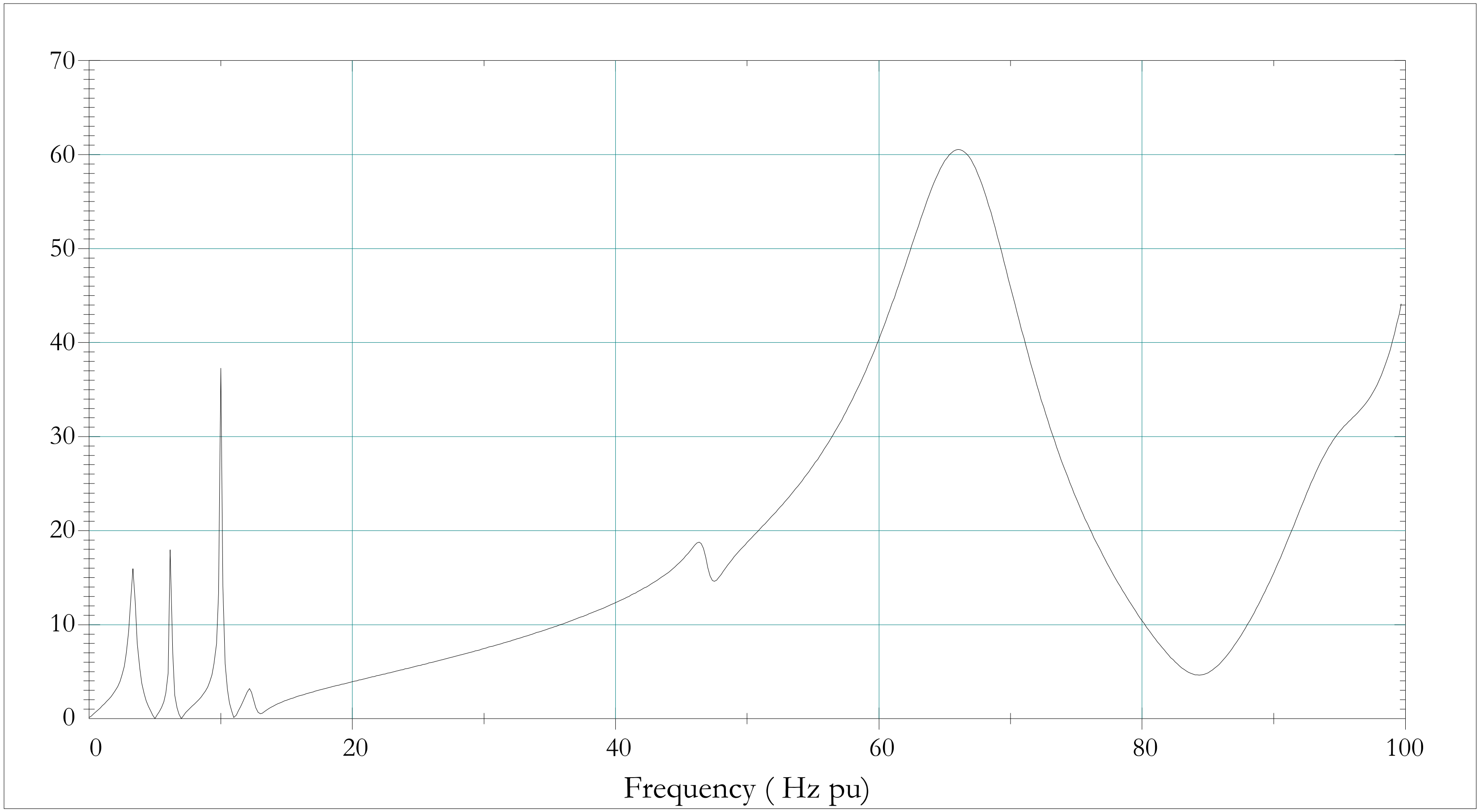
The Problem

- System resonance near the 60th harmonic causes oscillations at each notch.

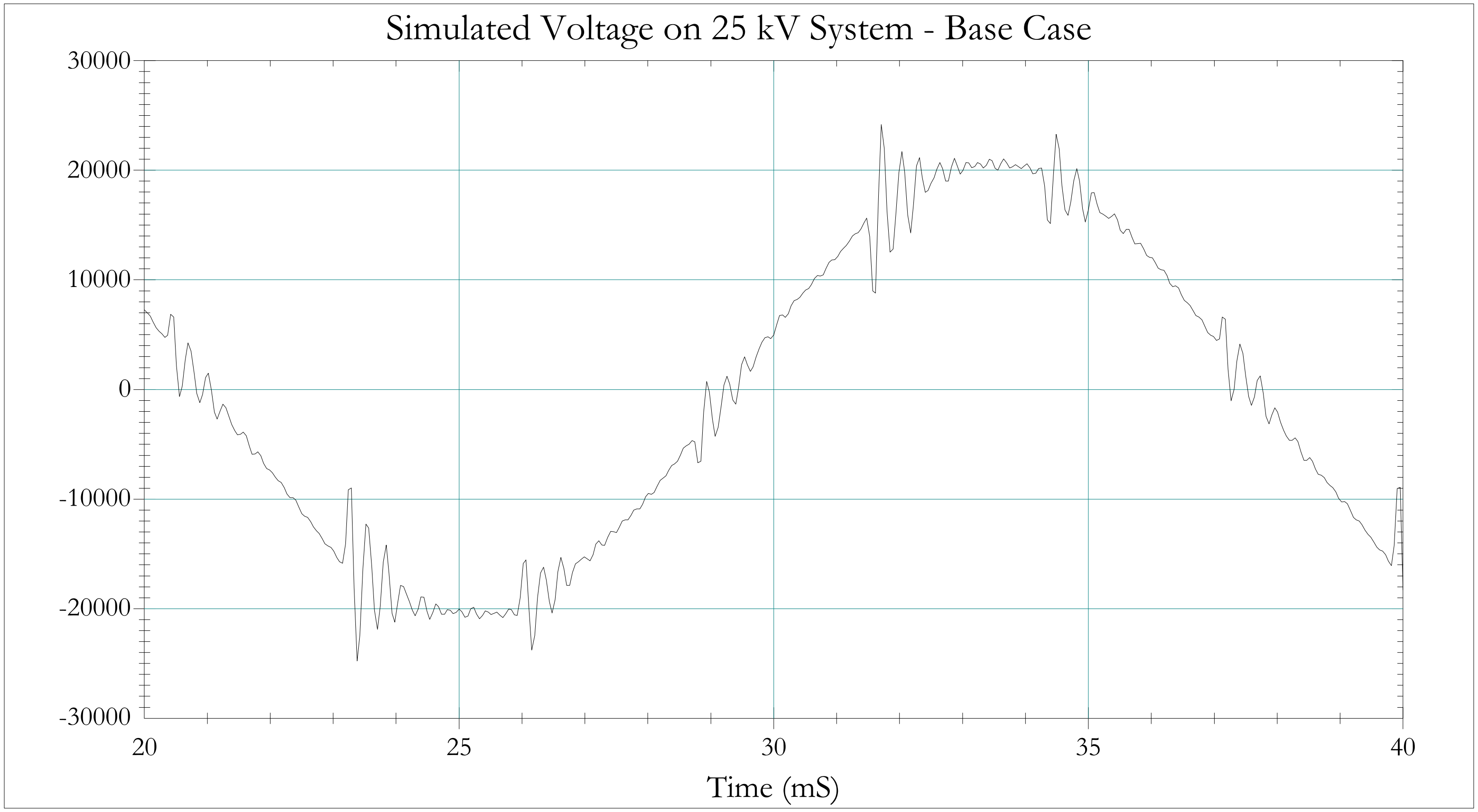




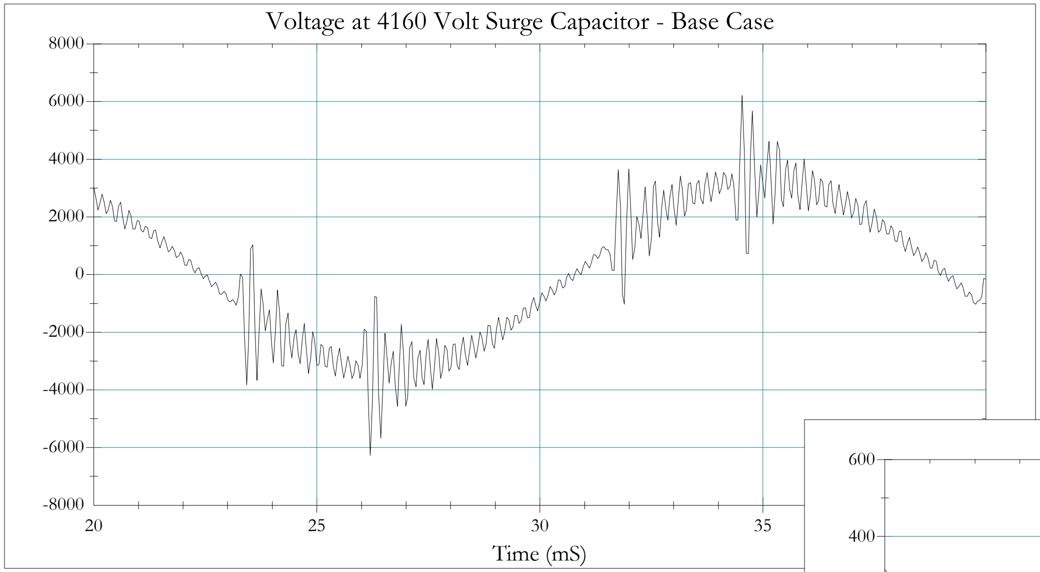
System Frequency Response Illustrating Resonance



Simulation Result

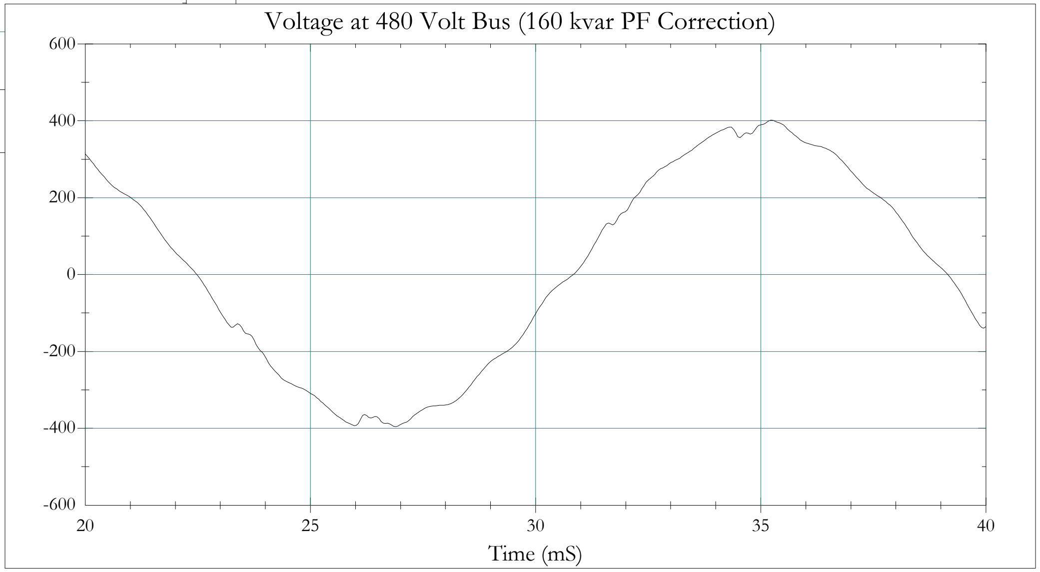


Waveforms at Nearby Customer



4160 volt bus with surge capacitors

480 volt bus with PF correction capacitors

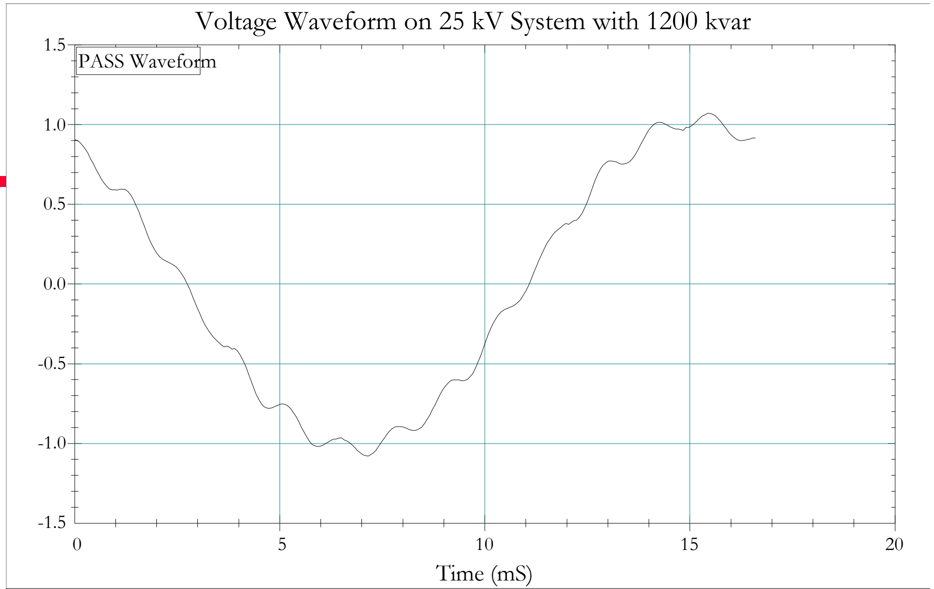


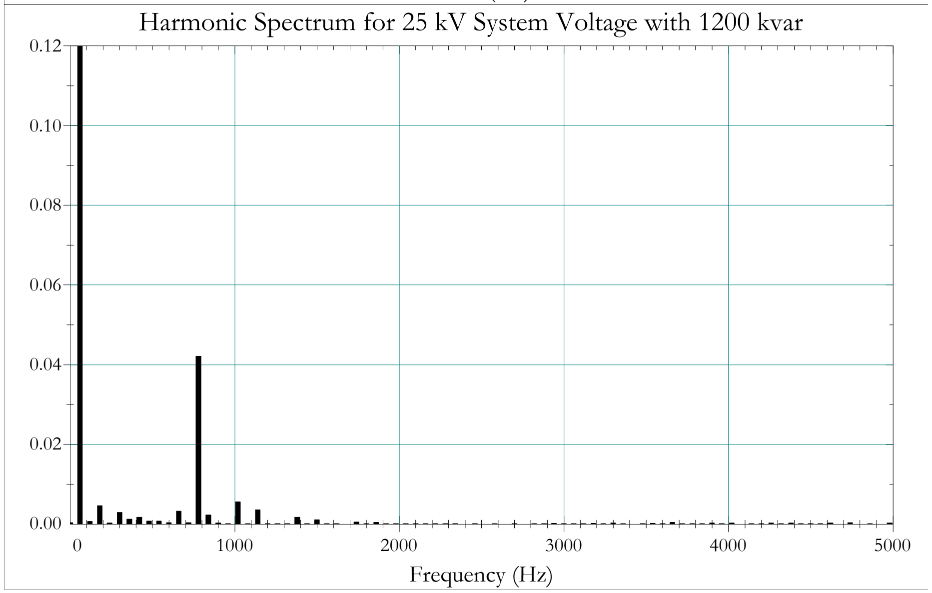
Possible Solutions

- Choke inductance at drive input
- Larger surge capacitors at customer bus
- High pass filter at drive bus
- 25 kV capacitors to change system resonance

Sizing the Capacitor Bank

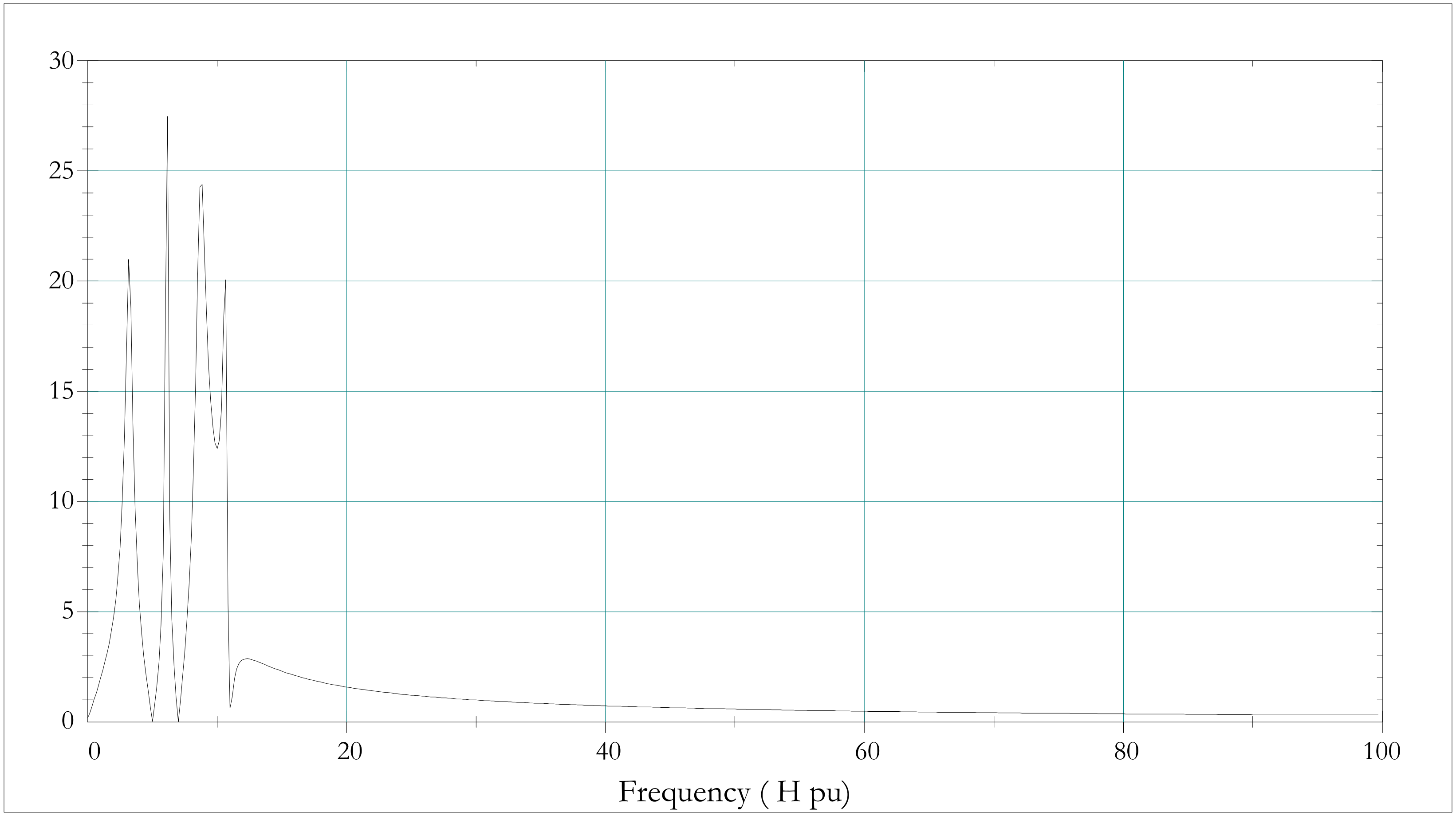
- Must avoid resonance at a characteristic harmonic of the drive



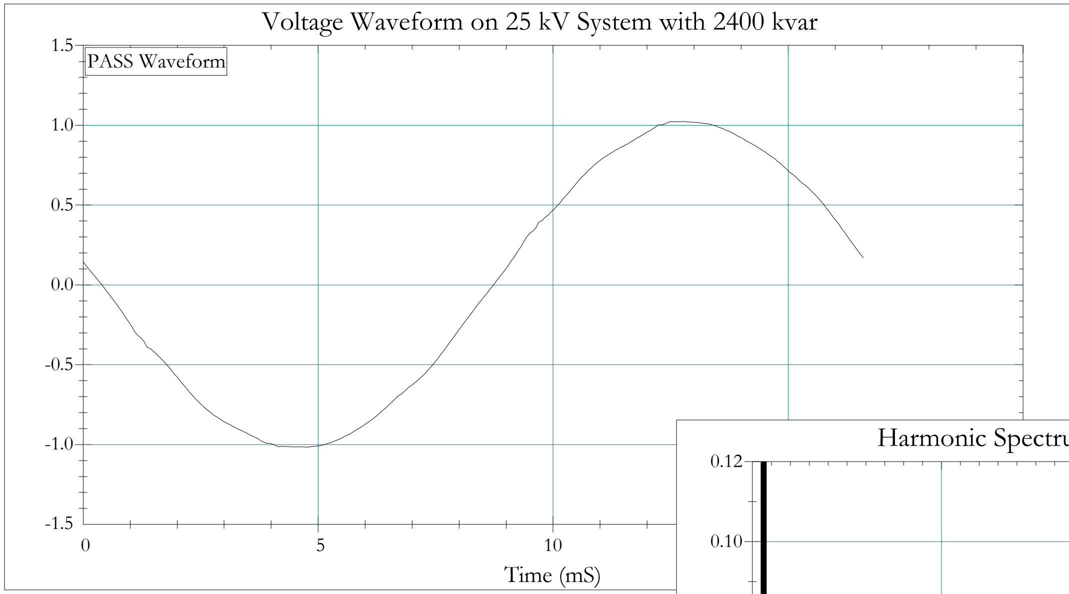


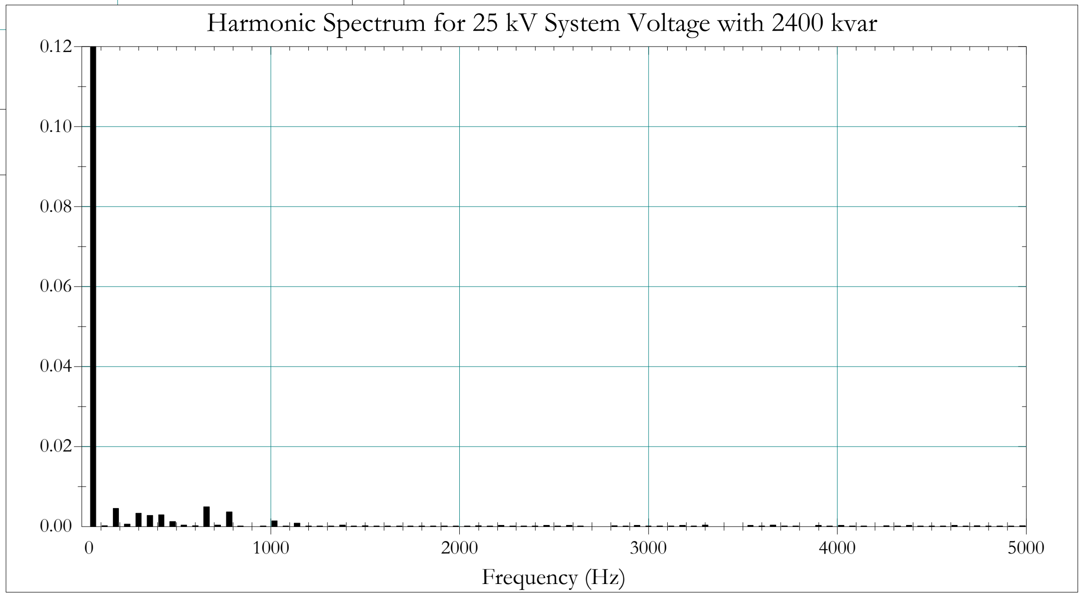
1200 kvar causes 13th harmonic resonance

Impedance vs. frequency with 2400 kvar bank

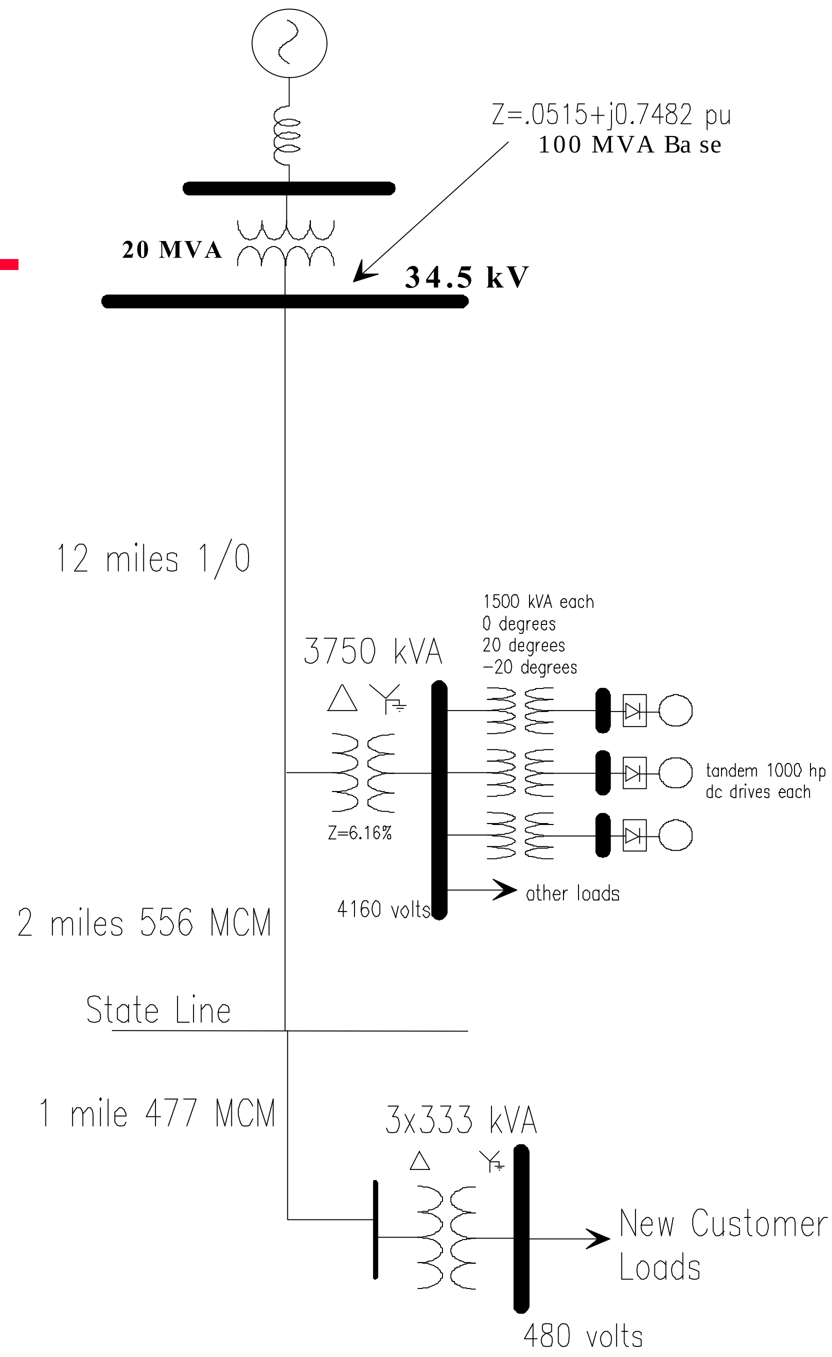


Waveform with 2400 kvar bank (measured)





Example 2 - Large dc Drive

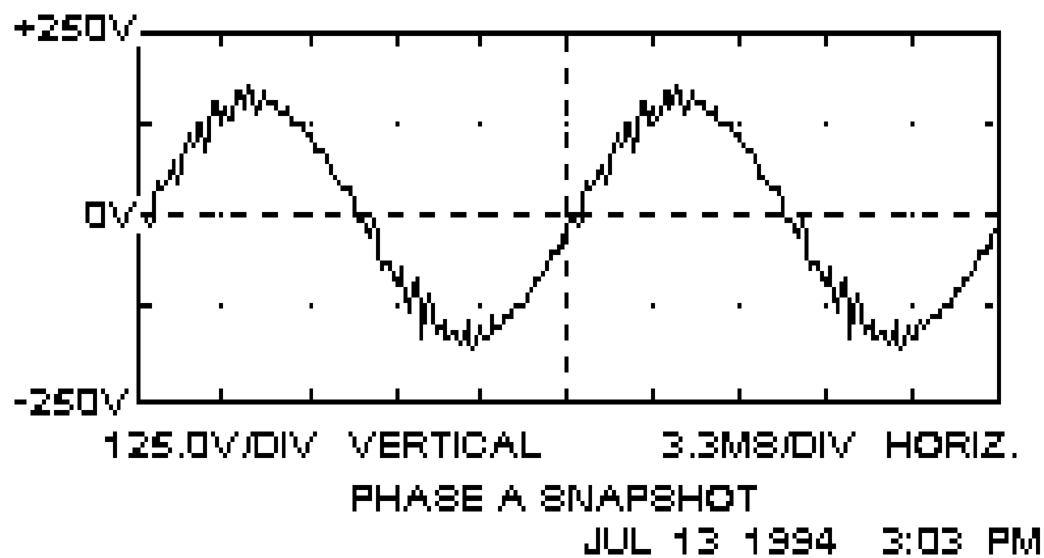


The Problem

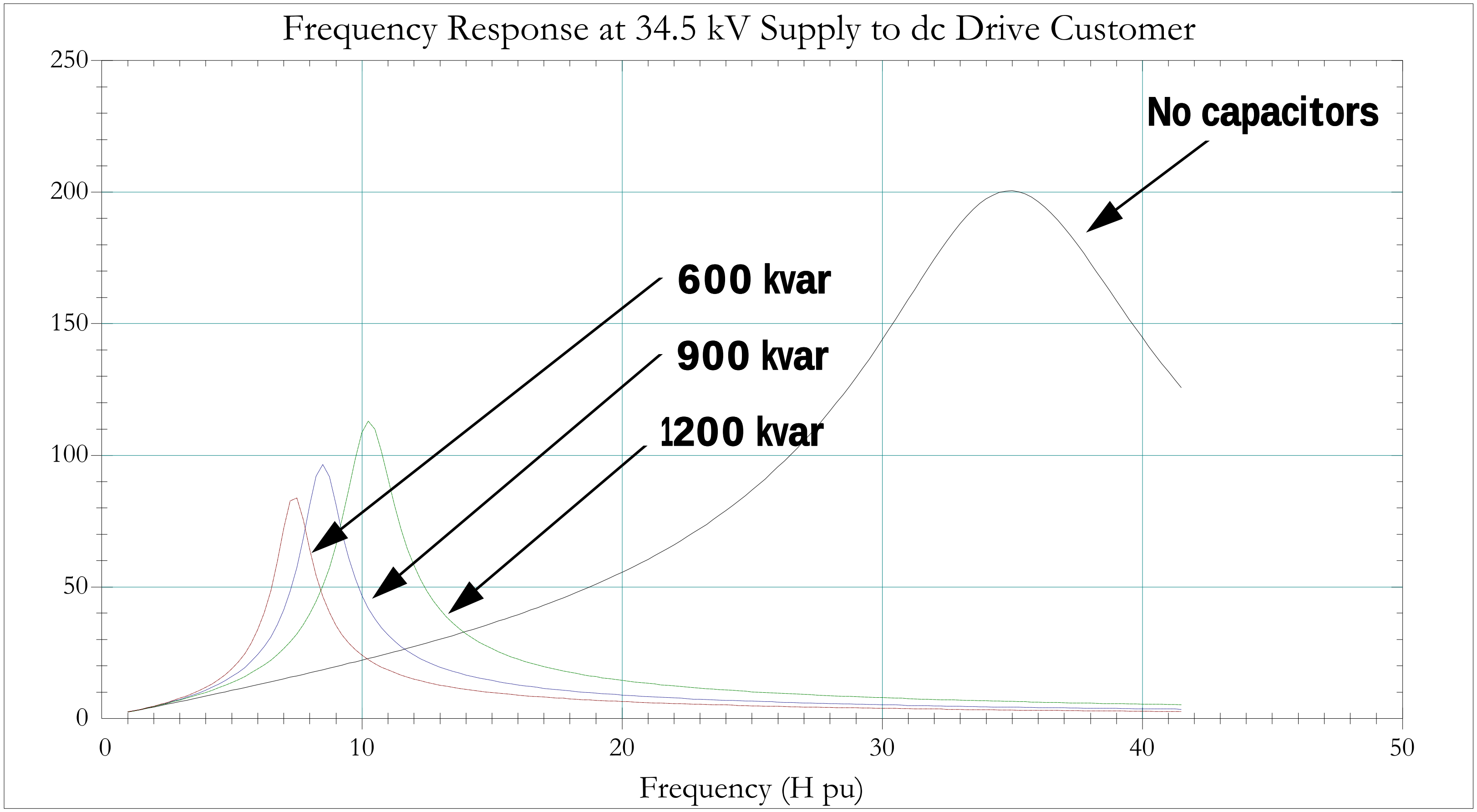
S.F. PHOSPHATES Jul 13 1994 (Wed)
PHASE A VOLTAGE SPECTRUM 3:00:51 PM
Fundamental volts: 67.6 Vrms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	0°	2nd	0.9%	87°
3rd	0.4%	170°	4th	0.3%	35°
5th	0.2%	167°	6th	0.2%	95°
7th	0.4%	62°	8th	0.6%	-51°
9th	0.1%	-69°	10th	0.7%	-63°
11th	0.4%	-40°	12th	0.4%	-158°
13th	0.9%	-142°	14th	1.6%	18°
15th	0.6%	107°	16th	1.3%	-36°
17th	1.6%	-37°	18th	1.0%	-48°
19th	1.0%	-80°	20th	0.6%	158°
21st	0.9%	-46°	22nd	0.5%	176°
23rd	1.1%	-102°	24th	1.7%	157°
25th	0.9%	175°	26th	2.7%	44°
27th	1.5%	-87°	28th	4.0%	-32°
29th	1.6%	107°	30th	1.6%	-27°
31st	1.0%	69°	32nd	3.3%	-36°
33rd	4.1%	59°	34th	3.2%	-68°
35th	3.6%	-54°	36th	2.8%	172°
37th	0.6%	-121°	38th	0.3%	-147°
39th	0.6%	169°	40th	0.7%	136°
41st	0.3%	17°	42nd	0.3%	155°
43rd	0.3%	20°	44th	0.4%	50°
45th	0.4%	35°	46th	0.5%	11°
47th	0.5%	72°	48th	0.2%	7°
49th	0.2%	-34°	50th	0.5%	-35°
ODD	6.7%		EVEN	8.2%	
THD:	9.2%				

- System resonance near the 34th harmonic causes oscillations at each notch.

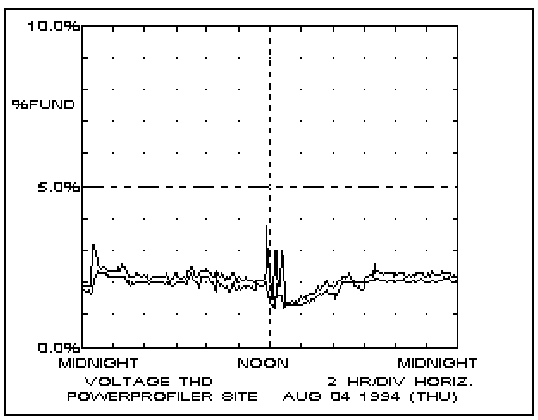


Will distribution capacitors work again?



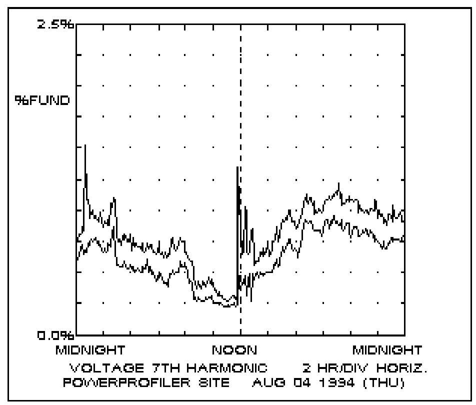
Results with a 900 kvar capacitor bank

POWERPROFILER SITE Aug 05 1994 (Fri)
VOLTAGE THD MIDNIGHT
FROM: MIDNIGHT Aug 03 1994 (Wed)
To: MIDNIGHT Aug 04 1994 (Thu)
Average:
MAX: 3.8% THD, 11:44 AM
MIN: 1.2% THD, 12:46 PM
Phase A-N:
MAX: 3.9% THD, 11:44 AM
MIN: 1.3% THD, 12:13 PM
Phase B-N:
MAX: 3.6% THD, 11:44 AM
MIN: 1.1% THD, 12:07 PM
Phase C-N:
MAX: 3.8% THD, 11:44 AM
MIN: 1.1% THD, 12:46 PM



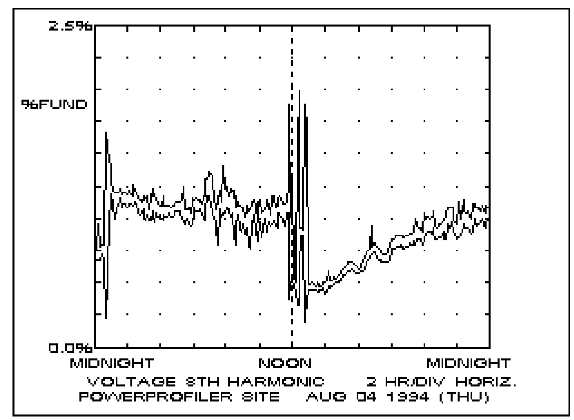
(Uncalibrated data.)
VOLTAGE THD (ACCUMULATED):
MAX: 5.9% THD
5:07 PM Aug 01 1994 (Mon)
MIN: 0.4% THD
6:06 AM Aug 03 1994 (Wed)

POWERPROFILER SITE Aug 05 1994 (Fri)
VOLTAGE 7th HARMONIC 12:00:12 AM
FROM: MIDNIGHT Aug 03 1994 (Wed)
To: MIDNIGHT Aug 04 1994 (Thu)
Average:
MAX: 1.5%, 12:36 AM
MIN: 0.2%, 10:50 AM
Phase A-N:
MAX: 1.7%, 12:36 AM
MIN: 0.1%, 11:01 AM
Phase B-N:
MAX: 1.2%, 12:36 AM
MIN: 0.0%, 11:44 AM
Phase C-N:
MAX: 1.7%, 12:36 AM
MIN: 0.0%, 9:07 AM



(Uncalibrated data.)
VOLTAGE 7th HARMONIC (ACCUMULATED):
MAX: 1.5%
12:36 AM Aug 04 1994 (Thu)
MIN: 0.2%
10:50 AM Aug 04 1994 (Thu)

POWERPROFILER SITE Aug 05 1994 (Fri)
VOLTAGE 8th HARMONIC 12:00:24 AM
FROM: MIDNIGHT Aug 03 1994 (Wed)
To: MIDNIGHT Aug 04 1994 (Thu)
Average:
MAX: 2.0%, 12:17 PM
MIN: 0.2%, 12:41 PM
Phase A-N:
MAX: 2.3%, 11:44 AM
MIN: 0.1%, 12:18 PM
Phase B-N:
MAX: 1.9%, 12:17 PM
MIN: 0.0%, 12:39 AM
Phase C-N:
MAX: 2.3%, 12:17 PM
MIN: 0.0%, 11:52 AM



(Uncalibrated data.)
VOLTAGE 8th HARMONIC (ACCUMULATED):
MAX: 2.0%
12:17 PM Aug 04 1994 (Thu)
MIN: 0.2%
12:41 PM Aug 04 1994 (Thu)

Conclusions

- Oscillations associated with converter notching can be a problem
- Oscillations can be magnified at customer locations with small capacitors, causing equipment misoperation and failure. Motor surge capacitors and even power supply capacitors can cause problems.

Conclusions

- Problem can be solved by careful selection of a capacitor size for the primary distribution system.
- The capacitor should not introduce a new resonance at one of the characteristic harmonics of the drive. The interaction of the proposed capacitor with other system capacitors and harmonic filters must be evaluated.

