Power Line Harmonic Disturbances

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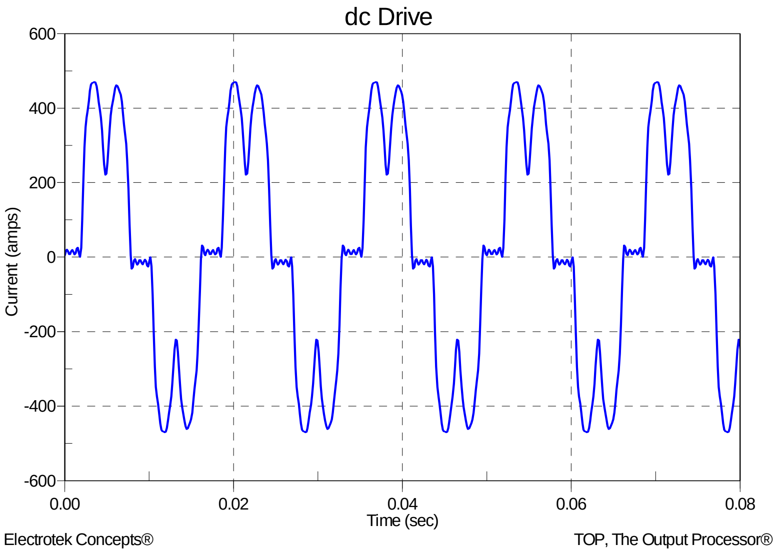
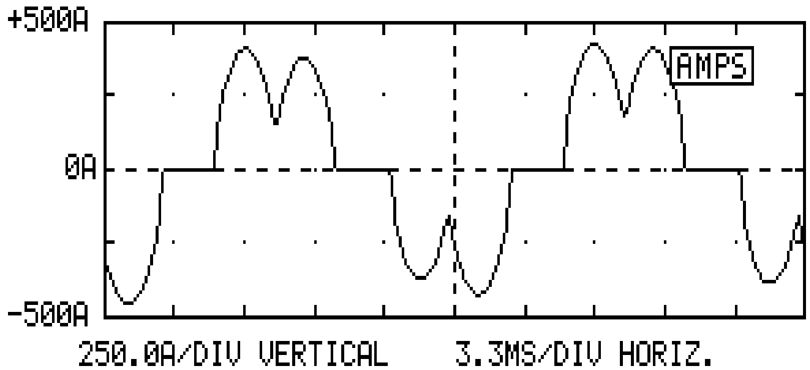
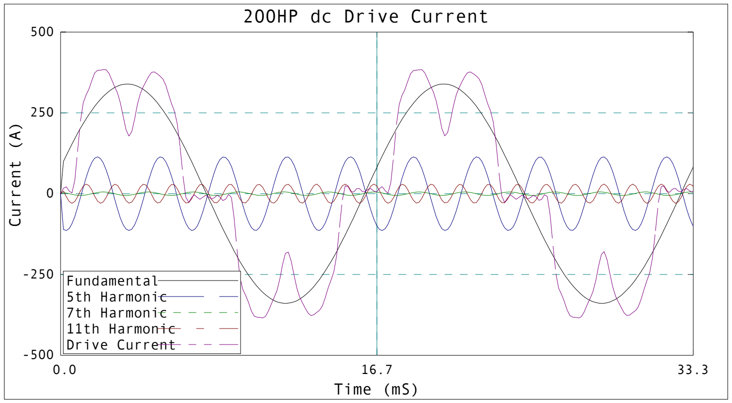
Power Line Harmonic Disturbances

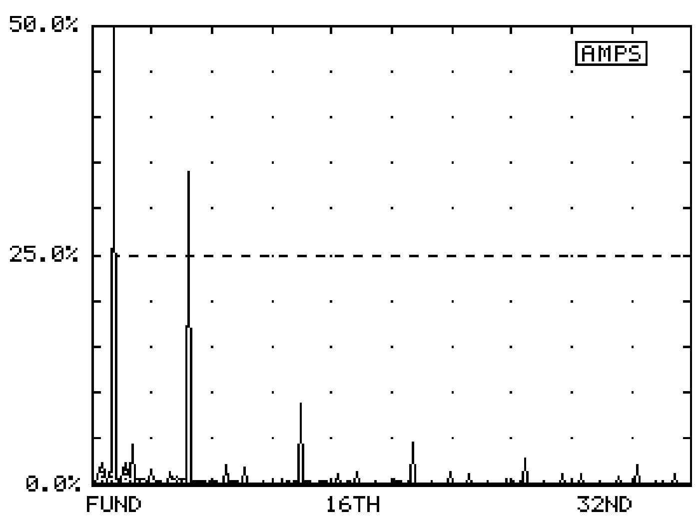
- Sources of Harmonics
- System Response Characteristics
- Effect of Capacitors on Frequency Response
- Basic Harmonic Filter Design



Harmonic Distortion - Definition







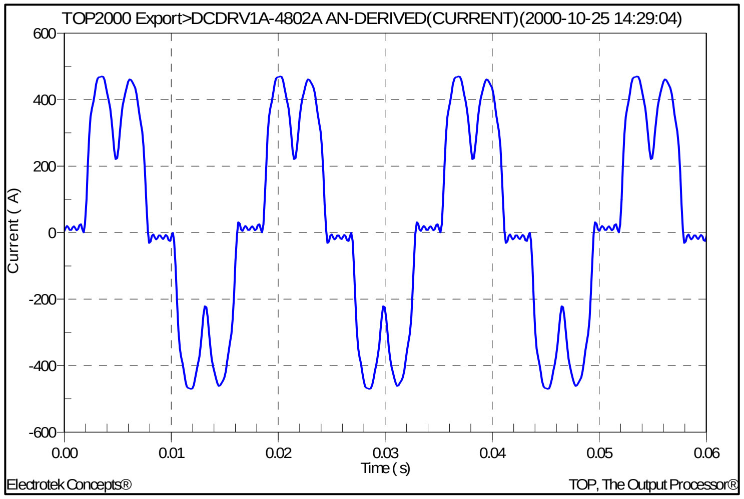
Sources of Harmonics

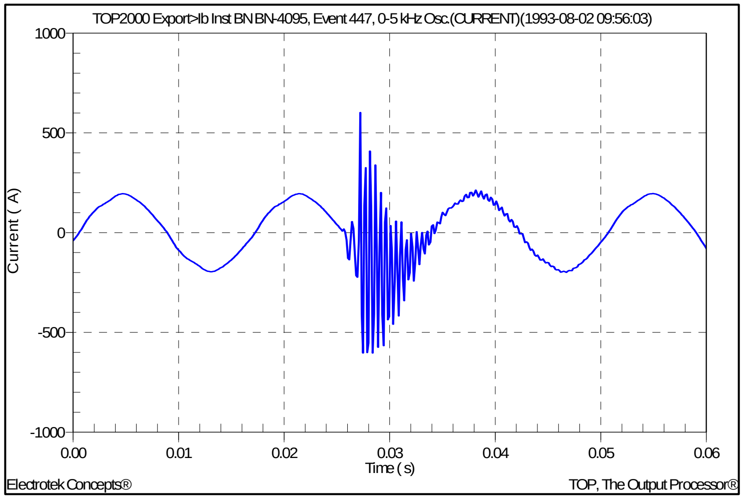
- Saturable devices (e.g., transformers, and nonlinear inductors/reactors).
- Arcing devices (e.g., arc furnaces, welders, and fluorescent lighting – magnetic ballast).
- Power electronics equipment (e.g., adjustable-speed motor drives, dc motor drives, electronic power supplies (SMPS), fluorescent lighting – electronic ballast).

Harmonics vs. Transients

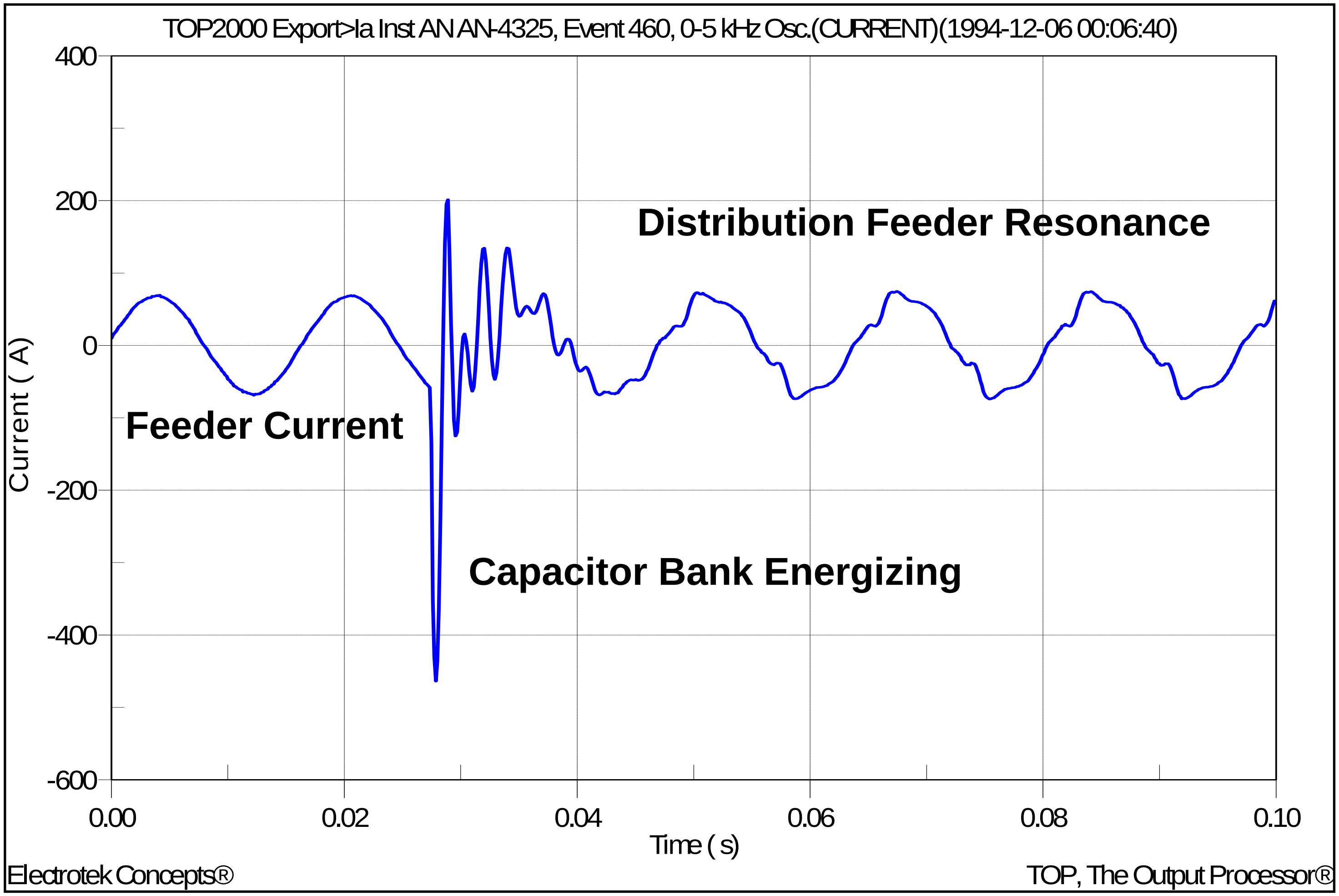
- Steady-state distortion of the waveform.
- Periodic and continuous in nature.

- Sudden changes in the power system.
- Classified by peak magnitude, frequency, and duration.





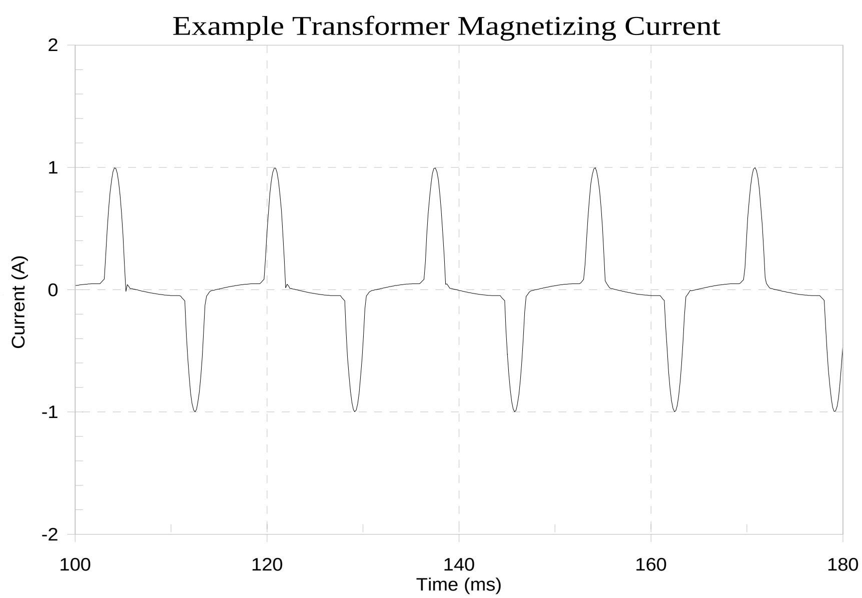
Harmonics vs. Transients - continued



Source: D-BMI 8010 PQNode

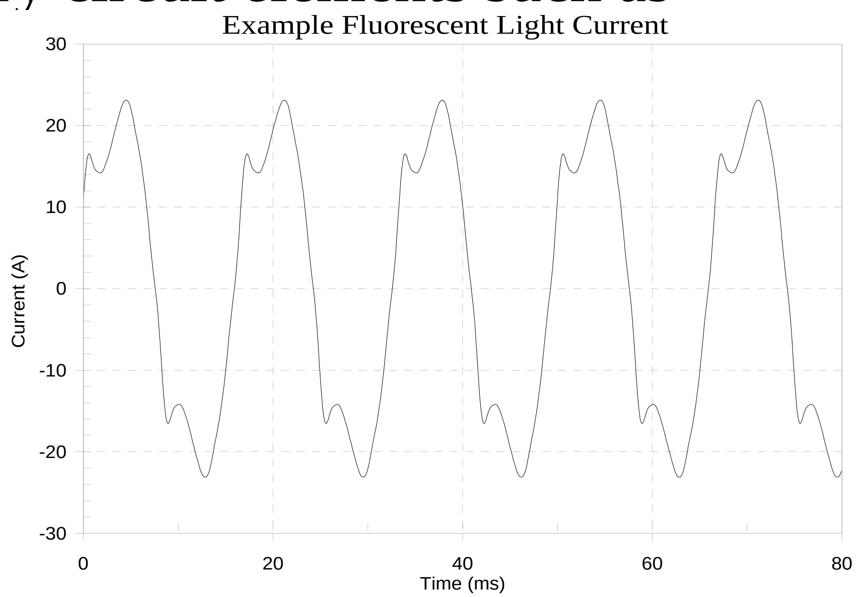
Saturable Loads

- Transformers and nonlinear reactors
- Harmonics are generated due to the nonlinear magnetizing characteristics
- Small, harmonic rich magnetizing currents from normal operation are usually not a problem, but will contribute to background voltage distortion.

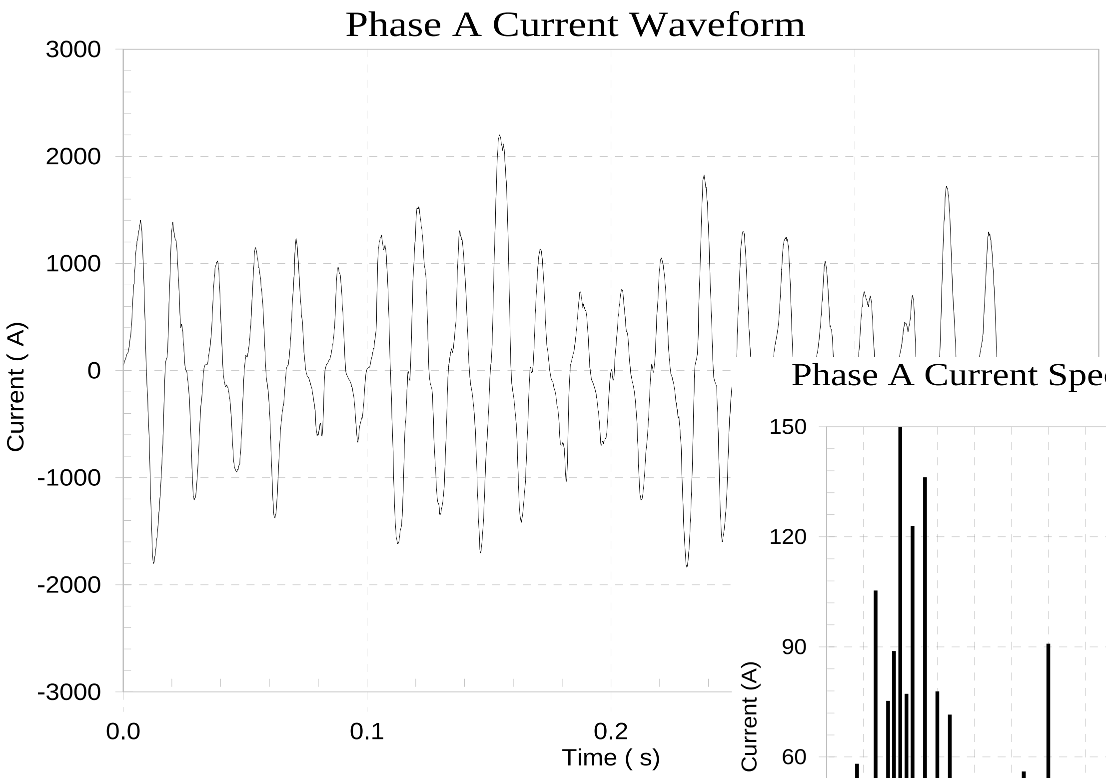


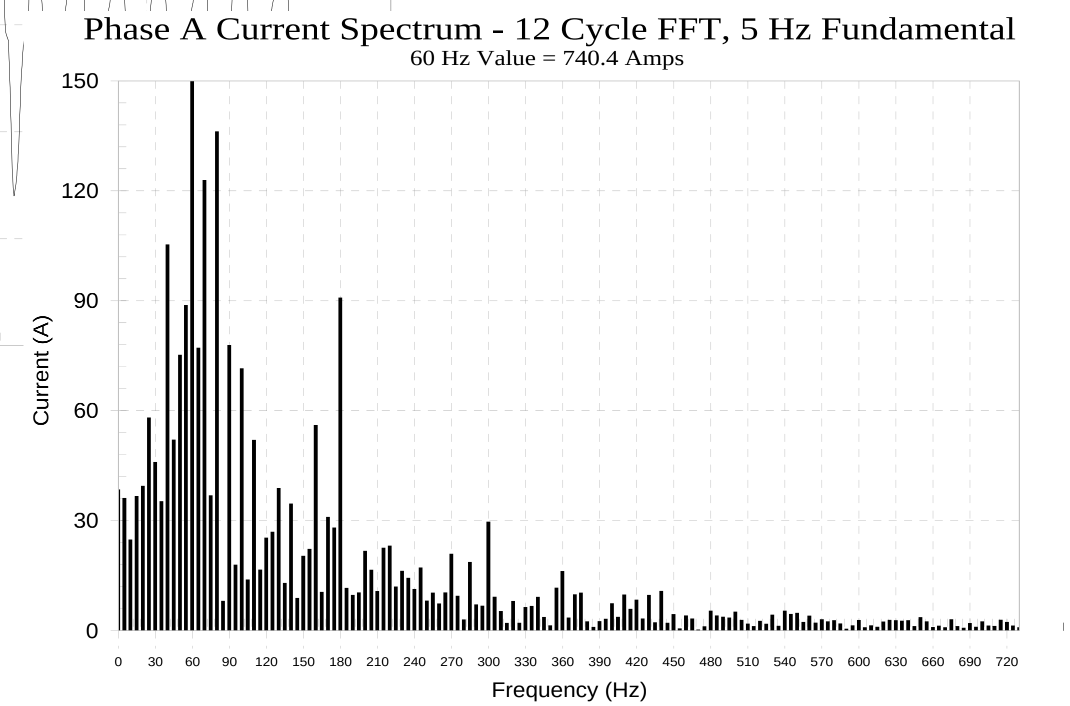
Arcing Loads

- Welding loads, arc furnaces, fluorescent lighting (without electronic ballasts)
- Distorted voltage, current due to non-linear nature of electric arc
- The electric arc itself is actually a source of voltage harmonics, but when auxiliary circuit elements such as ballasts or arc furnace leads are considered, the current source approximation is quite valid.



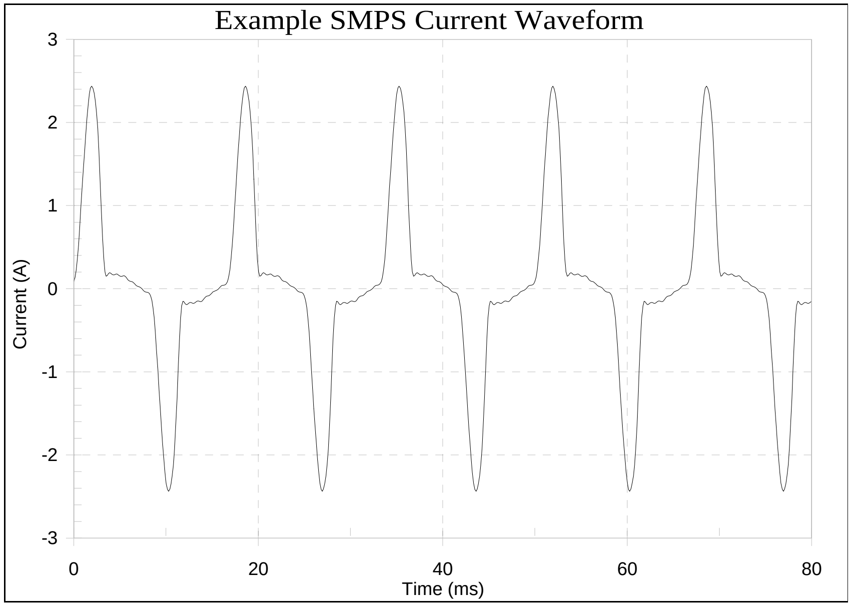
Example – Arc Furnace Snapshot



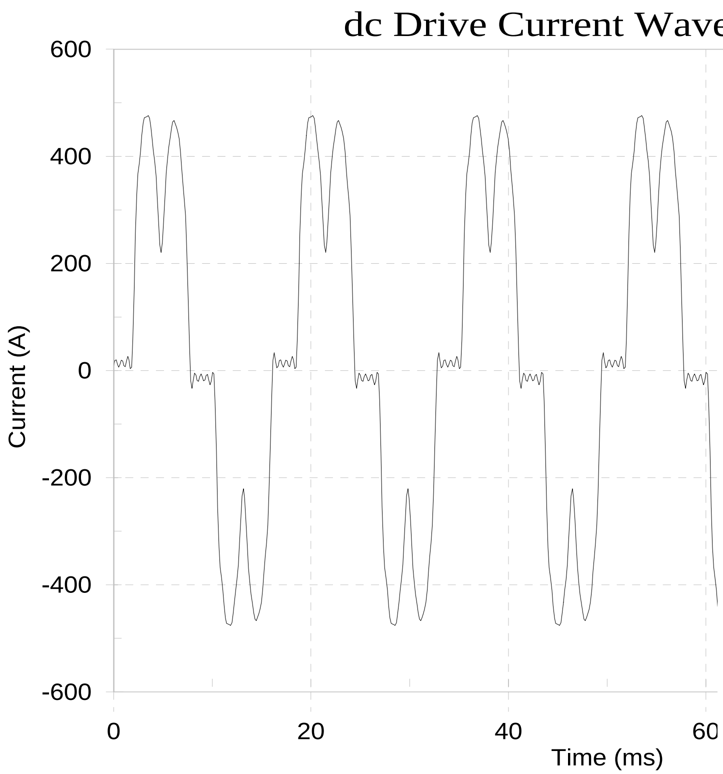


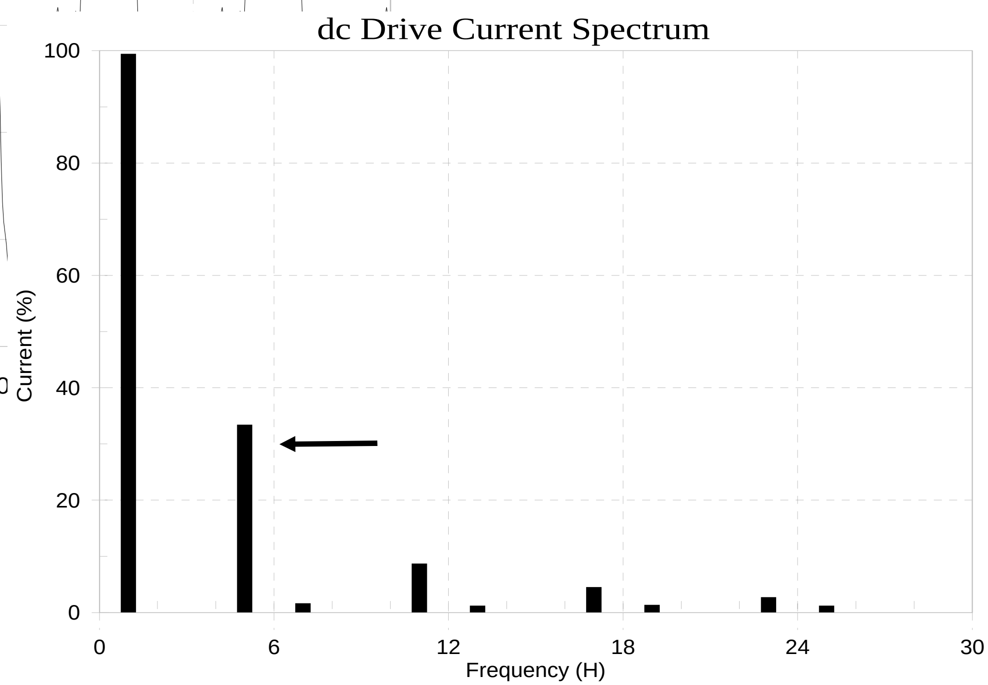
Power Electronic Loads

- Power supplies for electronic equipment, adjustable-speed motor drives (ASDs), d.c. motor drives, fluorescent lighting (electronic ballasts), battery chargers, and power converters for many industrial applications.
- Power electronics devices produce harmonics by the switching action of diodes, SCRs, or other switching devices that can switch current on and off within a cycle of the fundamental frequency.



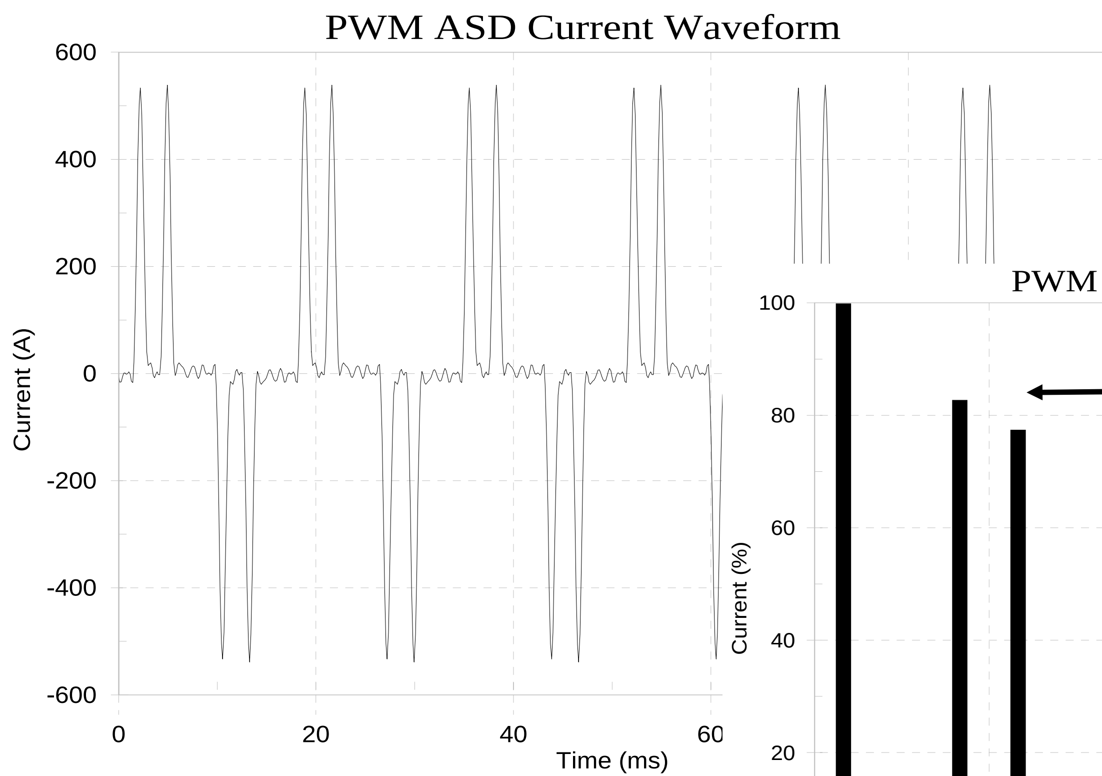
Example - dc Motor Drive Snapshot

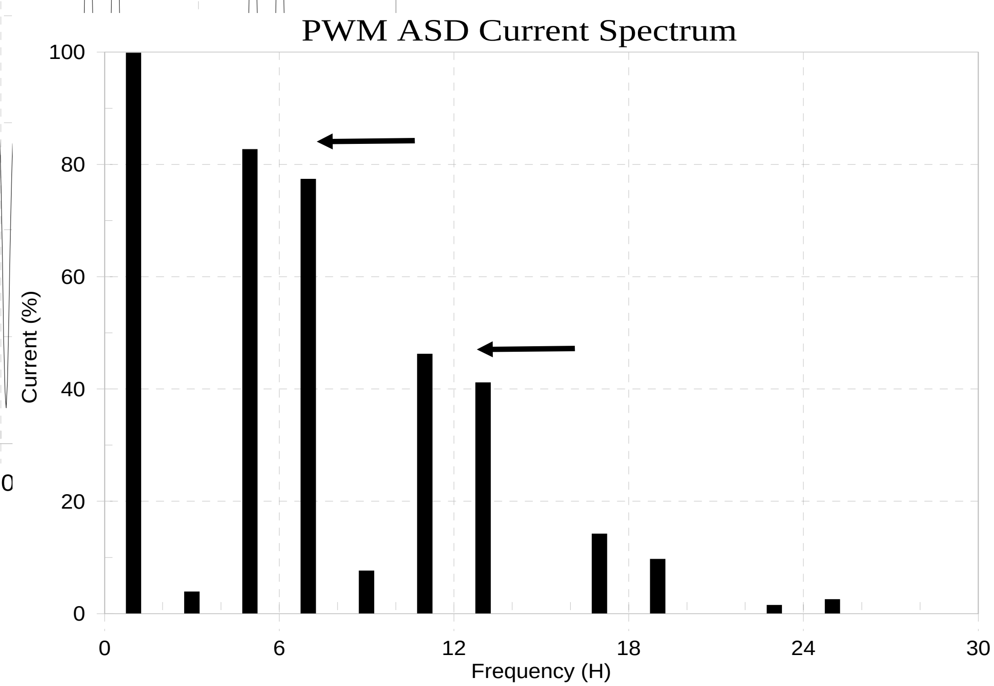




Example - PWM Drive – Snapshot #1

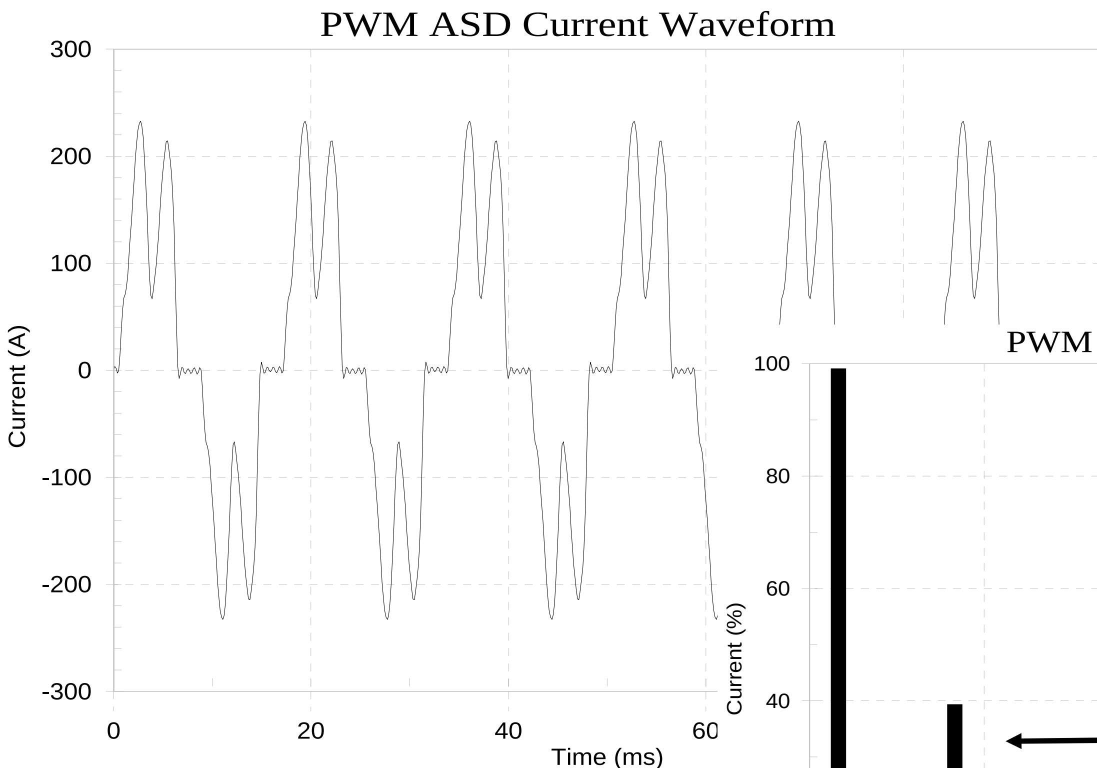
PWM ASD with small (or no) input choke:

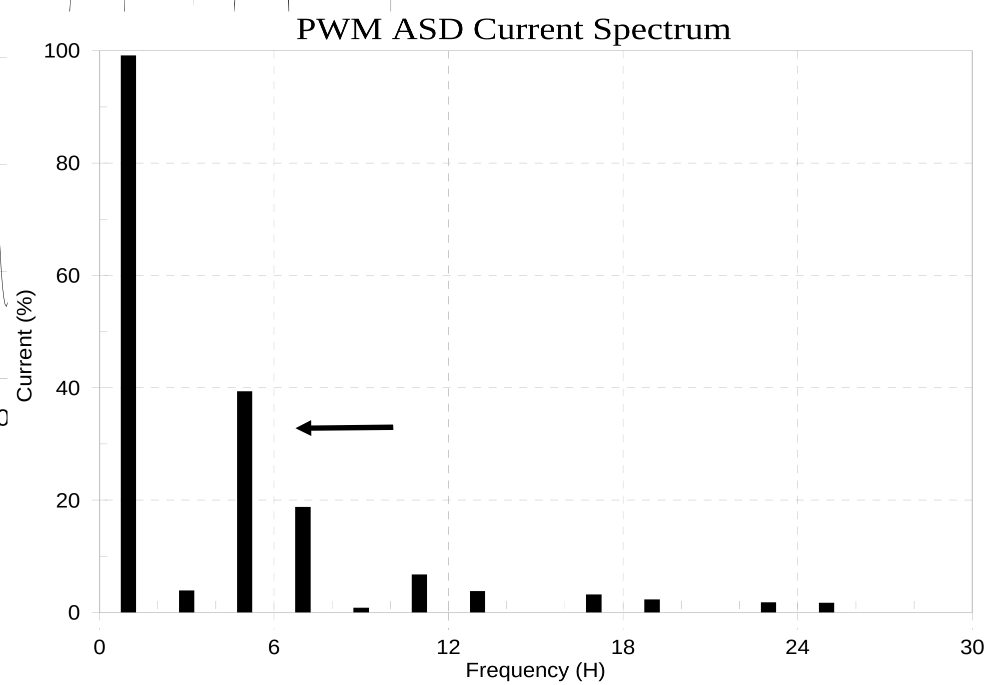




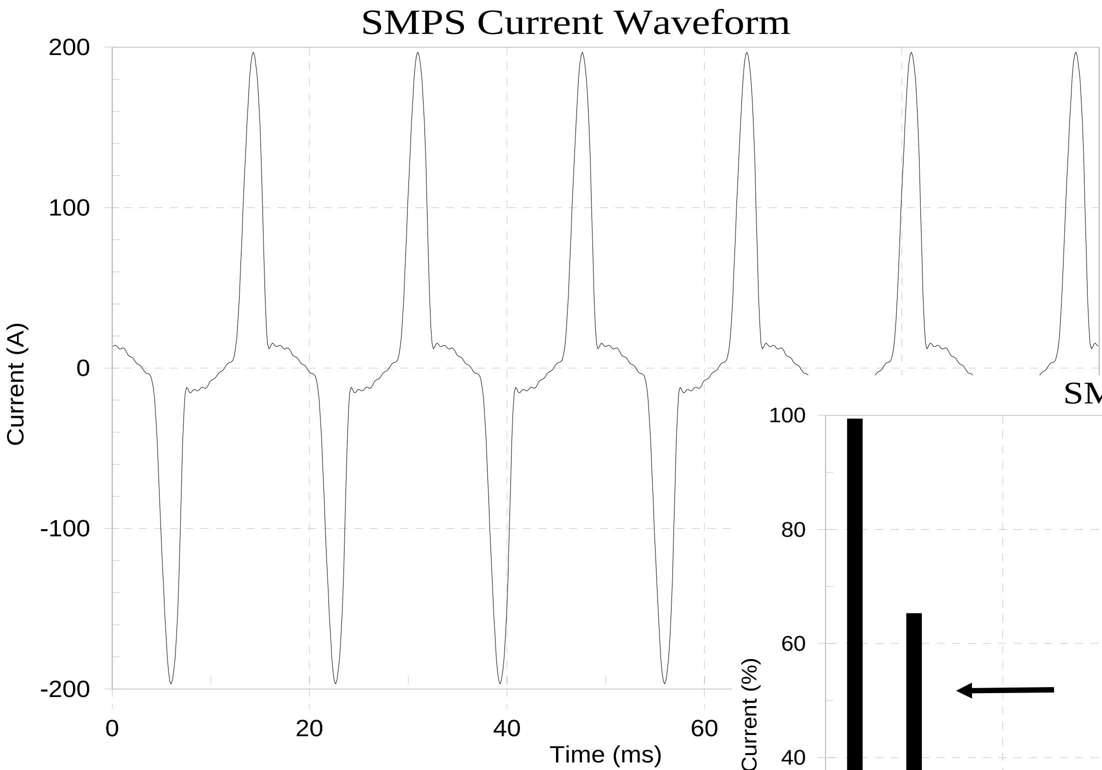
Example - PWM Drive – Snapshot #2

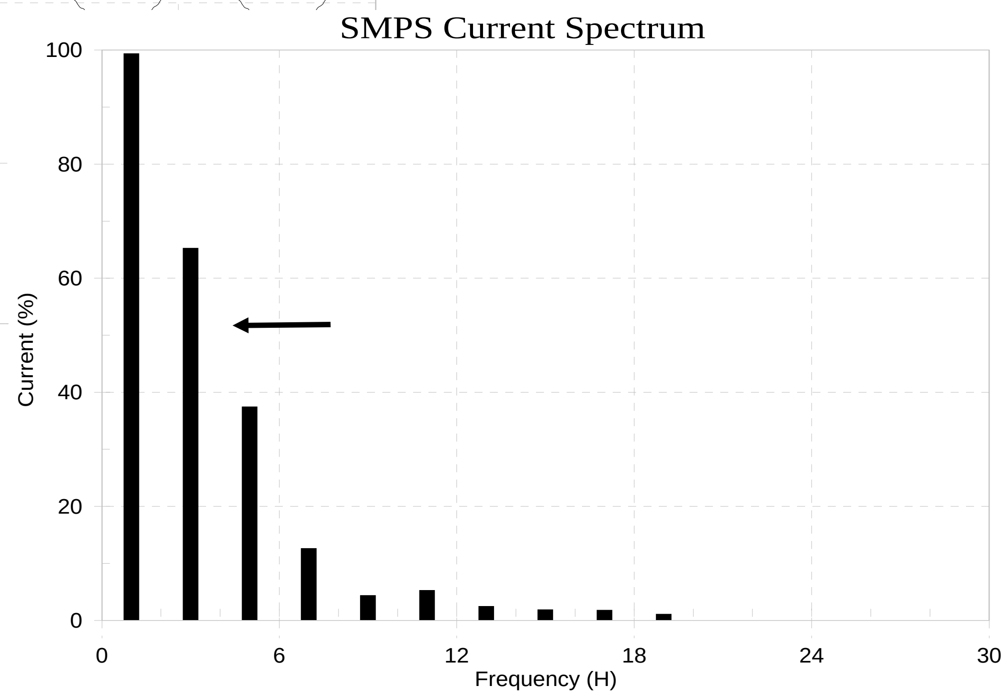
PWM ASD with 3% input choke added:





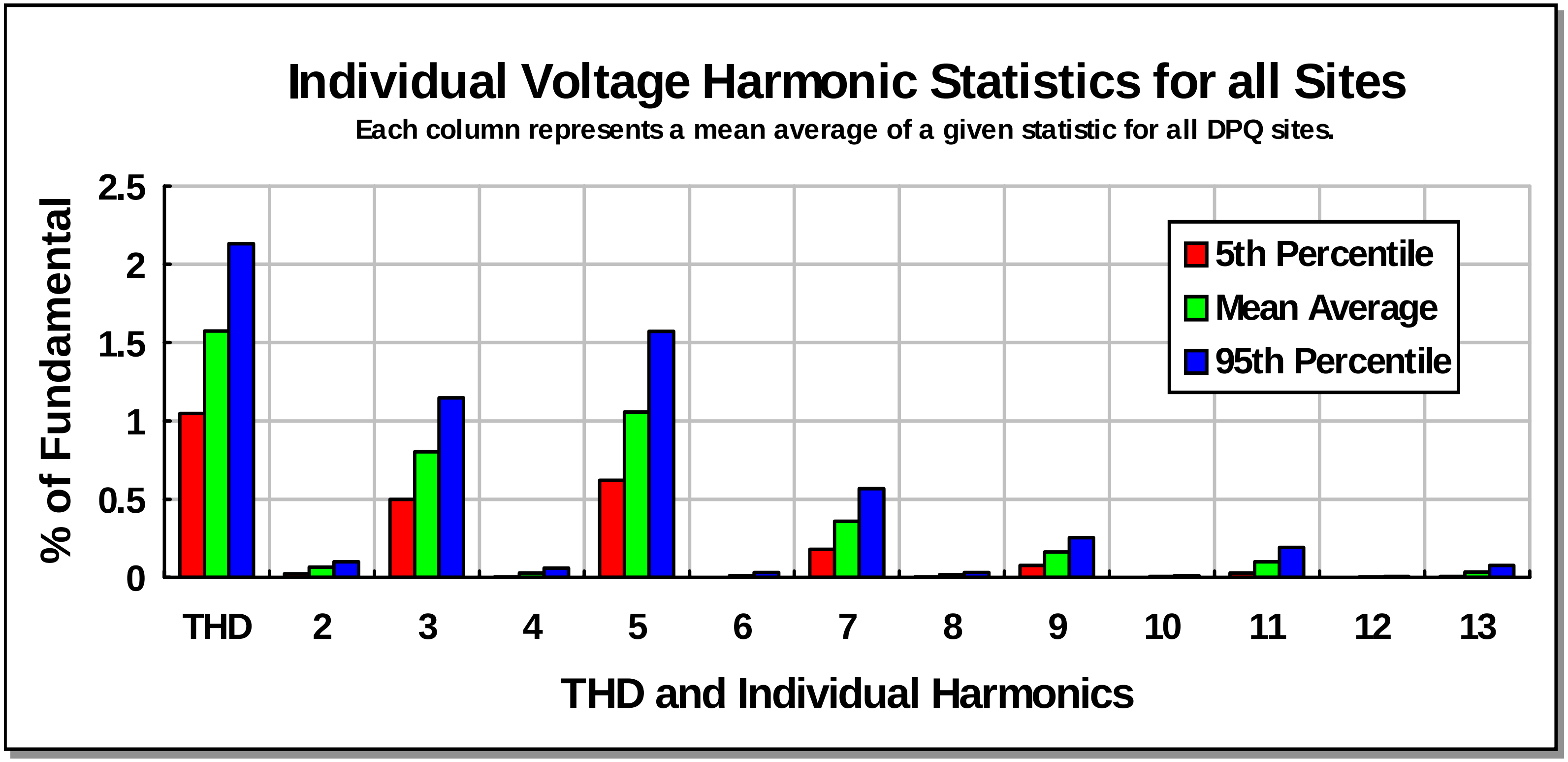
Example - SMPS Snapshot





Utility Background Distortion Levels

- Individual voltage harmonic statistics showing 5%, mean, and 95% point for each harmonic through the 13th:



All EPRI DPQ Sites, 6/1/93 to 6/1/94 (2,045,994 measurements from 222 sites)

Harmonics from Different Sources / Flow

- Low-order (e.g., 3rd,5th,7th) harmonic currents from multiple similar sources add nearly arithmetically.

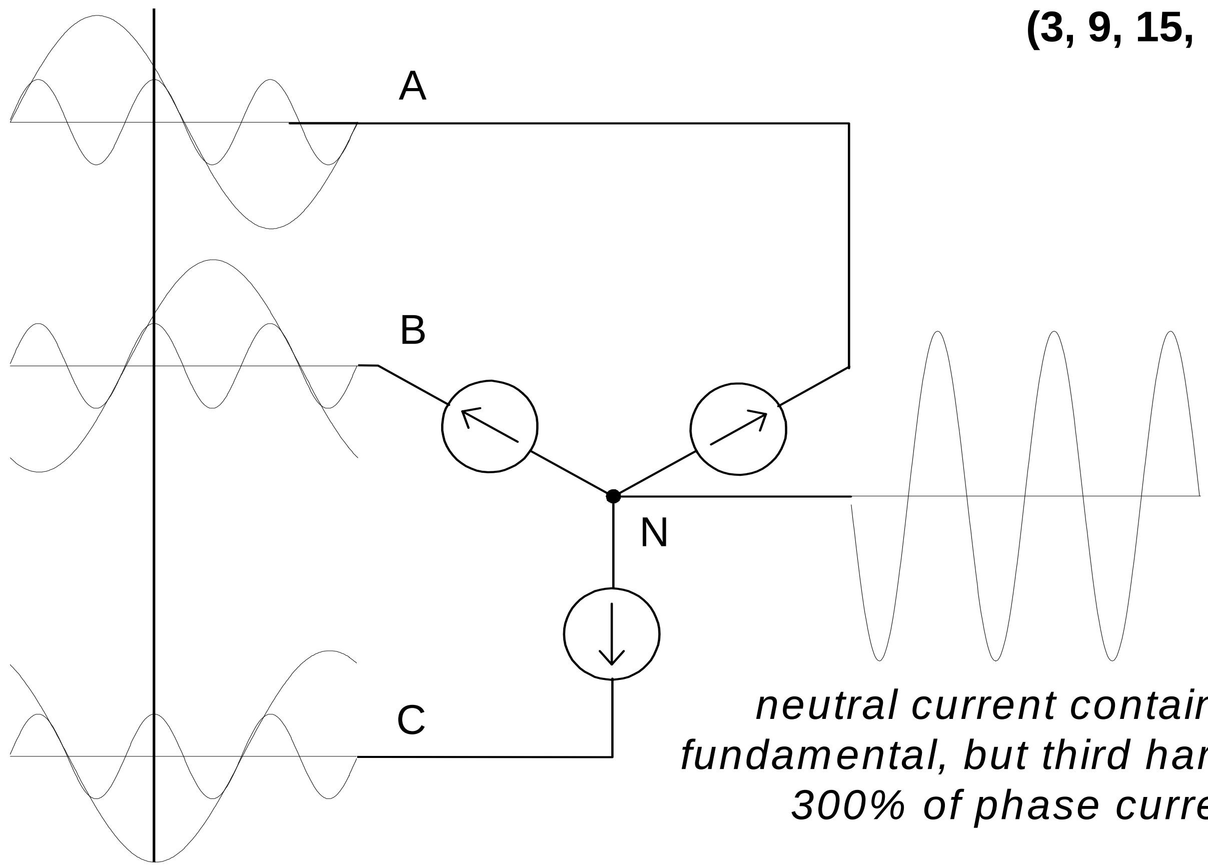
- Higher-order harmonic currents will tend to cancel each other.

- Delta-wye transformer connections can have a significant influence on harmonic currents at the service entrance (especially 3rd).

Triplen Harmonics

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

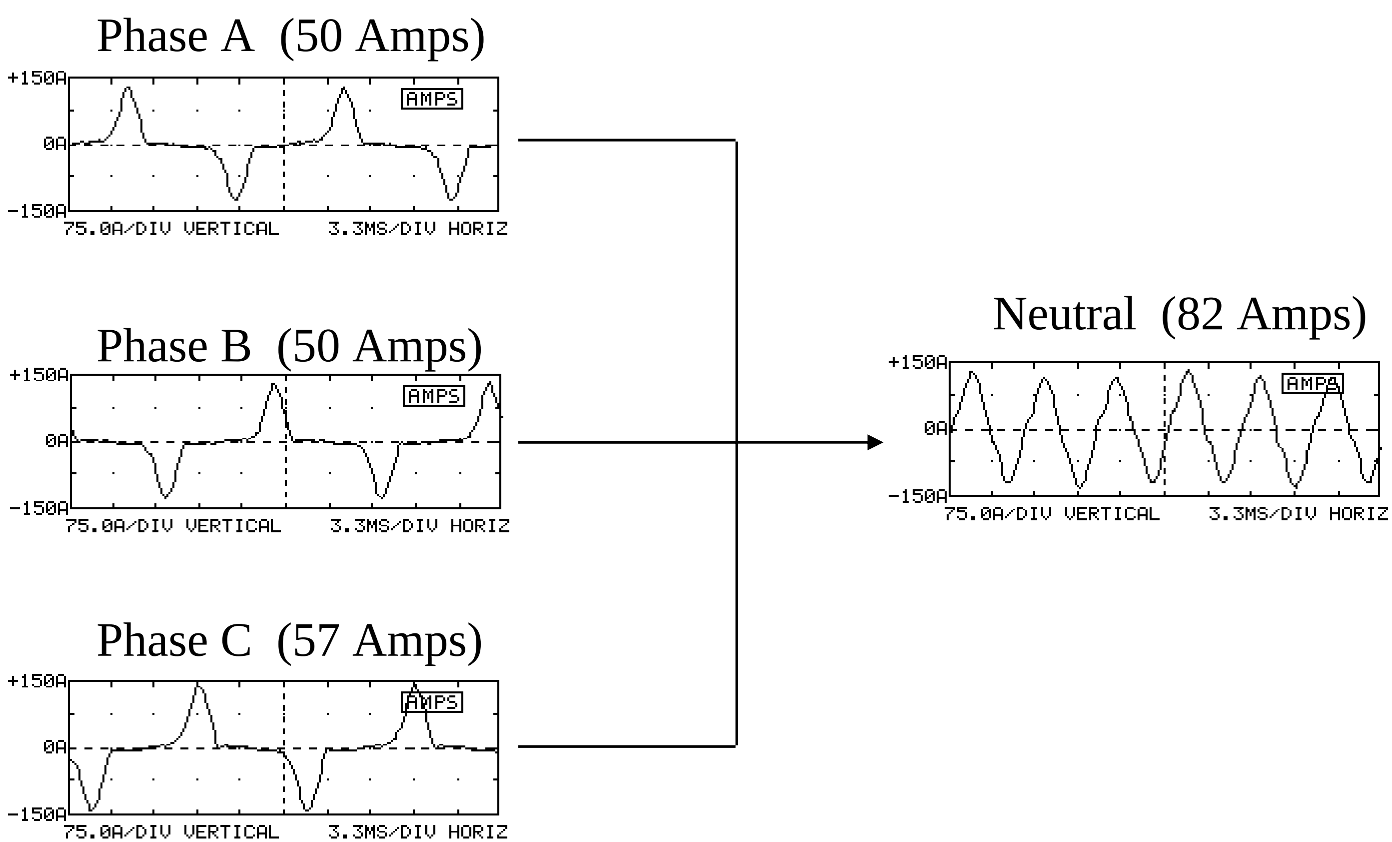
Triplen harmonic:
Odd multiples of 3
(3, 9, 15, 21…)



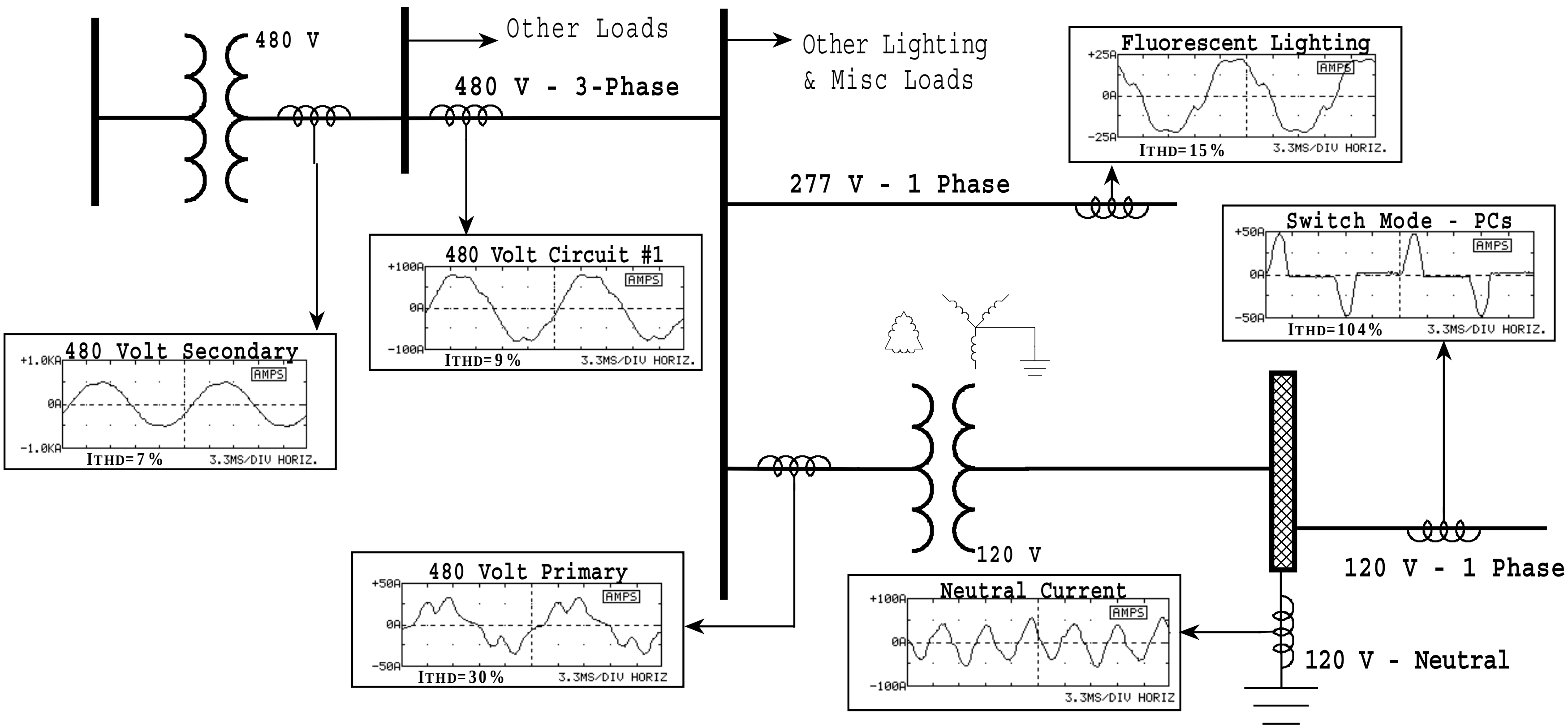
neutral current contains no fundamental, but third harmonic is 300% of phase current

Example - SMPS Snapshots

- Three phase and neutral currents for an example office computer circuit:

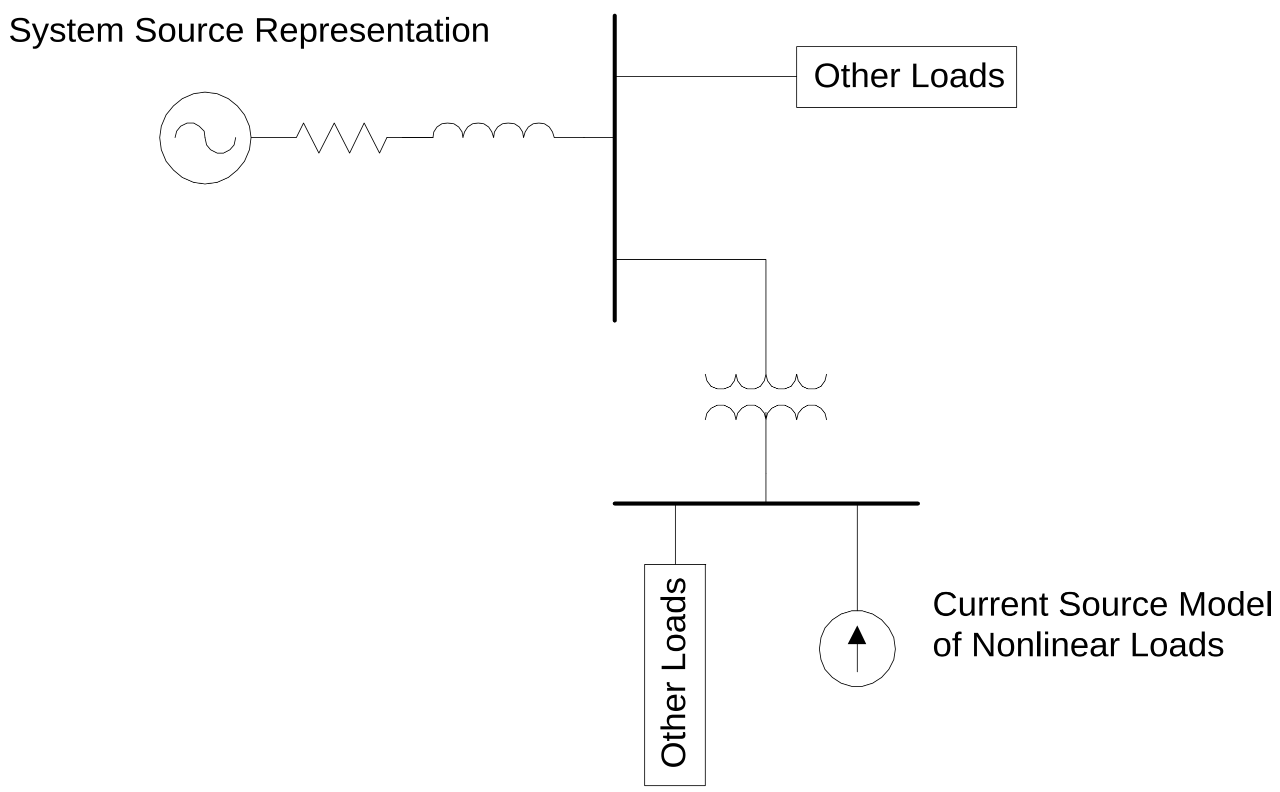


Case Study - Office Building



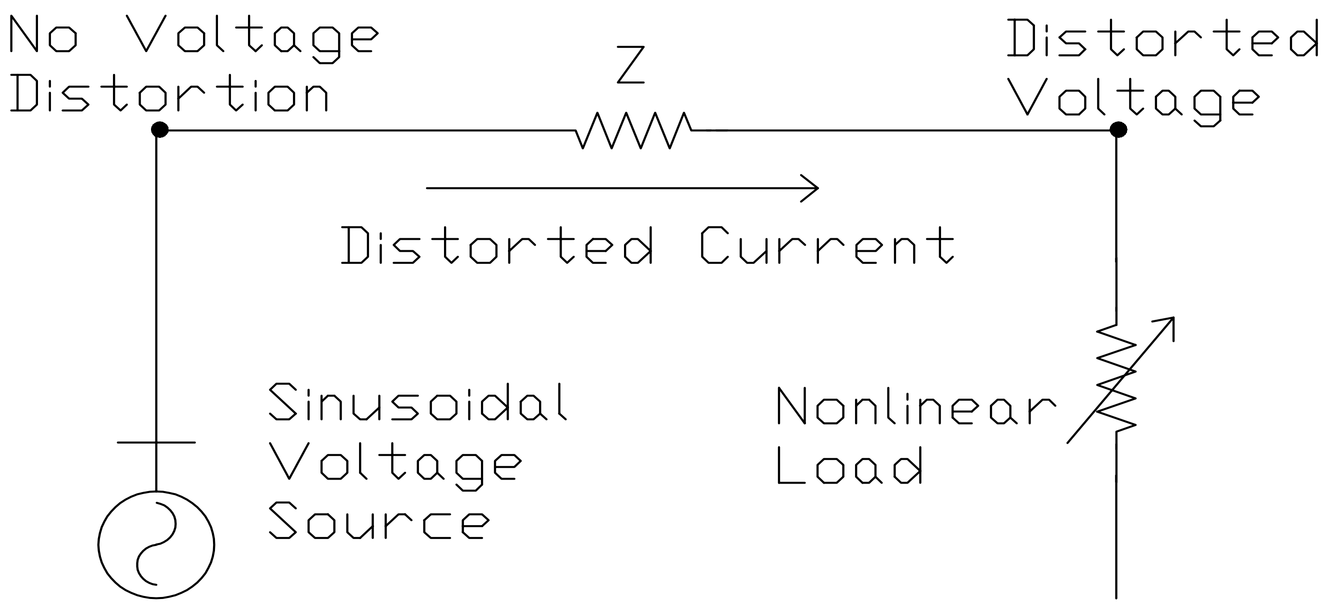
Representation of Nonlinear Loads

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



Voltage Distortion vs. Current Distortion

- Nonlinear loads inject harmonic current components into the power system.
- The system impedance vs. frequency characteristics determine the harmonic voltage distortion levels.



System Response Characteristics

- Voltage distortion is a result of the voltage drop created across the equivalent power system impedance.
- At 60 Hz, power systems are primarily inductive. The equivalent inductance can be calculated:

$$L_{eq} = \frac{X_{sc}}{2\pi * f}$$

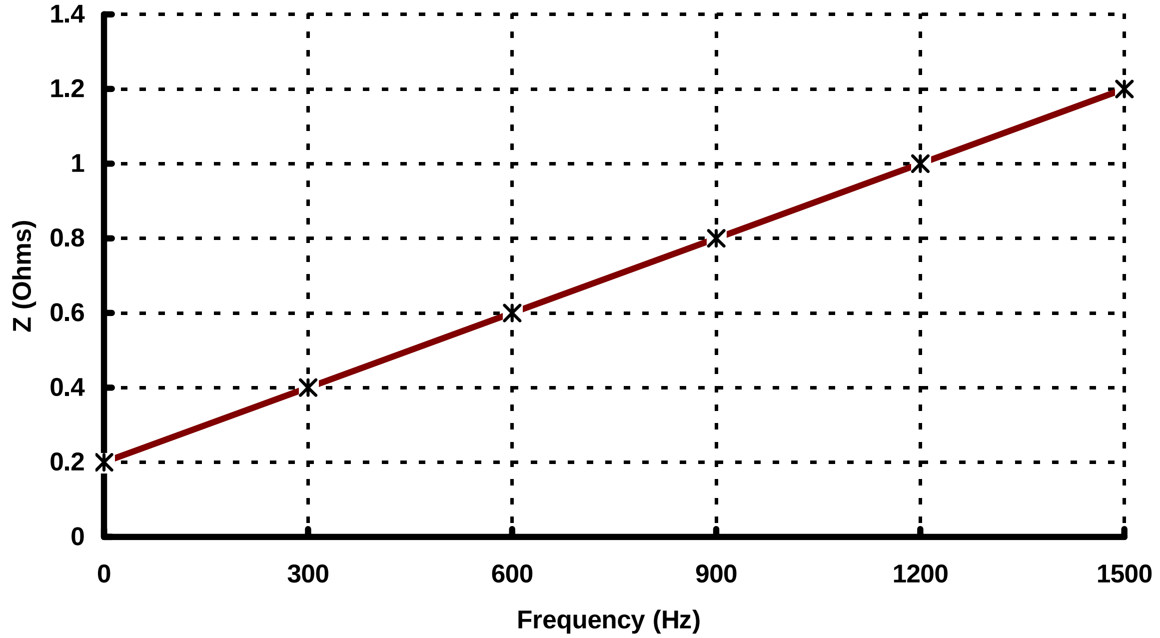
X_{sc} = system short circuit reactance

f = power system fundamental frequency (60 Hz)

Impedance vs. Frequency

- At harmonic frequencies, the impedance of the equivalent inductance is:

$$X_h = 2 \cdot \pi \cdot f_h \cdot L_{eq} = 2 \cdot \pi \cdot 60 \cdot h \cdot L_{eq}$$



Voltage Distortion Calculation

$$V_{THD} = \sqrt{\frac{\sum V_h^{\ 2}}{V_1^{\ 2}}}$$

500 HP Drive, 1500 kVA, 6% Transformer

Harmonic Number h	Harmonic Current (Amps) Ih	System Impedance (Ohms) Xh	Harmonic Voltage (Volts) Vh
5	186	0.046	8.55
7	38	0.064	2.43
11	61	0.101	6.16
13	28	0.119	3.33

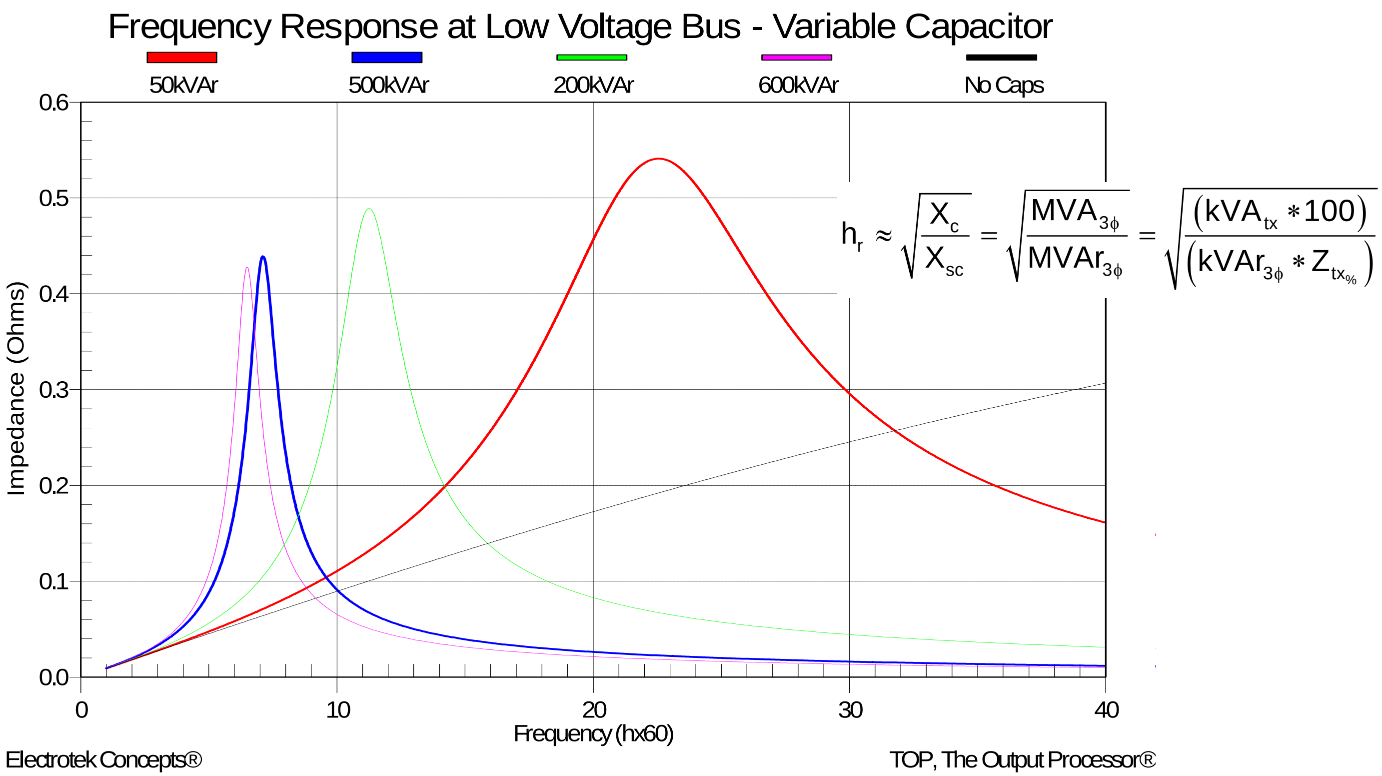
THD: 4.09%

$$V_{THD} = \sqrt{\frac{\left(8.55^2 + 2.43^2 + 6.16^2 + 3.33^2\right)}{\left(480 / \sqrt{3}\right)^2}} = 4.09\%$$

Note: No capacitors in service

Effect of Shunt Capacitors

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



$$h_r \approx \sqrt{\frac{X_c}{X_{sc}}} = \sqrt{\frac{MVA_{3\phi}}{MVAr_{3\phi}}} = \sqrt{\frac{(kVA_{tx} * 100)}{(kVAr_{3\phi} * Z_{tx_{\%}})}}$$

Resonant Frequency

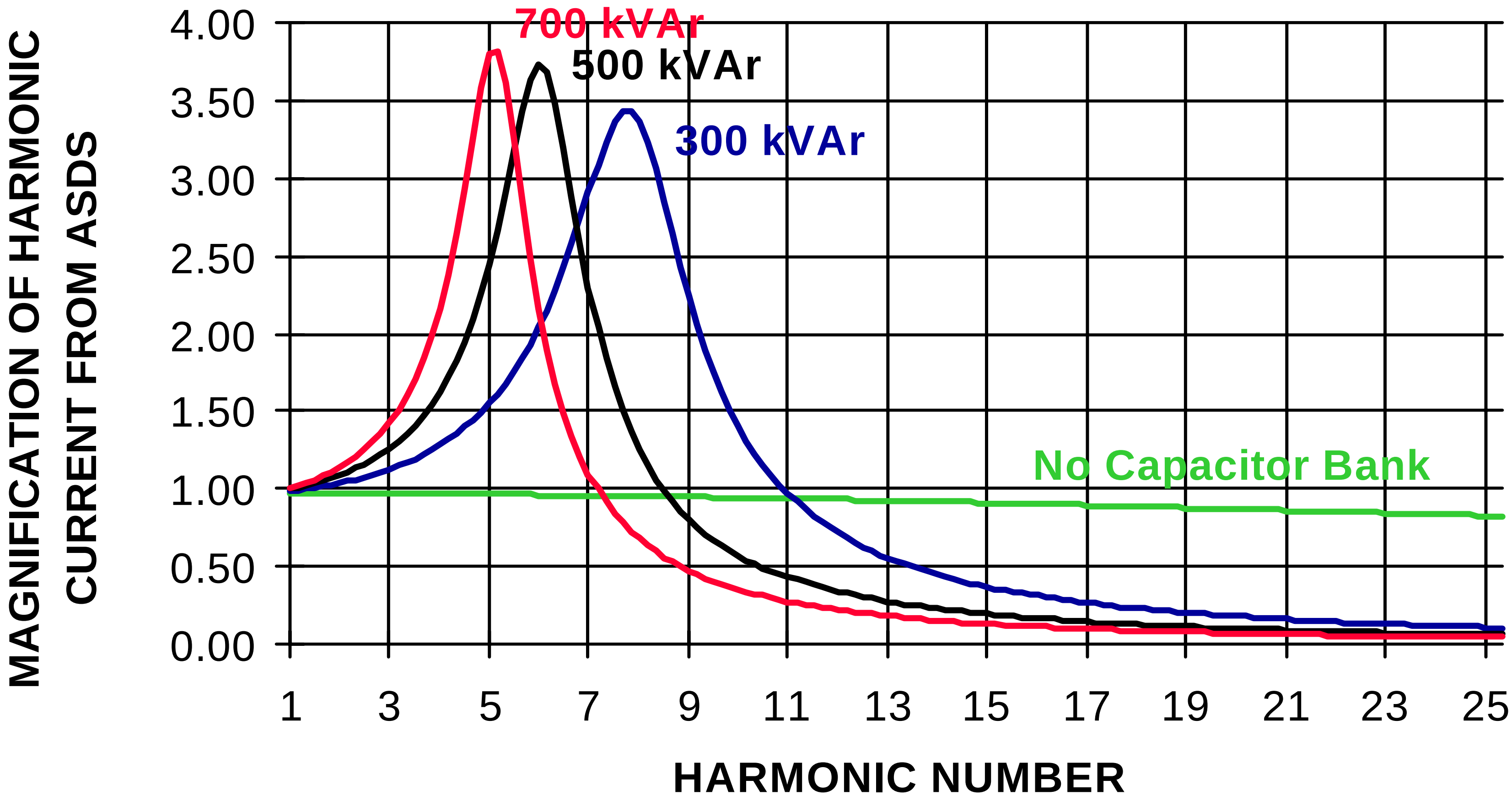
- At the frequency where the capacitive reactance (X_C) and the inductive reactance (X_L) are equal, the impedance seen by the nonlinear load becomes very large.
- This is known as the parallel resonant frequency and can be approximated using:

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}} = \sqrt{\frac{MVA_{SC}}{MVAr_C}} \cdot 60$$

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

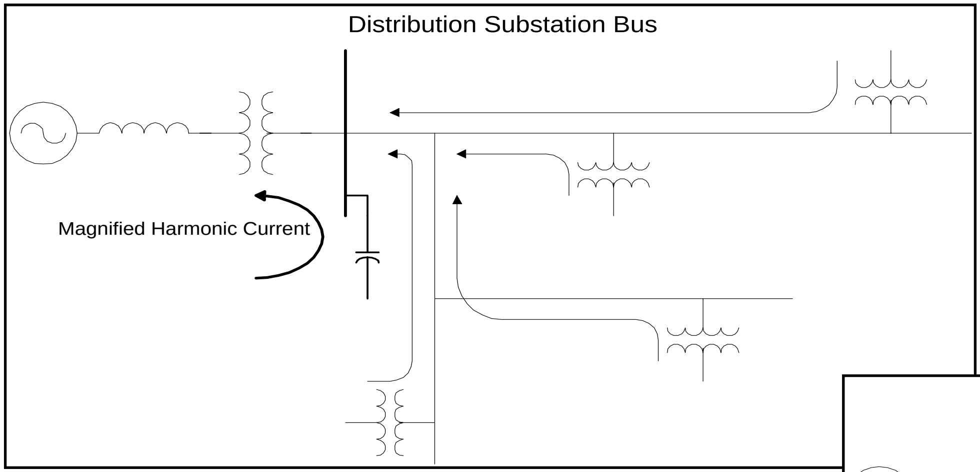
Frequency Response Example

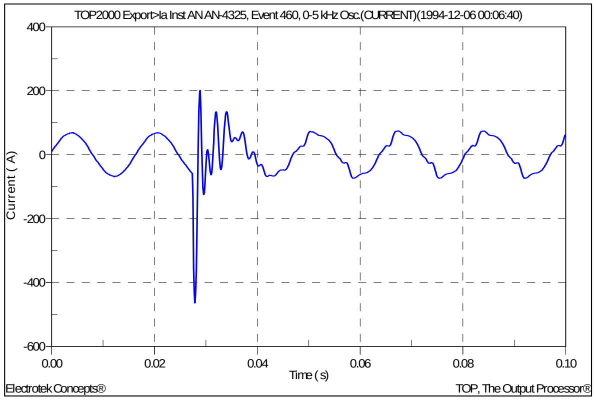
- 1500kVA transformer, Z_{tz} = 6%, 300, 500, 750 kVAr



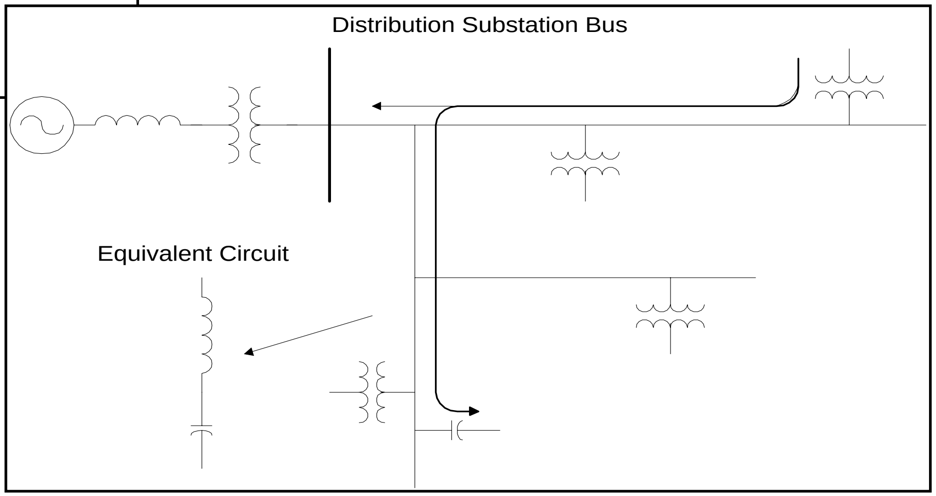
Distribution System Resonance Concerns

Parallel Resonance



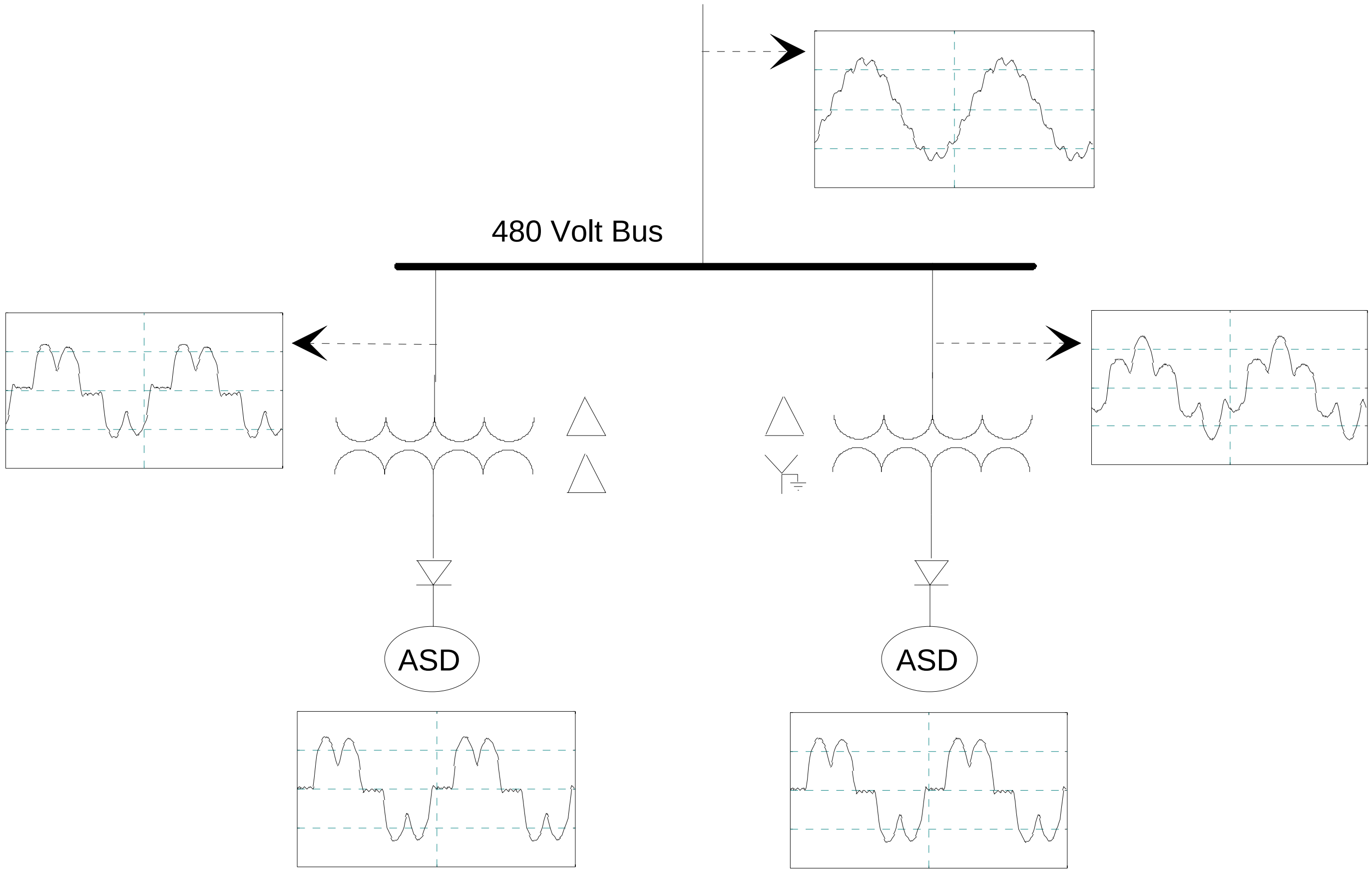


Series Resonance



Harmonic Current Cancellation

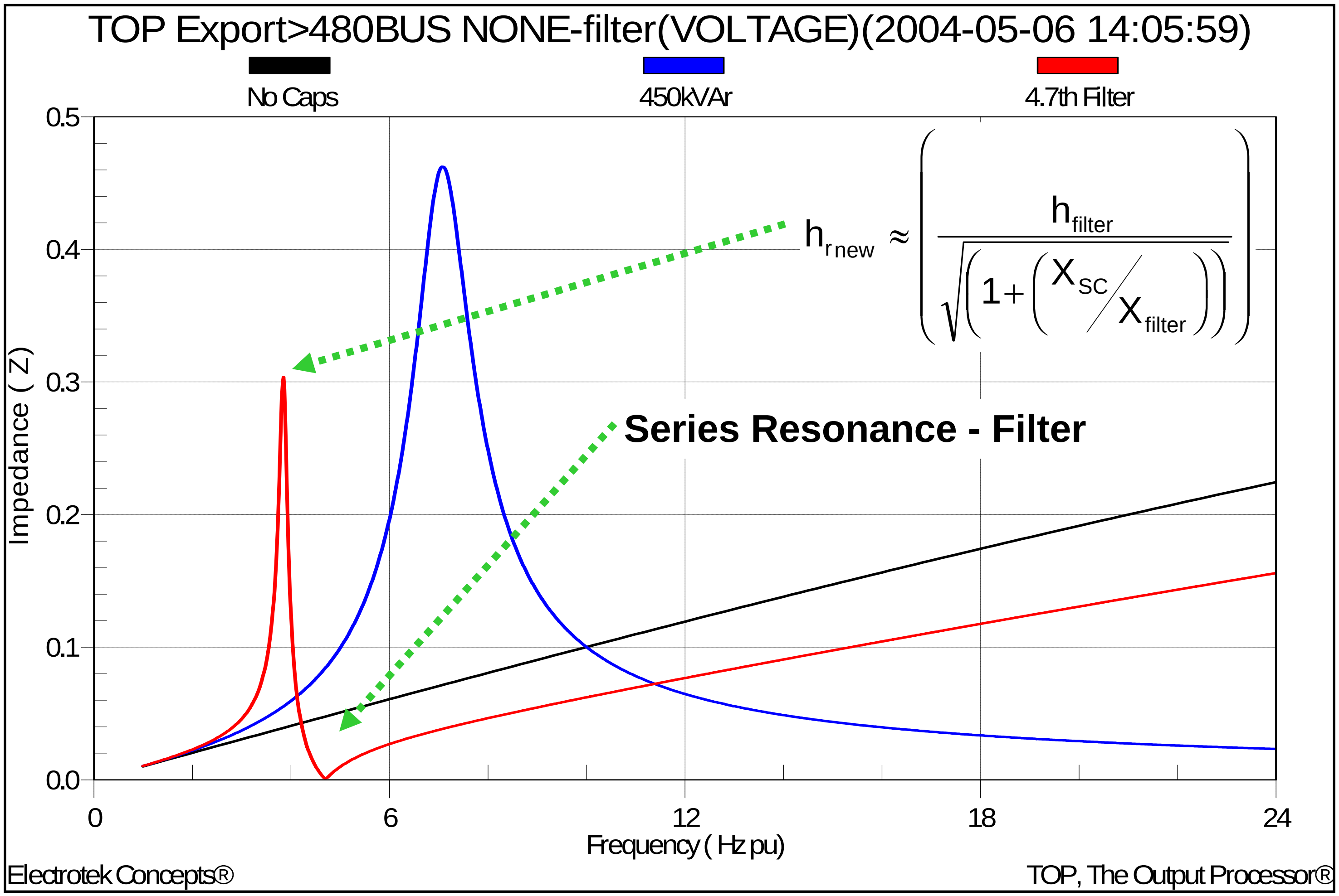
- Result of computer simulation illustrating harmonic current cancellation:



Reduction Methods - Basic Filter Design

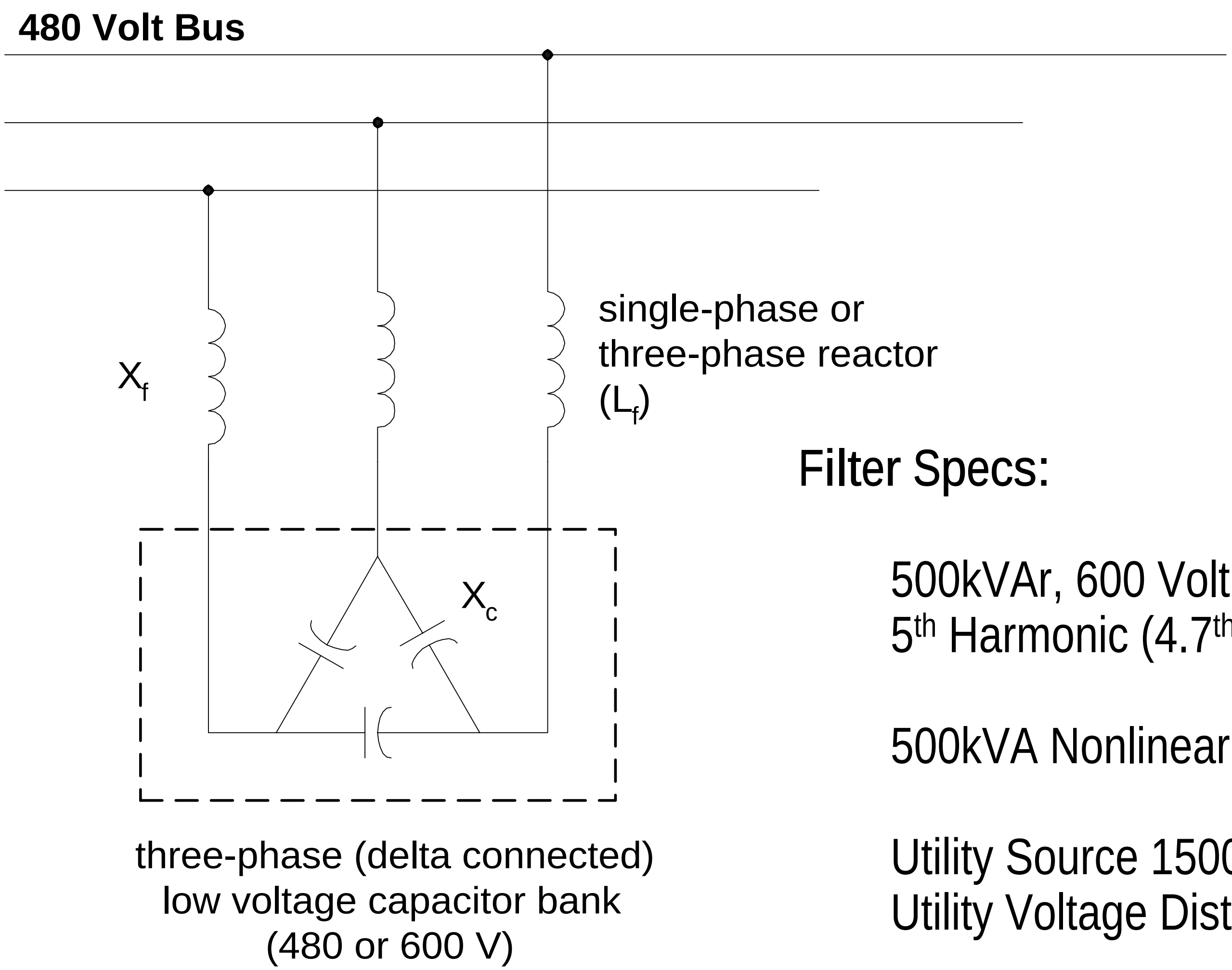
- Apply one single tuned filter first, and design it for the lowest generated frequency (i.e. 5^{th} harmonic - 4.7^{th} filter).
- Determine the voltage distortion at the low voltage bus, 5% is the commonly applied limit.
- Vary filter elements (tolerances) and check its effectiveness.
- Check the frequency response characteristic to verify that the newly created parallel resonance is not close to a harmonic frequency.
- If necessary, investigate the need for several filters, such as 5^{th} and 7^{th}.

Effect of Filter on Frequency Response



Source: SuperHarm

Filter Design - continued



Filter Specs:

500kVAr, 600 Volt Capacitors
5th Harmonic (4.7th tuning)

500kVA Nonlinear Load (30% 5th)

Utility Source 1500kVA, Z_{tx}=6%
Utility Voltage Distortion (5th) 1%

Filter Design - continued

- First step is to determine the filter reactor rating (mH):

$$X_{C_Y} = \frac{kV^2{}_{rated}}{MVAr_{rated}} = \frac{0.600^2}{0.5} = 0.72\Omega \qquad X_f = \frac{X_{C_Y}}{n^2} = \frac{0.72}{4.7^2} = 0.0326\Omega \qquad L_f = \frac{X_f}{2\pi f} = \frac{0.0326}{2\pi 60} = 0.0865mH$$

- Then calculate the fundamental frequency full load current:

$$I_{FL_{filter}} = \frac{V_{bus}}{\sqrt{3}\left(X_{C_Y} + X_f\right)} = \frac{480}{\sqrt{3}(-0.72 + 0.0326)} = 403.2\,amps$$

- Then calculate the resultant compensation level:

$$kVAr_{supplied} = \sqrt{3} * V_{bus} * I_{FL_{filter}} = \sqrt{3} * 480 * 403.2 = 335.2\,kVAr$$

- Wasn't the capacitor rated 500kVAr ?

$$kVAr_{actual} = kVAr_{rated} * \left(\frac{kV_{actual\,(bus)}}{kV_{rated\,(can)}}\right)^2 = 500 * \left(\frac{0.480}{0.600}\right)^2 = 320\,kVAr$$

Filter Design - continued

- The next step involves evaluating the harmonic limits of the filter bank:
  - current from nonlinear load:

$$I_{L_h} = I_{h_{(\%)}} * \left(\frac{kVA_{load}}{\sqrt{3} * kV_{bus}} \right) = 30\% * \left(\frac{500}{\sqrt{3} * 0.480} \right) = 180.4 \text{ amps}$$

  - current from utility (t = harmonic number for major component):

$$I_{h_{utility}} = \frac{V_{bus} * V_{harm_{(\%)}}}{\sqrt{3}\left[\left(-X_{C_Y}/t\right) + \left(X_f * t\right) + \left(\frac{Z_{tx_{(\%)}} * kV^2{}_{bus} * t}{MVA_{tx}}\right)\right]} = \frac{480 * 1\%}{\sqrt{3}\left[\left(-0.72/5\right) + \left(0.0326 * t\right) + \left(\frac{6\% * 0.480^2 * 5}{1.5}\right)\right]} = 42.6 \text{ amps}$$

  - assuming that the currents add, the harmonic filter load would be:

$$I_{h_{filter(total)}} = 180.4 + 42.6 = 223.0 \text{ amps}$$

  - and the total rms current would be:

$$I_{f_{rms}} = \sqrt{\left(I^2{}_{FL_{filter}} + I^2{}_{h_{filter(total)}}\right)} = \sqrt{\left(403.2^2 + 223.0^2\right)} = 460.8 \text{ amps}$$

Filter Design - continued

- The next step involves evaluating the harmonic limits of the filter bank:
  - The fundamental frequency capacitor voltage is determined using:

$$V_{cap_{60}} = \sqrt{3} * I_{FL_{filter}} * X_{C_Y} = \sqrt{3} * 403.2 * 0.72 = 502.8 \text{ volts}$$

  - and the harmonic voltage:

$$V_{cap_{harm}} = \sqrt{3} * I_{h_{filter(total)}} * \left(X_{C_Y} / t \right) = \sqrt{3} * 223.0 * \left(0.72 / 5 \right) = 55.6 \text{ volts}$$

  - and the total rms voltage would be:

$$V_{cap_{rms}} = \sqrt{\left(V^2{}_{cap_{60}} + V^2{}_{cap_{harm}} \right)} = \sqrt{\left(502.8^2 + 55.6^2 \right)} = 505.9 \text{ volts}$$

  - the peak voltage and current assume “in-phase” addition:

$$V_{cap_{pk}} = V_{cap_{60}} + V_{cap_{harm}} = 502.8 + 55.6 = 558.4 \text{ volts}$$

$$I_{cap_{pk}} = I_{cap_{60}} + I_{cap_{harm}} = 403.2 + 223 = 626.2 \text{ amps}$$

Filter Design - continued

- The final step is a check against ratings (IEEE Std. 18):
  - Peak Voltage:

$$V_{pk} = \frac{558.4}{600} = 93.1\%$$

  - RMS Current:

$$I_{rms} = \frac{460.8}{481} = 95.6\%$$

where: $I_{rated} = \frac{500kVAr}{\sqrt{3} * 600V} = 481 amps$

  - RMS Voltage:

$$V_{rms} = \frac{505.8}{600} = 84.3\%$$

  - kVAr:

$$kVAr = \% I_{rms} * \% V_{rms} = 95.6\% * 84.3\% = 80.6\%$$

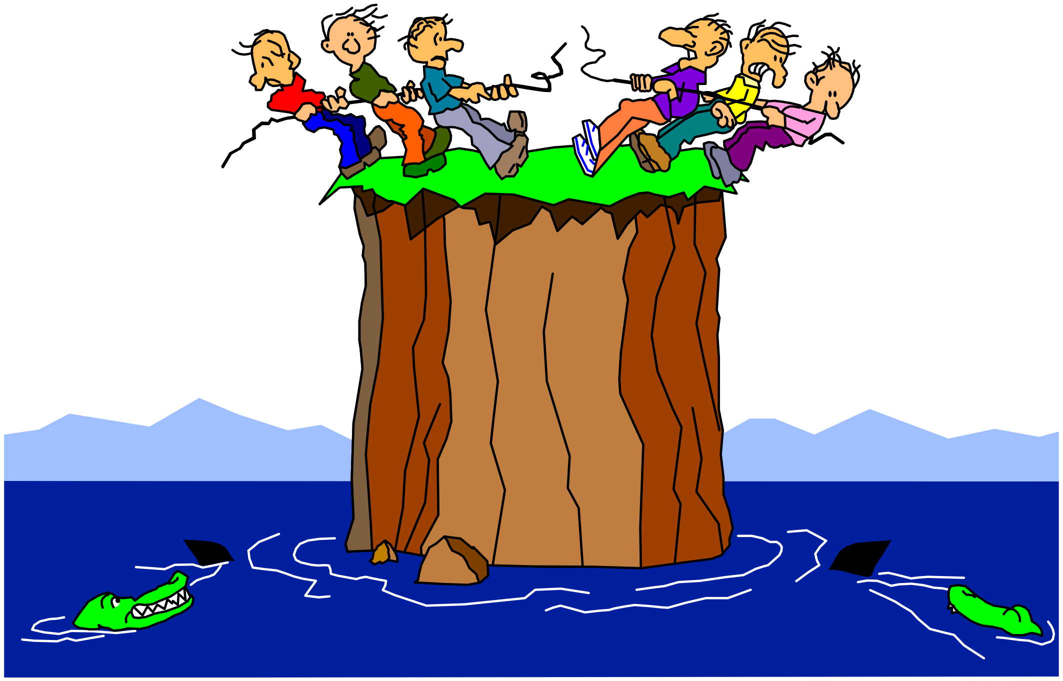
IEEE Standard 519-1992

- Introduction to IEEE Standard 519-1992:
  Recommended Practices and Requirements for Harmonic Control in Electric Power Systems:

  - Introduction, History, & Scope
  - Definitions
  - Analysis Methods / Measurements
  - References
  - Case Study

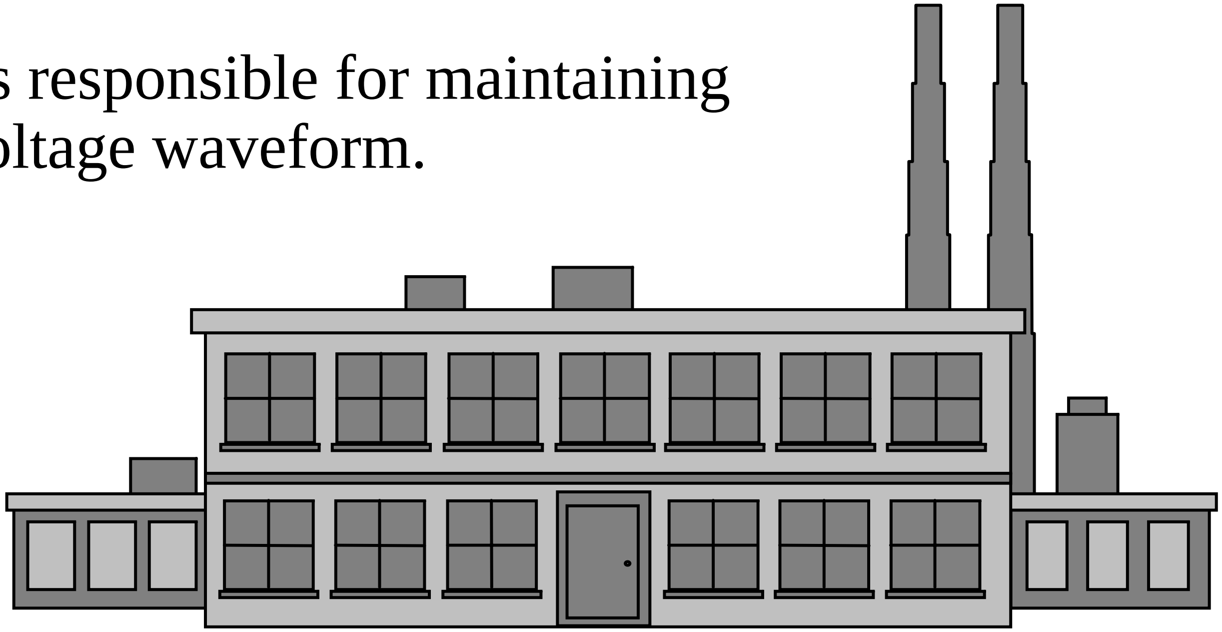
Scope of the IEEE Standard 519-1992

- Provide methodology for controlling harmonic voltage and current distortion levels on the power system.



Limits on Harmonic Levels

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



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%

How to Meet 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 ration (utility short circuit current at point of common coupling divided by customer average maximum demand load current)

Important Concepts

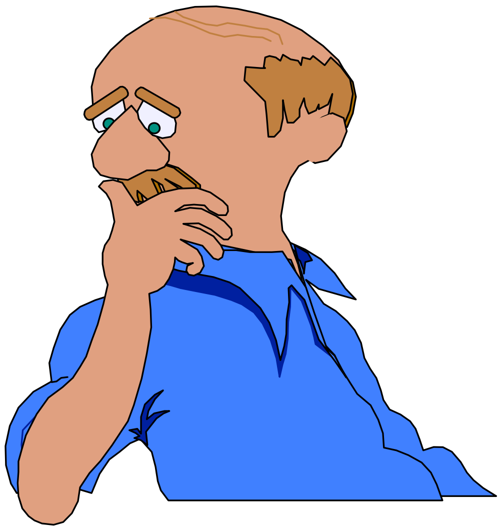
- Point of Common Coupling:
  - Interface between the utility and the customer
  - This is where limits are applied
(NOT AT INDIVIDUAL PIECES OF EQUIPMENT)
- Average Maximum Demand Load Current:
  - Maximum monthly demand load current averaged over 12 months
  - All percentages in the table are based 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”

Evaluating a Customer

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

How to Use 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 judgement needed!!!

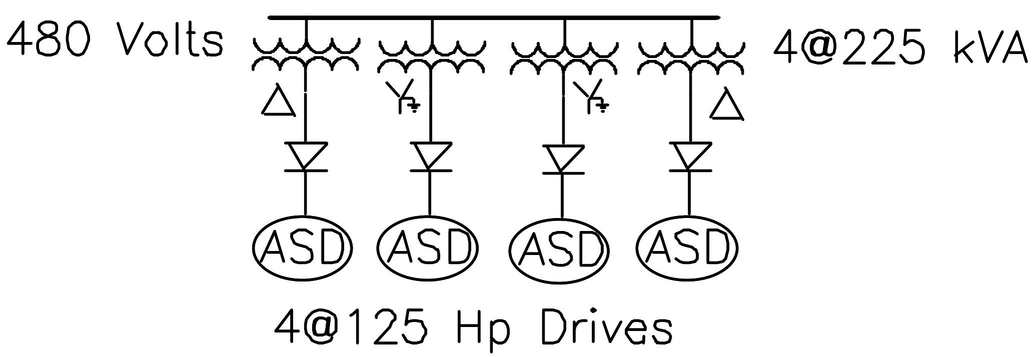


IEEE 519A - Application Guide

- IEEE Harmonics Working Group - ongoing development
  - Introduction and Scope
  - References / Background
  - General Procedure for Applying Harmonic Limits
    - General Evaluation Procedure
      - Stage 1 - Automatic Acceptance
      - Stage 2 - Evaluation According to the Current Limits
    - Evaluating the Time Varying Characteristics of Harmonics
      - Probability Distributions
      - Magnitude / Duration Limits for Short Duration Harmonic Levels
    - Measurement Considerations
  - Applying Harmonic Limits:
    - Industrial / Commercial / Residential Customers
  - Utility System Considerations

Case Study - Wastewater Treatment Plant

- Waste water treatment plant will have three pumping stations.
- Each pumping station will use four 125 HP PWM ASDs to control pumps.
- Each pumping station must meet new IEEE Std. 519 harmonic current limits during both normal and backup generator operation.

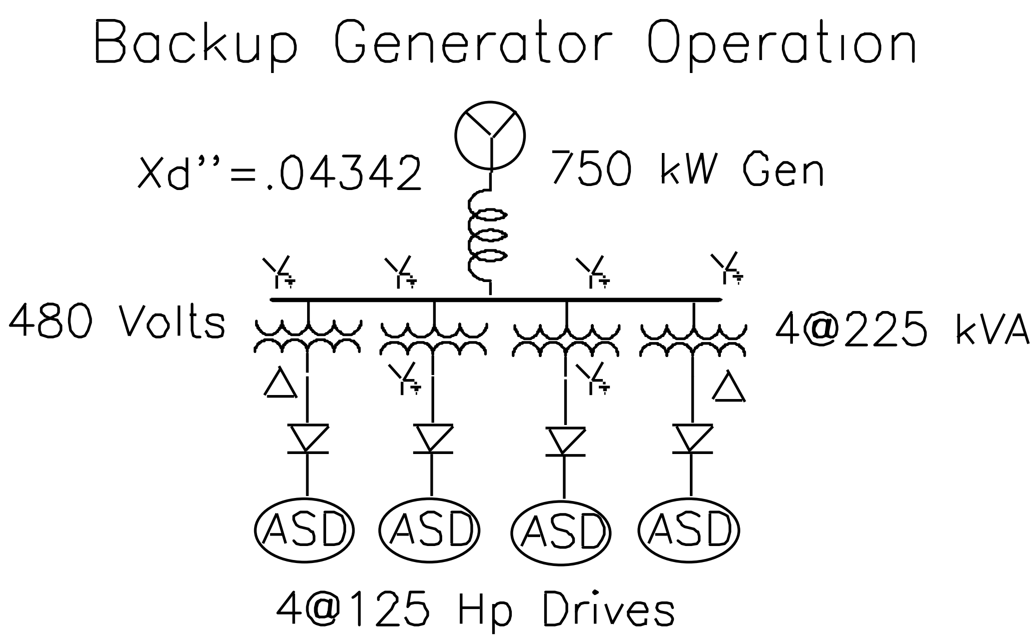


Assumptions

- Drives run in pairs
- Isolation transformers on ASDs are connected wye-wye and wye-delta for each pair of ASDs
  - 5^{th} and 7^{th} components will cancel
  - For study purposes it was assumed 10% of 5^{th} and 7^{th} harmonic components do not cancel
- Two operating conditions analyzed
  - 2 drives running at same speed
  - 4 drives running at same speed
- Maximum average demand current assumed to be 250 kVA (300 Amps at 480 Volts)
- ASD harmonic levels provided by manufacturer

Backup Generator - Where's the PCC?

- If no other information is available, the IEEE limits may be reasonable to apply for the backup generator loading.
- However, it would be better to get information from the generator manufacturer.



519 Current Limits - Two Drives Running

- 5^{th} harmonic component may exceed limit even with cancellation assumed
- The condition of 4 drives running will clearly be worse

PCC: Generator Terminals

Harmonic Number	Frequency (Hz)	Load Curr (Amps)	IEEE Limit %	Current (% Demand)	Exceeds Limit
1	**60**	**N/A**	**N/A**	**N/A**	**N/A**
5	**300**	12.05	**4.0**	**4.0**	**Exceeds**
7	**420**	4.14	**4.0**	**1.4**	**OK**
11	**660**	10.74	**2.0**	**3.6**	**Exceeds**
13	**780**	4.02	**2.0**	**1.3**	**OK**
17	**1020**	3.71	**1.5**	**1.2**	**OK**
19	**1140**	5.48	**1.5**	**1.8**	**Exceeds**
TDD:	**>>>>>>>>>>>>>>>>>>>>>>>**		**5.0**	**6.1**	**Exceeds**

Isc/IL Ratio (low voltage bus):16

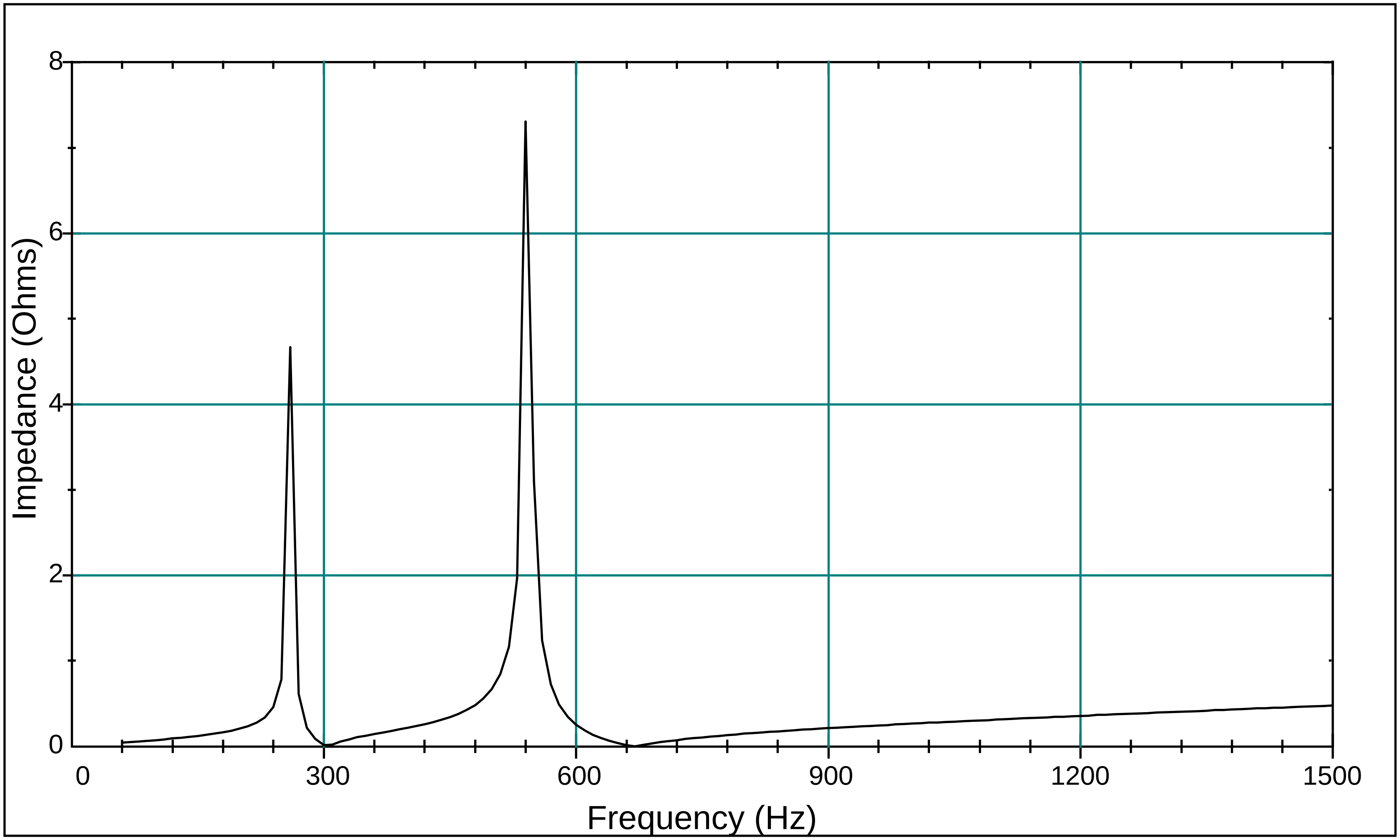
Harmonic Filter Design

- 5^{th} harmonic filter:
  - This filter must be able to handle the emergency condition of one drive running at full speed, no harmonic cancellation
- 11^{th} harmonic filter:
  - 5^{th} harmonic filter reduces the overall system impedance at higher frequencies but the harmonic control is not sufficient to handle the 11^{th} and 13^{th} components when two drives are running
- No 7^{th} harmonic filter:
  - Not needed in this case, although care must be taken to avoid a condition where resonance results at the 7^{th} harmonic due to the addition of the 11^{th} harmonic filter

Harmonic Filter Design - continued

- Since the filters should be the minimum possible size to avoid leading power factor problems, the component tolerances can be very important.
- Filters must be tuned very close to the desired frequency in order to work effectively
- With a capacitor tolerance of 0 to +10% and a reactor tolerance of +/- 5%, the filter performance could easily be unacceptable
- For this reason, the filter reactors were specified with taps at +5% and -5% reactance values

Frequency Response with Filters



Measurement Results

- After the stations were built, harmonic measurements were taken
- Measurements showed that the assumptions were a bit on the conservative side
- Almost all 5th and 7th harmonic components canceled resulting in extremely low current distortion
- IEEE Std. 519 Limits were met during normal and backup generator operation with 2 drives running even without the filters in
- However, with 4 drives running the filters were needed

Measurement Results - continued

- 2 Drives Running at 30 Hz - No Filters, Backup Generator Operation:

CAROL BCK SE NL Apr 27 1993 (Tue)
PHASE A CURRENT SPECTRUM 4:57:05 PM
Fundamental amps: 46.7 A rms
Fundamental freq: 60.1 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	-39°	2nd	8.6%	39°
3rd	11.3%	173°	4th	4.7%	-140°
5th	7.4%	85°	6th	0.6%	-75°
7th	11.3%	117°	8th	2.2%	-142°
9th	0.6%	-45°	10th	1.0%	-28°
11th	7.6%	72°	12th	0.4%	76°
13th	3.0%	168°	14th	0.3%	95°
15th	0.2%	176°	16th	0.1%	12°
17th	0.7%	-165°	18th		
19th	0.8%	-122°	20th	0.3%	-34°
21st	0.2%	-60°	22nd	0.3%	-4°
23rd	1.0%	163°	24th		
25th	1.0%	-143°	26th	0.2%	-161°
27th	0.1%	-163°	28th	0.1%	-156°
29th	0.4%	-103°	30th		
31st	0.5%	-40°	32nd	0.2%	-47°
33rd	0.2%	11°	34th	0.2%	89°
35th	0.2%	-147°	36th		
37th	0.3%	-64°	38th		
39th			40th	0.1%	-31°
41st	0.3%	-32°	42nd		
43rd	0.2%	6°	44th		
45th	0.3%	74°	46th		
47th	0.2%	-105°	48th		
49th	0.3%	15°	50th	0.2%	-62°
ODD	19.5%		EVEN	10.1%	
THD:	21.9%				

IEEE 519 Current Distortion Limits:

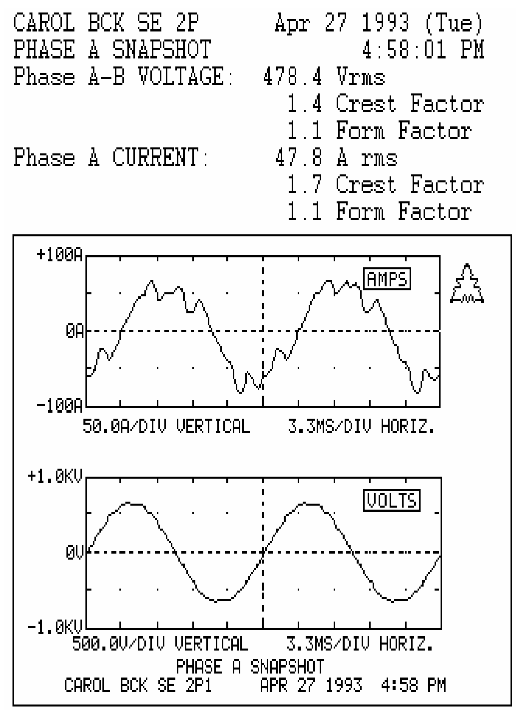
PCC: Generator Terminals

Harmonic Number	Frequency (Hz)	Load Curr (Amps)	IEEE Limit %	Current (% Demand)	Exceeds Limit
1	60	N/A	N/A	N/A	N/A
3	180	5.3	4.0	1.8	OK
5	300	3.5	4.0	1.1	OK
7	420	5.3	4.0	1.8	OK
9	540	0.3	4.0	0.1	OK
11	660	3.5	2.0	1.2	OK
13	780	1.4	2.0	0.5	OK
17	1020	0.3	1.5	0.1	OK
19	1140	0.4	1.5	0.1	OK
21	1260	0.1	1.5	0.0	OK
23	1380	0.5	0.6	0.2	OK
25	1500	0.5	0.6	0.2	OK
29	1740	0.2	0.6	0.1	OK
TDD:	>>>>>>>>>>>>>>>>>>>>>>		5.0	3.0	OK

Isc/IL Ratio (low voltage bus): 16

Measurement Results - continued

- 4 Drives Running at 60 Hz - No Filters, Backup Generator Operation



IEEE 519 Current Distortion Limits:

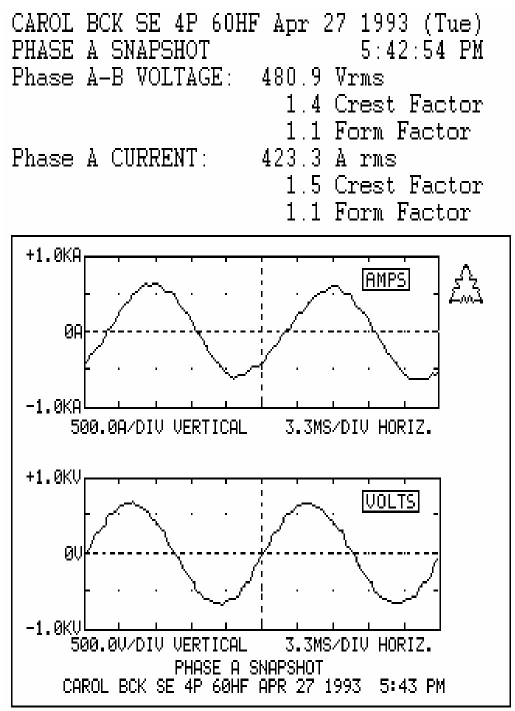
PCC: Generator Terminals

Harmonic Number	Frequency (Hz)	Load Curr (Amps)	IEEE Limit %	Current (% Demand)	Exceeds Limit
1	60	N/A	N/A	N/A	N/A
3	180	2.9	4.0	1.0	OK
5	300	4.2	4.0	1.4	OK
7	420	3.4	4.0	1.1	OK
9	540	0.4	4.0	0.1	OK
11	660	8.0	2.0	2.7	Exceeds
13	780	7.6	2.0	2.5	Exceeds
17	1020		1.5		OK
19	1140		1.5		OK
21	1260		1.5		OK
23	1380	1.3	0.6	0.4	OK
25	1500	1.3	0.6	0.4	OK
29	1740		0.6		OK
TDD:	>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>		5.0	4.2	OK

Isc/IL Ratio (low voltage bus): *16*

Measurement Results - continued

- 4 Drives Running at 60 Hz - Filters In



IEEE 519 Current Distortion Limits:

PCC: Generator Terminals

Harmonic Number	Frequency (Hz)	Load Curr (Amps)	IEEE Limit %	Current (% Demand)	Exceeds Limit
1	60	N/A	N/A	N/A	N/A
3	180	4.9	4.0	1.6	OK
5	300	2.7	4.0	0.9	OK
7	420	0.4	4.0	0.1	OK
9	540		4.0		OK
11	660	3.6	2.0	1.2	OK
13	780	3.6	2.0	1.2	OK
17	1020		1.5		OK
19	1140	0.4	1.5	0.1	OK
21	1260		1.5		OK
23	1380	0.9	0.6	0.3	OK
25	1500	0.9	0.6	0.3	OK
29	1740		0.6		OK
TDD:	>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>		5.0	2.5	OK

Isc/IL Ratio (low voltage bus): 16