Power Quality Monitoring: Waveform Analysis

Music City Power Quality Group

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Outline

- Introduction
  - Describing a Power Quality Waveform
  - Sample PQ Monitoring Videos
  - Sample PQ Waveforms
- Monitoring Equipment
- PQ Definitions
- Power Quality Issues and Expected Waveforms
  - Voltage Variations
  - Transients
  - Harmonics
  - Wiring and Grounding Considerations
- Power Quality Lab Overview
- Final Exam

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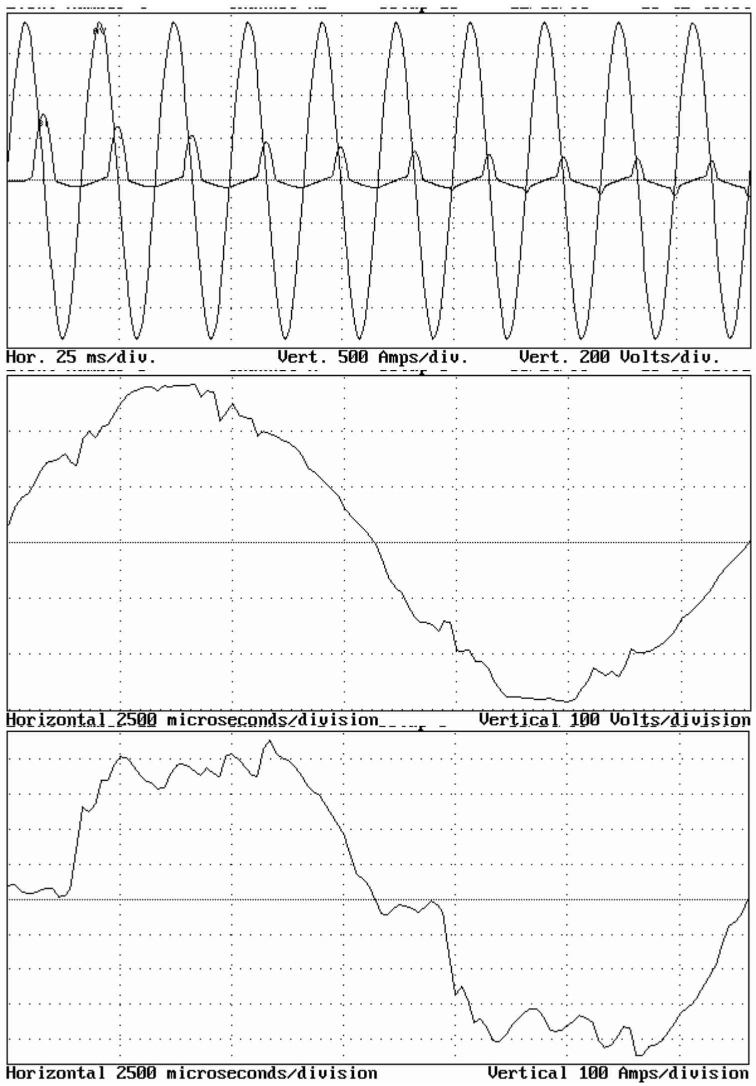
Waveform Analysis – What's Important?

- Waveshape
- Number of Phases Affected
- Voltage or Current?
- Monitoring Location
- Primary/Secondary (CT/PT)
- Monitoring Equipment (Capabilities)
- Who Captured the Measurements?
- Setup (Trigger on Event Type)
- Duration of Event
- Repetition/Time Between Events
- Definition of Good/Bad

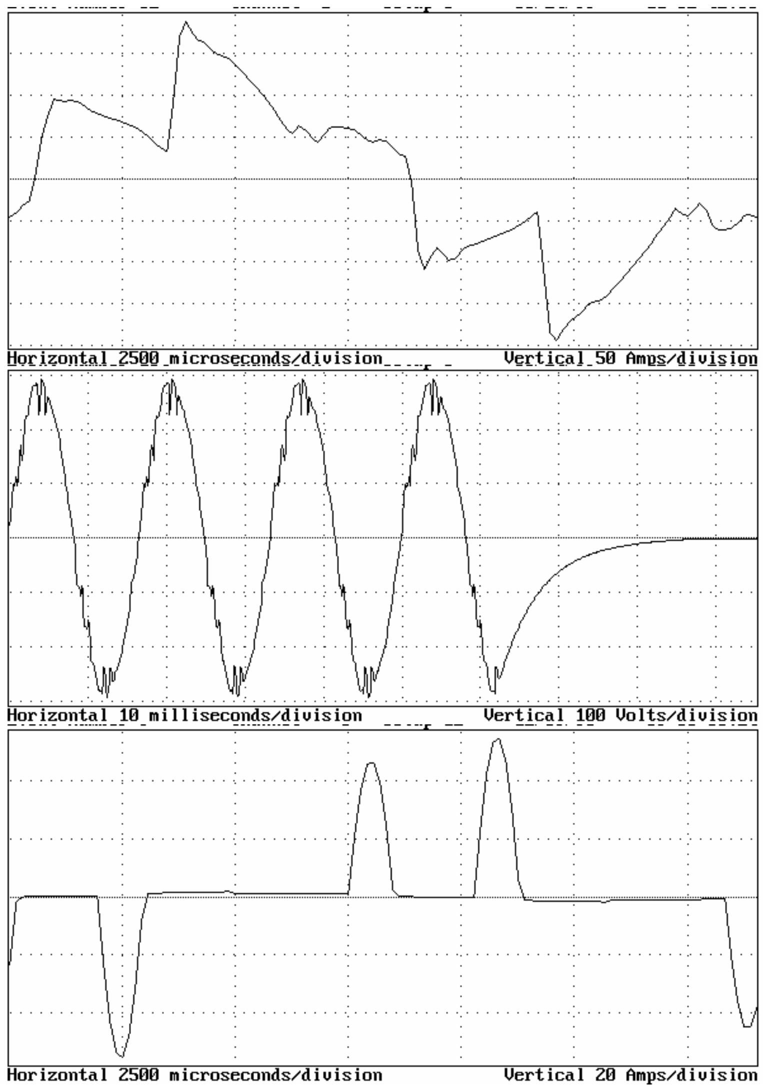
Videos of Measurements

- Phase Shifting
- Active Filter
- 18 Pulse Drive

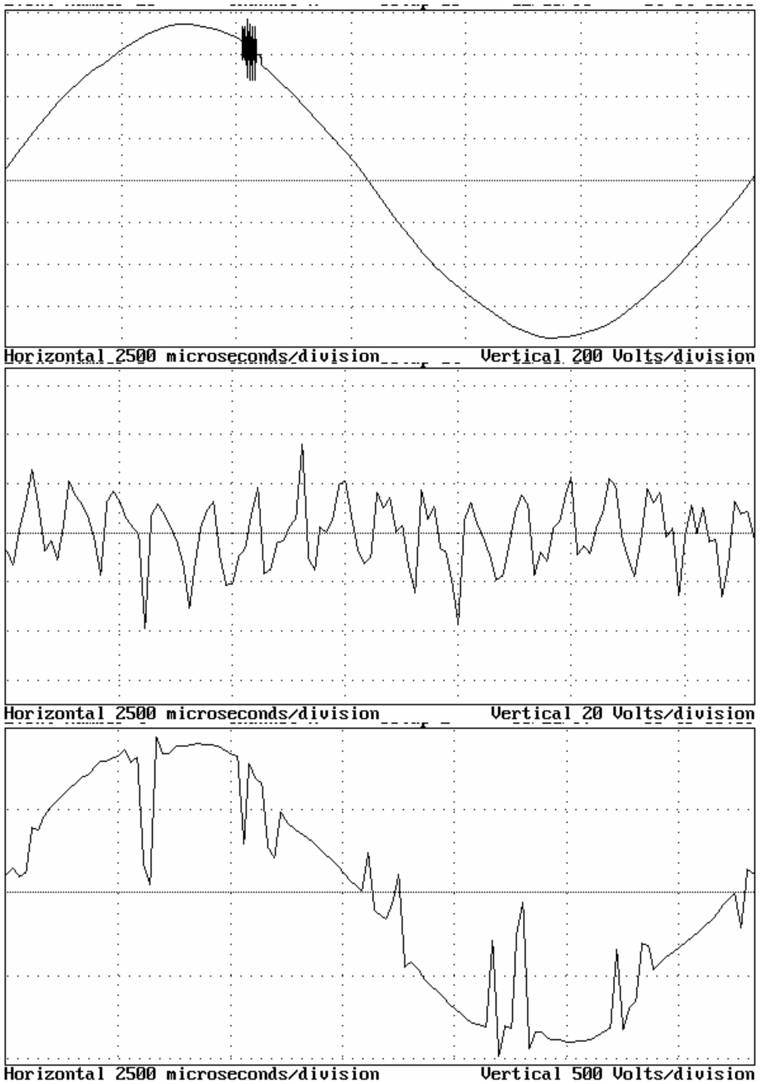
Sample Waveforms



Sample Waveforms



Sample Waveforms



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Monitoring Equipment

PQ Monitors

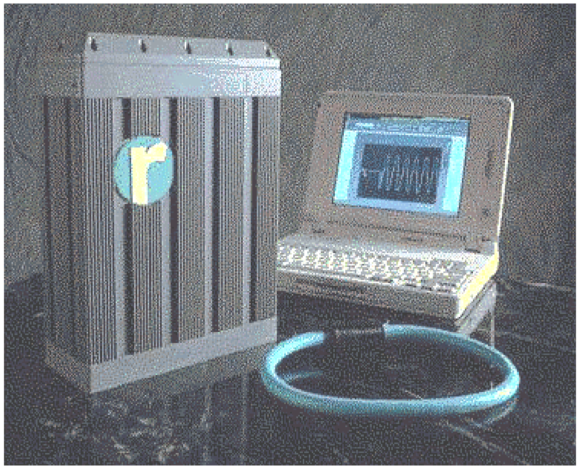
- Portable
- Permanent/Fixed

Accessories

- Current Transformers
- Voltage Probes
- High Voltage Dividers
- Special Connectors and Cables
- Compensated Cables
- Battery Backup
- Disk Storage

Portable Monitors

Fluke 1750 and iPAQ



Reliable Power Meter (RPM) - 1650

Dranetz 658

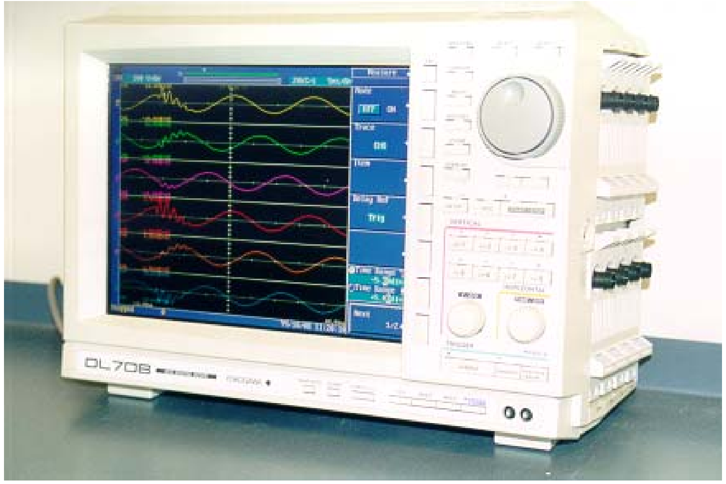
Portable Monitors

Fluke 41B Harmonics Analyzer

Fluke 434 PQ Analyzer

Portable Monitors

Tektronix 720P Power Scope



Yokogawa DL708

Portable Monitors

Dranetz-BMI Power Explorer PX5

Hioki 3196

EATON

Portable Monitors

Hobo Pro Series

Hobo Shuttle

EATON

Fixed Monitors

Cutler-Hammer IQ Analyzer

Cutler-Hammer PowerXpert

EATON

Low-End Plug-Ins

C-H Powerwatch

SST IGRID

Accessories

AC/DC Current Probes

Pearson High Frequency CT’s

Clamp-on Ammeters – Fluke 33 and 36

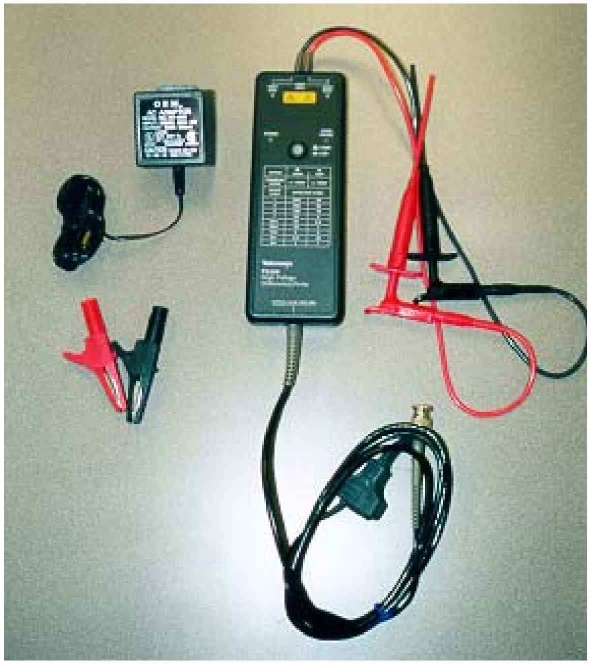
Accessories

100 kV High Voltage Divider

Tektronix 40 kV High Voltage Probe

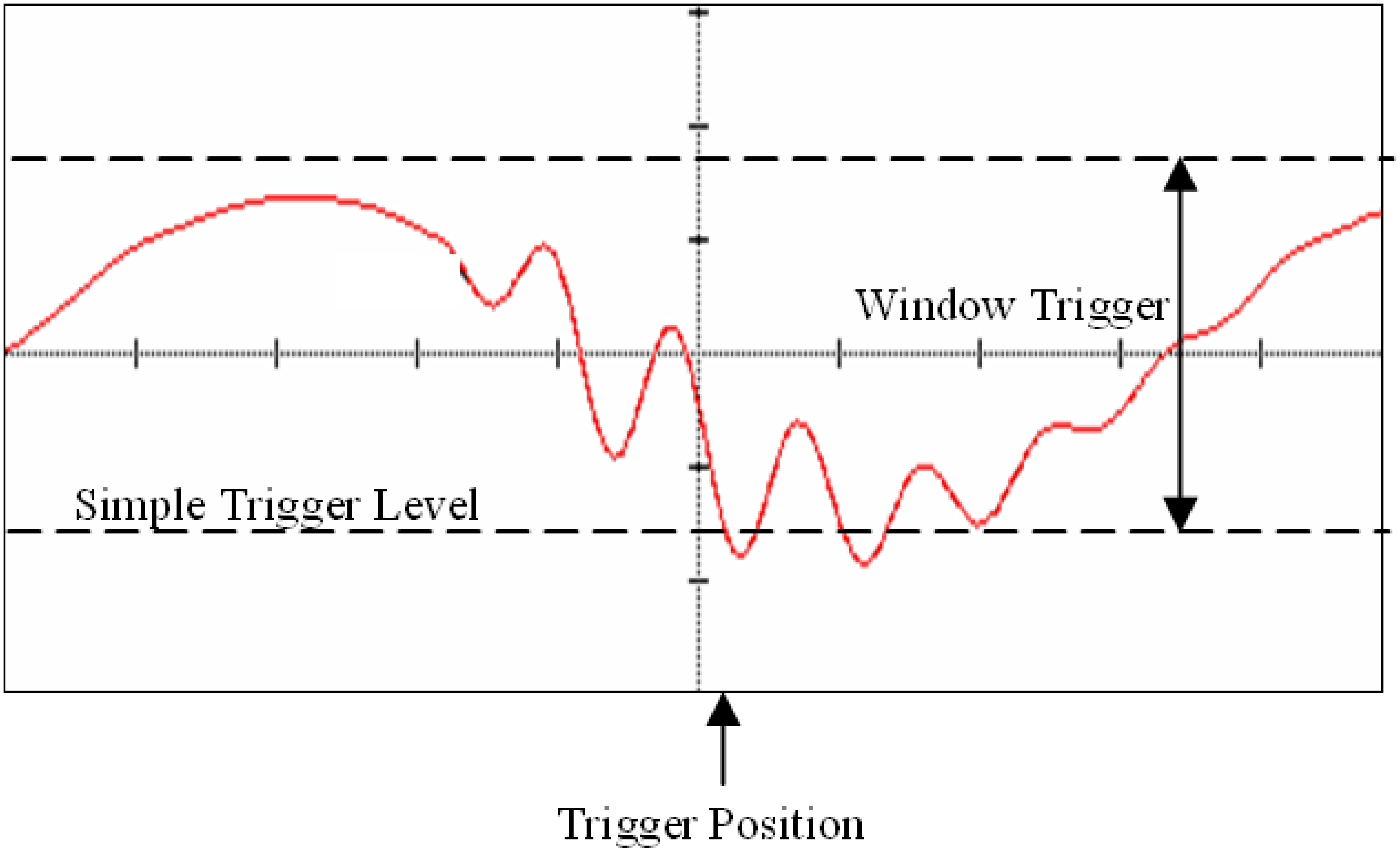
Accessories

High Voltage/Low Voltage (2,500 V) Probe - 100 X Tektronix Probe and Accessories



1000 V Differential Scope Probe

Triggering with a Scope



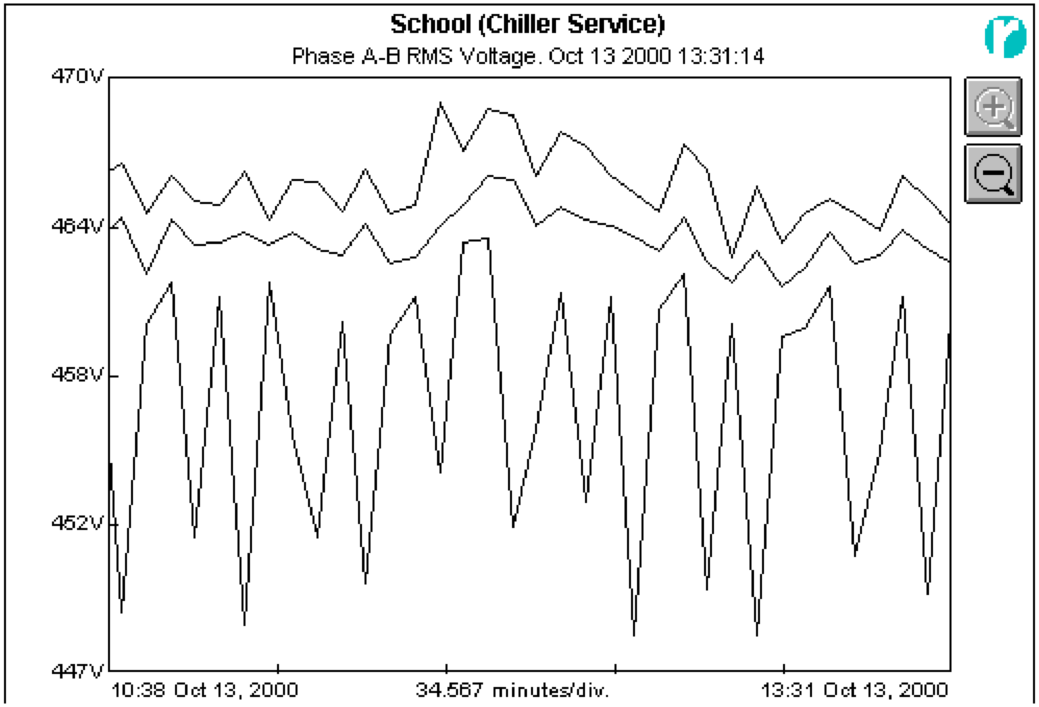
Power Quality Categories

Table 1. *Summary of IEEE Std 1159-1995 Power Quality Categories [1]*

CATEGORY	TYPES	TYPICAL DURATION	COMMON CAUSES
Transients	Impulsive, Oscillatory	Less than 1 cycle	Lightning, Switching Loads
Short Duration Variations	Sags, Swells, Interruptions	Less than 1 minute	Faults, Motor Starting, Utility Protective Equipment
Long Duration Variations	Sustained Interruptions, Undervoltages, Overvoltages	Over 1 minute	Poor Voltage Regulation, Incorrect Transformer Tap Setting, Overloaded Feeder, Utility Equipment
Voltage Imbalance	---	Steady state	Unbalanced Loads, Equipment Failure
Waveform Distortion	Harmonics, Notching, Noise	Steady state	Electronic Loads
Voltage Fluctuations	Flicker	Intermittent	Arcing Loads, Loose Connections
Power Frequency Variations	---	Less than 10 seconds	Poor Generator Control

Trend Data

It is **CRITICAL** to understand the method that your PQ instrument captures Max, Min and Average data or you could be easily mislead by the data.

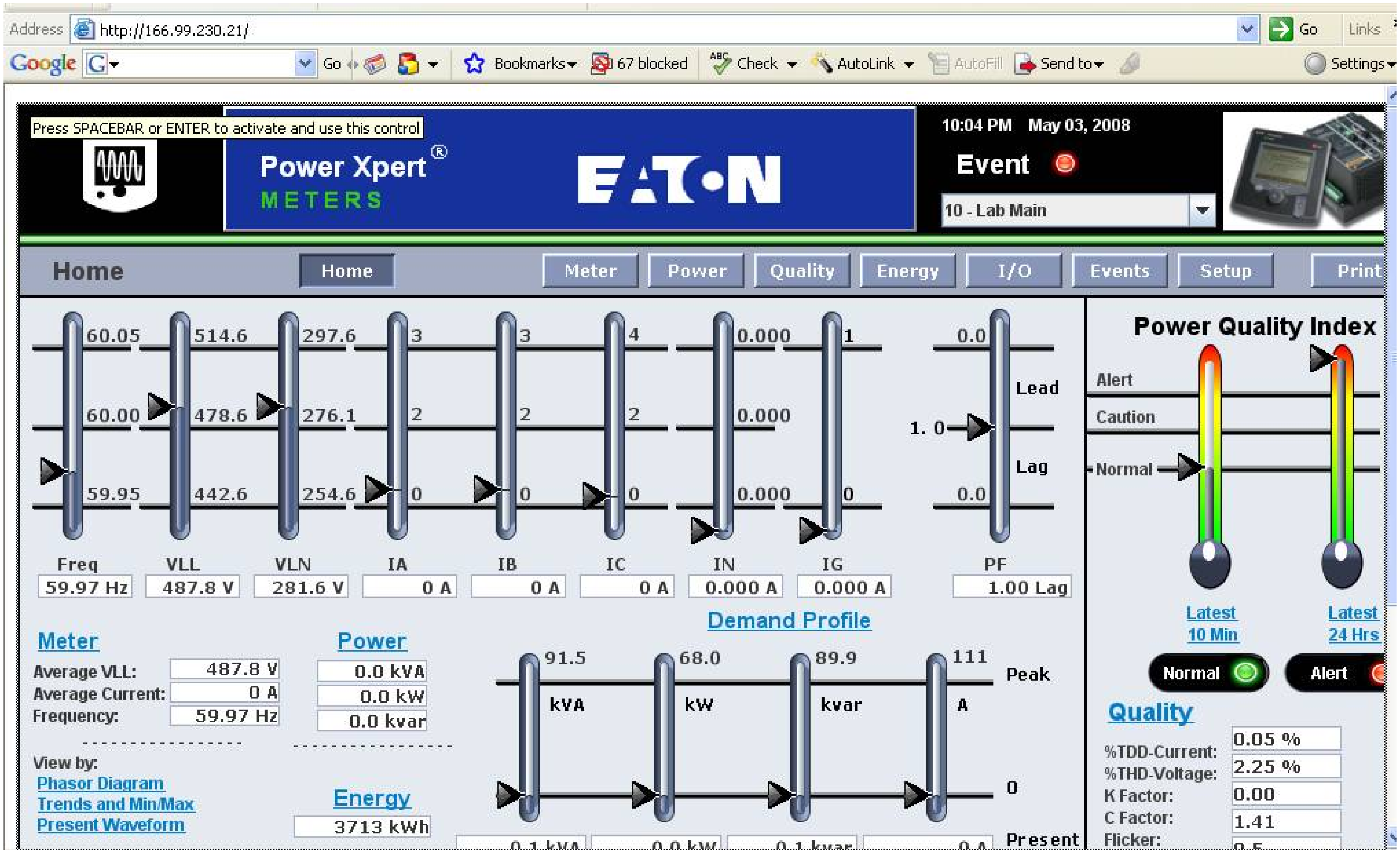


Minimum, Average, and Maximum Trends

Trend Data – RPM Resolution

Selected Monitoring Period	Normal Summaries		Demand Summaries		Harmonics Summaries		Flicker Summaries	
	Number of Samples	Resolution	Number of Samples	Resolution	Number of Samples	Resolution	Number of Samples	Observation Period
15 Min	3600	15 Cycle	3600	15 Cycle		N/A		N/A
30 Min	3600	30 Cycle	3600	30 Cycle		N/A		N/A
1 Hr	3600	1 Sec	3600	1 Sec	3600	1 Sec	120	30 Sec
3 Hr	3600	3 Sec	3600	3 Sec	3600	3 Sec	360	30 Sec
6 Hr	3600	6 Sec	3600	6 Sec	3600	6 Sec	360	1 Min
12 Hr	2880	15 Sec	2880	15 Sec	2880	15 Sec	144	5 Min
24 Hr	2880	30 Sec	2880	30 Sec	2880	30 Sec	144	10 Min
48 Hr	2880	1 Min	2880	1 Min	2880	1 Min	288	10 Min
5 Day	2400	3 Min	2400	3 Min	2400	3 Min	720	10 Min
1 Week	2016	5 Min	2016	5 Min	2016	5 Min	1008	10 Min
2 Week	2016	10 Min	4032	5 Min	2016	10 Min	2016	10 Min
4 Week	2688	15 Min	8064	5 Min	2688	15 Min	4032	10 Min
1 Mo (28 day)	2688	15 Min	8064	5 Min	2688	15 Min	4032	10 Min
1 Mo (29 day)	2784	15 Min	8352	5 Min	2784	15 Min	4176	10 Min
1 Mo (30 day)	2880	15 Min	8640	5 Min	2880	15 Min	4320	10 Min
1 Mo (31 day)	2976	15 Min	8928	5 Min	2976	15 Min	4464	10 Min
90 Day	2160	1 Hr	2160	1 Hr	2160	1 Hr	8640	15 Min
1 Year	2190	4 Hr	2190	4 Hr	2190	4 Hr	2190	4 Hr
1 Leap Year	2196	4 Hr	2196	4 Hr	2196	4 Hr	2196	4 Hr

Dashboard View of PQ Meters



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Special Considerations for Transients

The most important requirement is the sampling rate.

Many people have thought that they don't have a voltage transient problem, when really their monitor could not accurately capture the switching transient.

The sampling rate required should be selected based upon the frequency of interest.

Some users follow the Nyquist theory of having the sampling rate double the frequency of interest. As it is still possible to miss the peak of the transient, one should consider using at least 4 times the frequency of interest – 10X is better.

The monitor should be immune to external sources of error, such as VHF ratios, etc. These signals have been recorded as transients by some monitors.

Potential transformers (PT's) and current transformers (CT's), generally are bandwidth limited. They typically cannot pass frequencies higher than 3-5kHz and therefore, should not be relied upon to accurately reproduce the event when transient frequencies exceed these limits.

Other Considerations

- Time and Date Stamp
- Current Transducer Phase Shift
- CT Ratio and Scaling Capabilities
- PT Ratio and Scaling Capabilities
- Frequency range of steady state data (i.e. for monitoring output of variable frequency drives)
- RMS Sampling Rates if No Transient Event Occurs
- Pre-trigger Data
- Post Trigger Data
- Time Scaling and Zooming
- Full Scale Range of Input Voltage and Current

Monitoring Locations

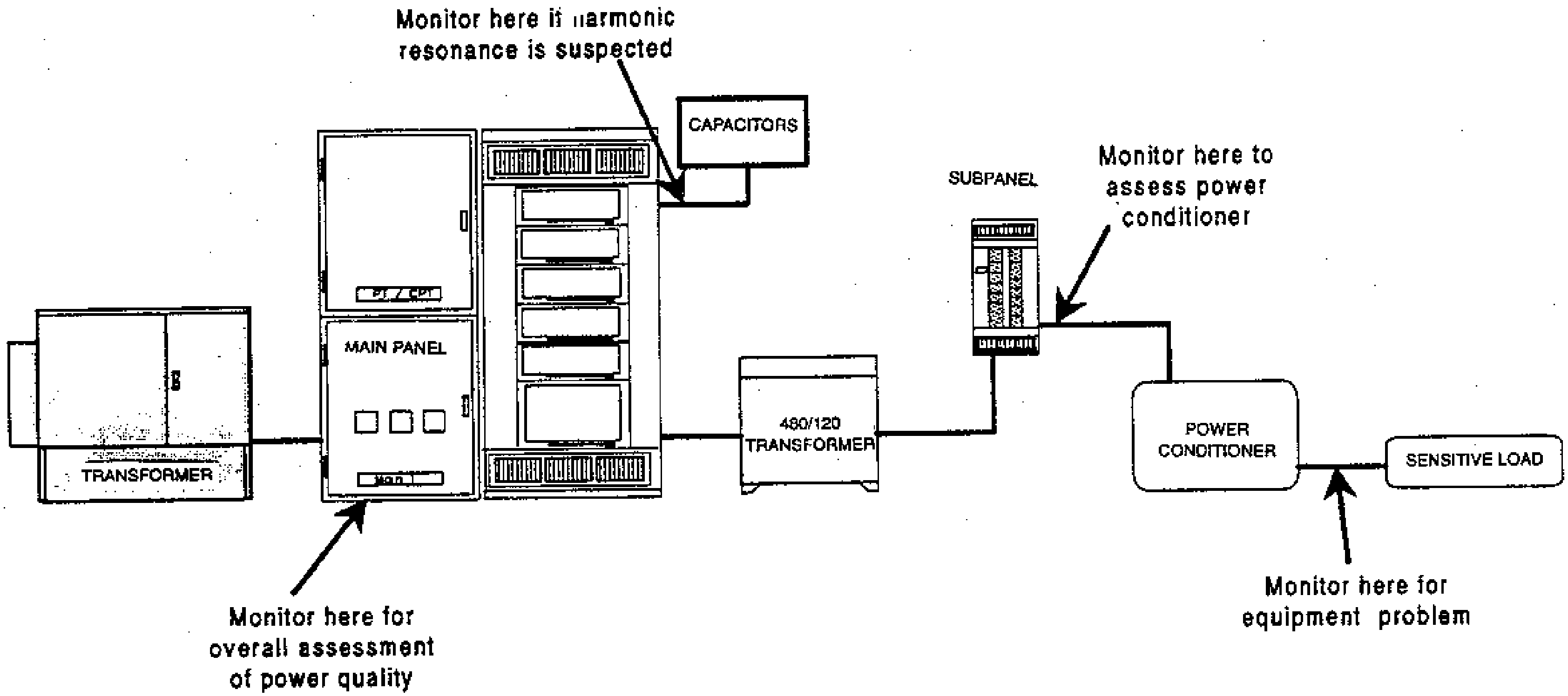

Figure 15—Suggested monitoring locations on a typical low voltage system

Setting Thresholds

This table shows suggested threshold settings for monitoring 120 V loads to determine various power quality problems (Source: IEEE Std. 1159-1995).

Table 4—Suggested threshold settings for 120 V loads

	Category	Suggested setting	Comments
Conducted phase voltage thresholds	Sag	108 V rms	Minus 10% of nominal supply voltage
	Swell	126 V rms	Plus 5% of nominal supply voltage
	Transient	200 V	Approximately twice the nominal phase-to-neutral voltage
	Noise	1.5 V	Approximately 1% of the nominal phase-to-neutral voltage
	Harmonics	5% THD	Voltage distortion level at which loads may be affected
	Frequency	±Hz	—
	Phase imbalance	2%	Voltage imbalance greater than 2% can affect equipment. (Three-phase induction motors should be derated when operated with imbalanced voltages [B11]).
Conducted neutral-to-ground differential voltage thresholds	Swell	3.0 V rms	Typical level of interest for neutral and/or ground problems
	Impulsive transient	20 V peak	Ten to twenty percent of phase-to-neutral voltage
	Noise	1.5 V rms	Typical equipment susceptibility level
Current thresholds	Phase/neutral current	Normal load current on true rms basis	Load current threshold may need to be raised well above normal load current, depending on the desired data and the amount of fluctuation in load current.
	Ground current	0.5 A true rms	Consider Section 250-21 of the NEC [B2] for safety, as well as noise currents, that lead to objectionable voltages, from both safety and data error points of view.
	Harmonics	20% THD (for small customers) to 5% THD (for very large customers)	Measured at service entrance (point of common coupling), and relative to maximum demand load current (refer also to IEEE Std 519-1992 [B13]); harmonic distortion reference values or measurements at a subpanel should be chosen relative to concerns about effects of harmonics on equipment in the circuit that is being monitored such as neutral sizing, transformer loading and capacitors.

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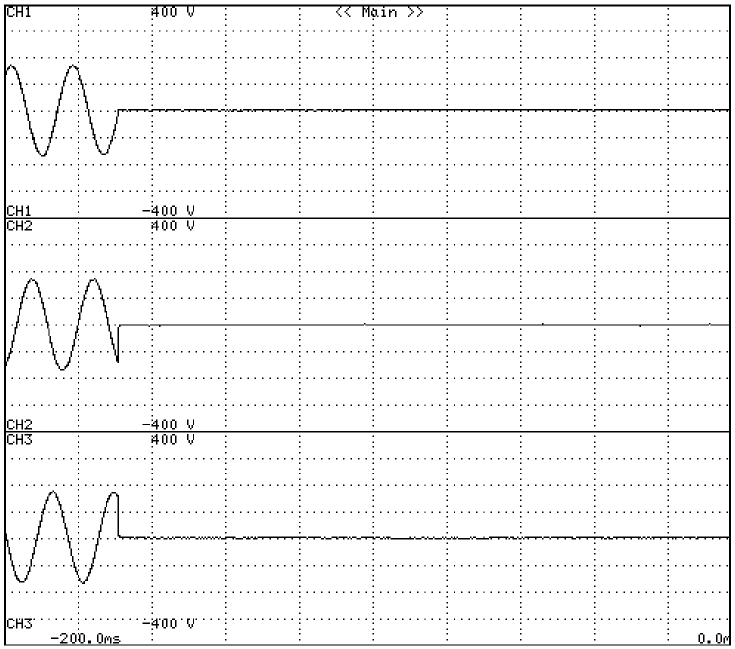
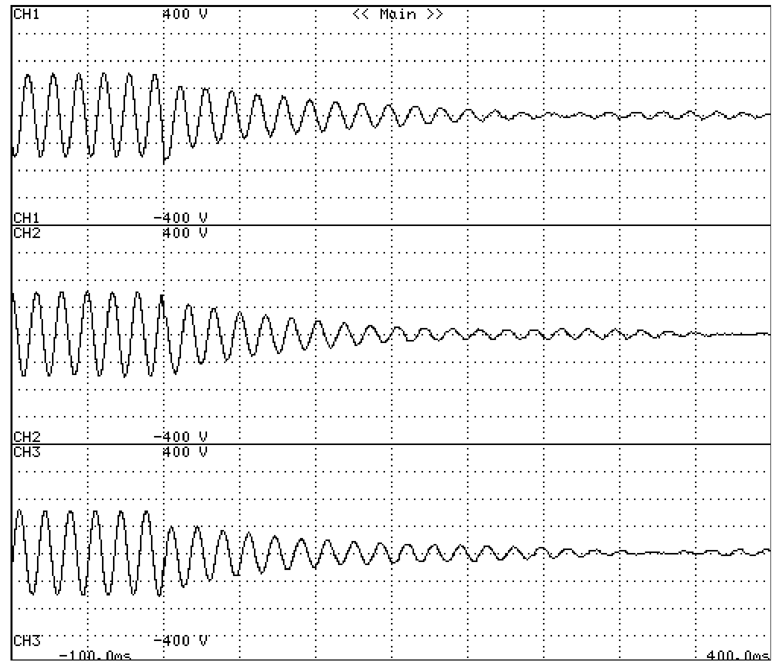
Definitions

Interruption – The complete loss of voltage for a period of time.

Waveform – Local Power Failure



Waveform – Utility Power Failure



Duration of Interruptions (as typically defined by utility personnel):

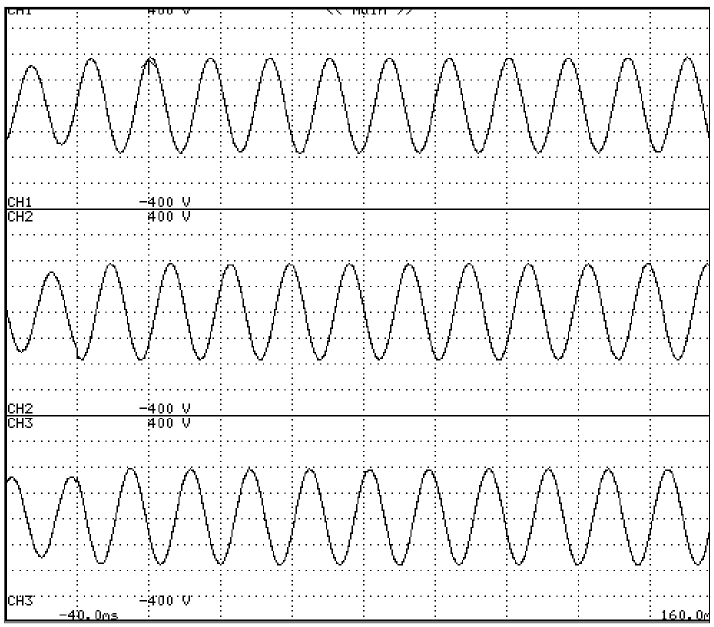
- ***Momentary: < 2 seconds***
- ***Temporary: Between two seconds and two minutes***
- ***Outage: > 2 minutes***

Note: Commercial, industrial and residential customers typically describe an outage as any event where the voltage is zero for any duration.

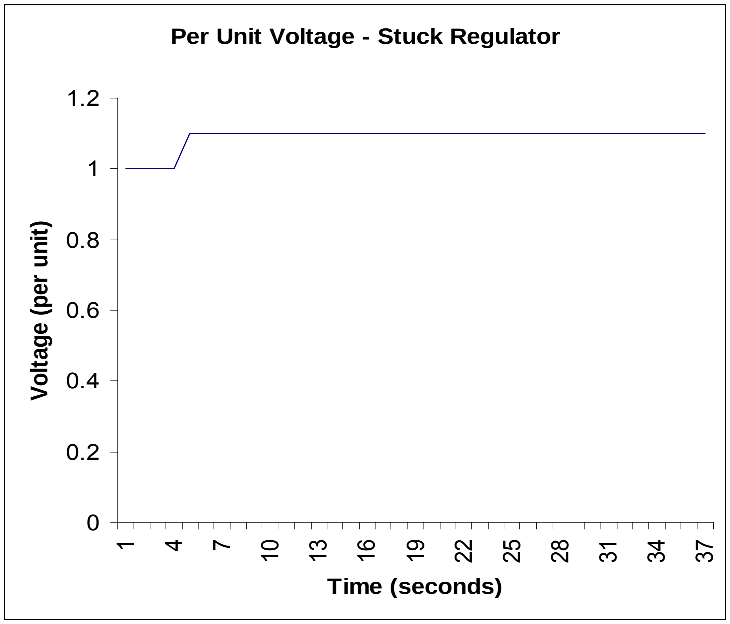
Definitions

Overvoltage – An rms increase in the ac voltage, at the power frequency, for a duration greater than a few seconds.

Waveform – Overvoltage



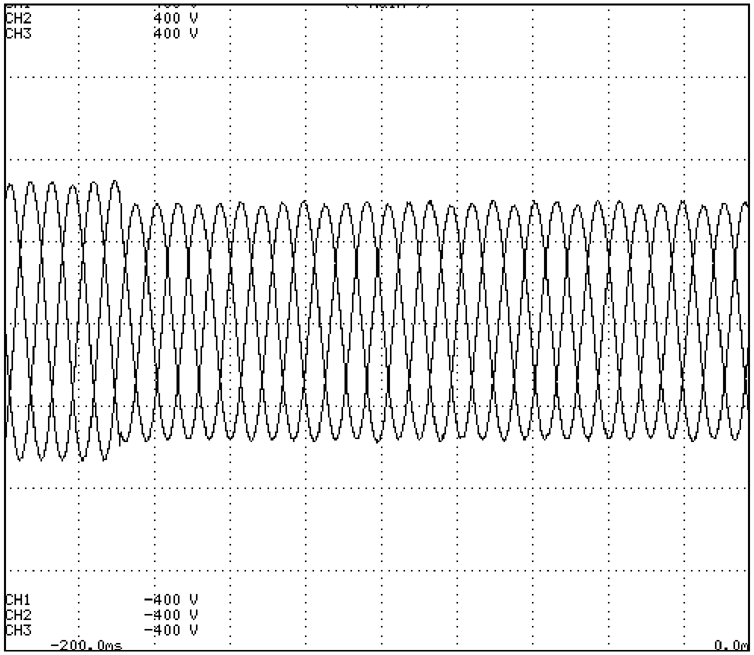
RMS Voltage Time Plot



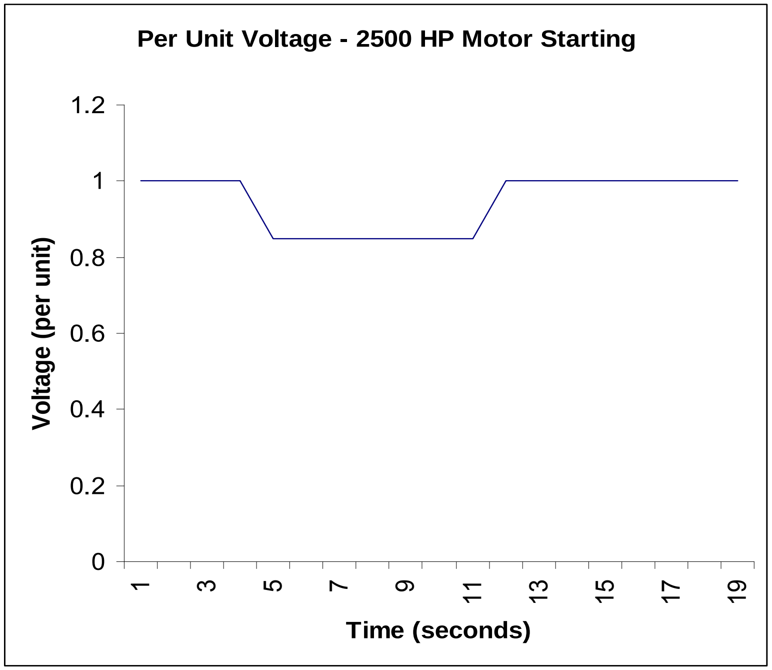
Definitions

Undervoltage - An rms decrease in the ac voltage, at the power frequency, for a duration greater than a few seconds.

Waveform – Undervoltage

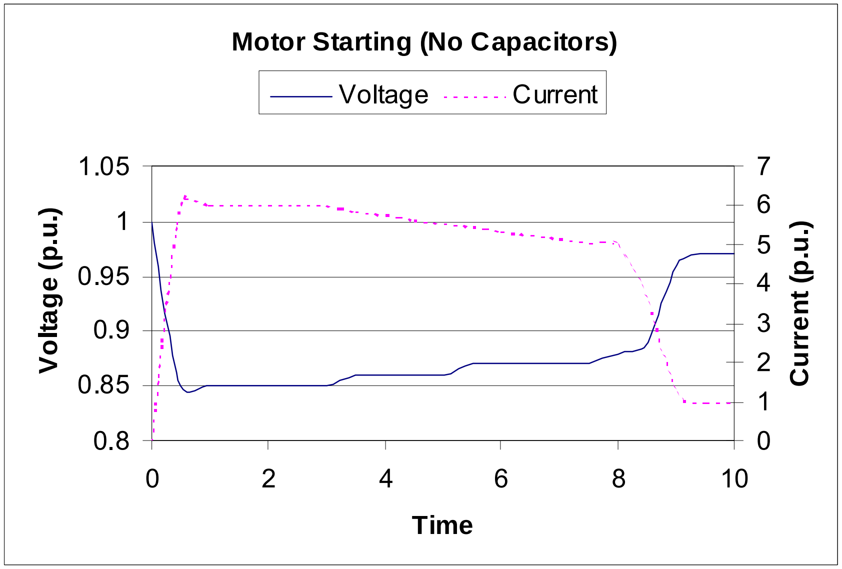


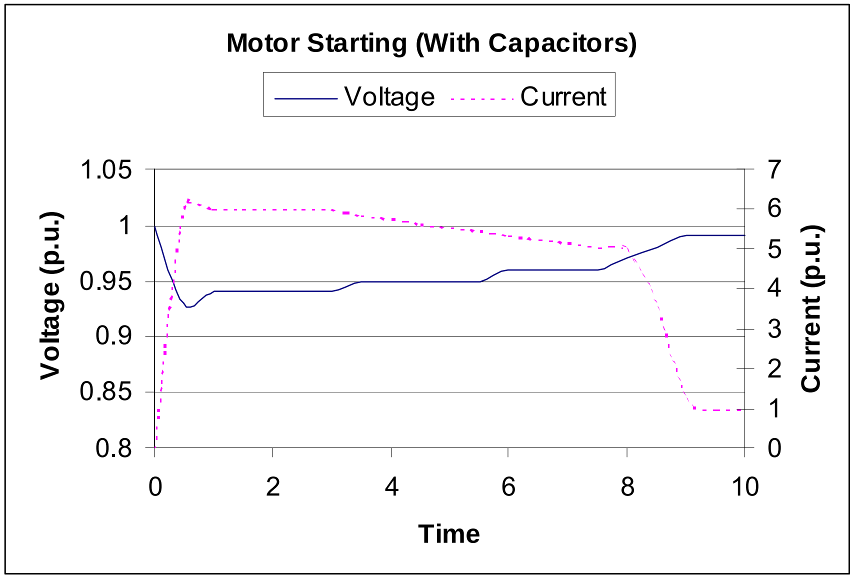
RMS Voltage Time Plot



Definitions

Undervoltage – Motor Starting - Capacitor Switched with Motor (Motor Terminal Voltage and Current)

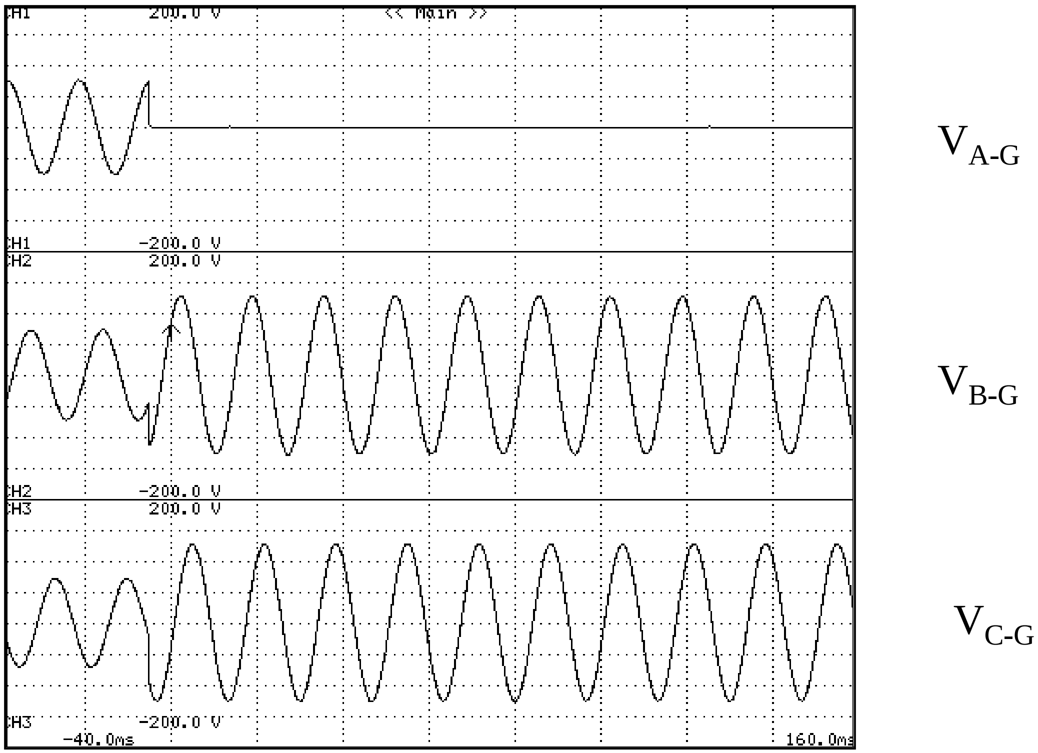




Definitions

Swell – An rms increase in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds.

This example will be discussed in greater detail the Special Grounding Considerations Section.



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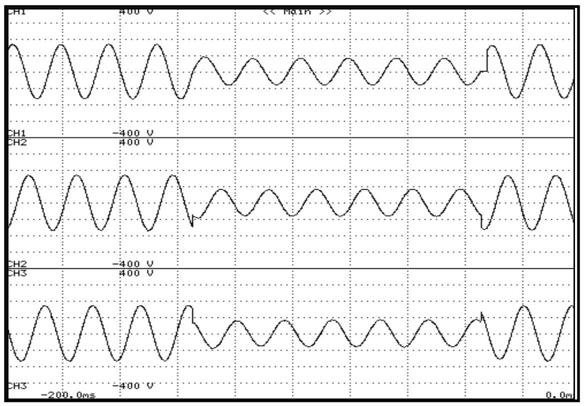
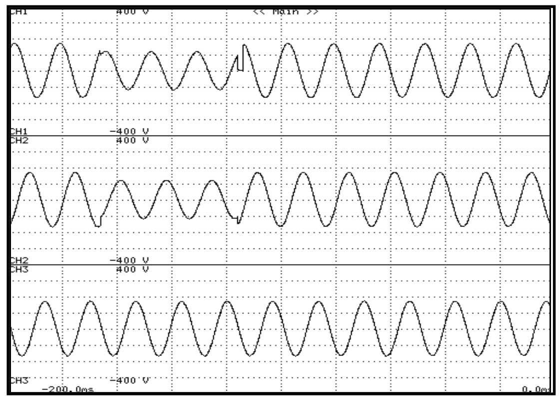
Definitions

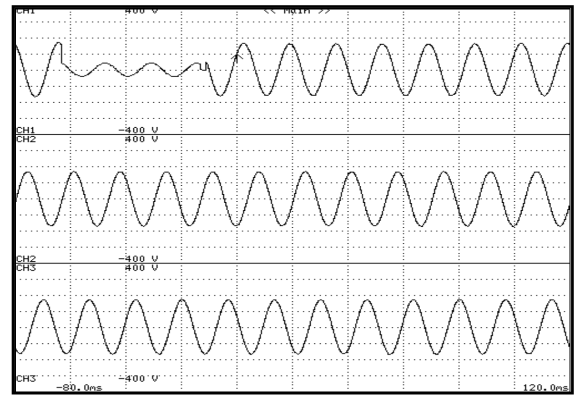
Sag - An rms reduction in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds.



Three Phase Sag (50% Retained Voltage)



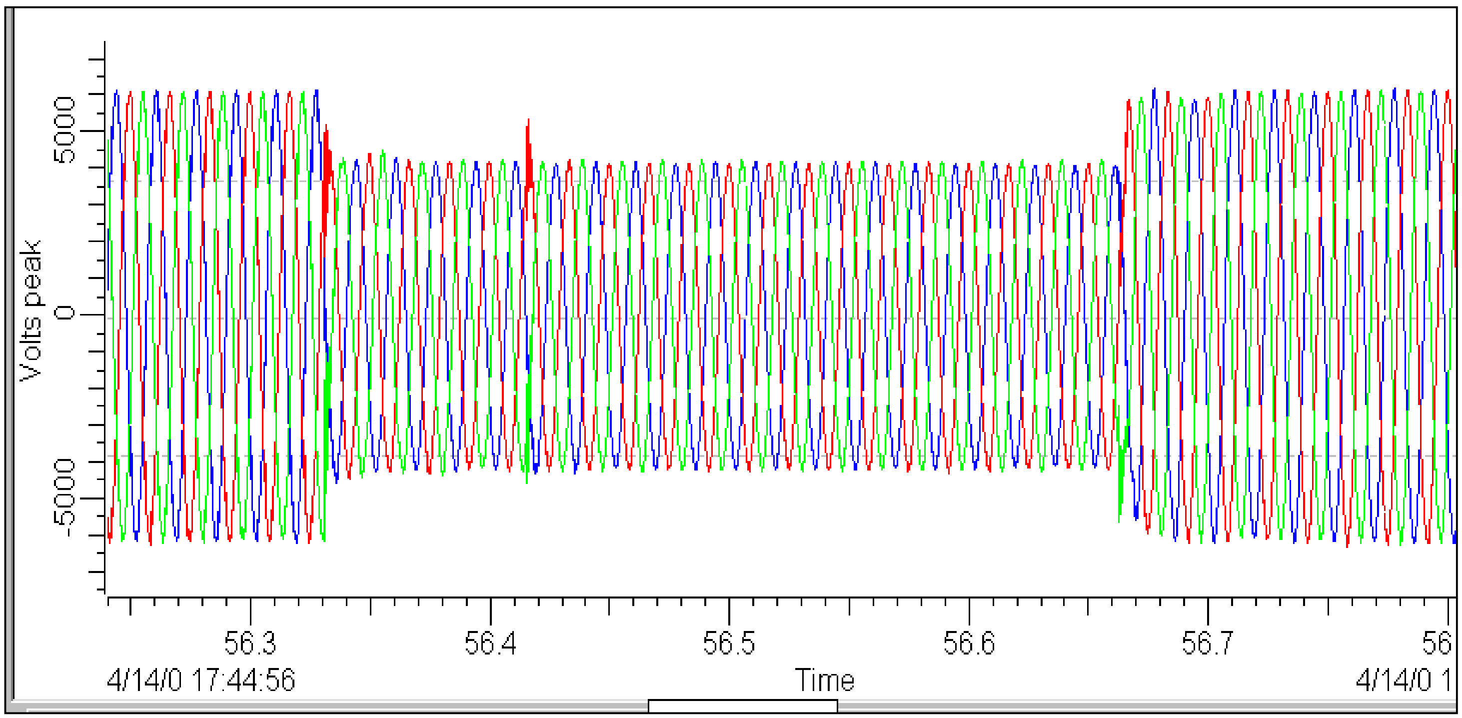
Two Phase Sag (70% Retained Voltage)



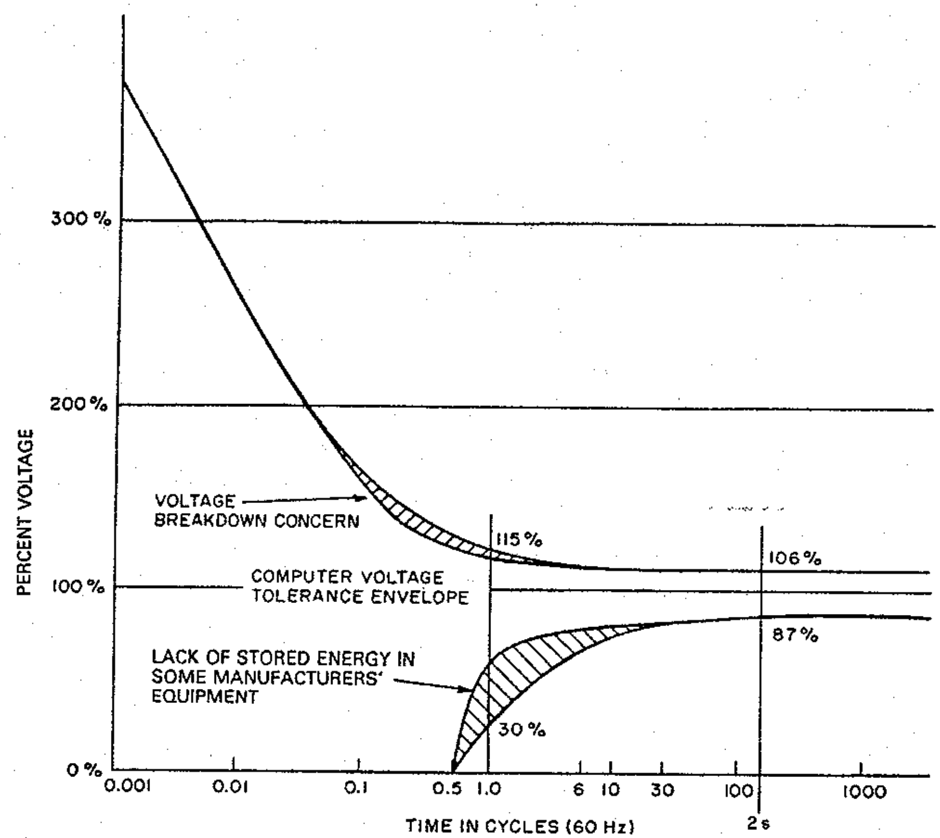
Single Phase Sag (25% Retained Voltage)

Voltage Sag Characteristics

- **Retained Voltage**
- **Duration**
- **Number of Phases Affected**



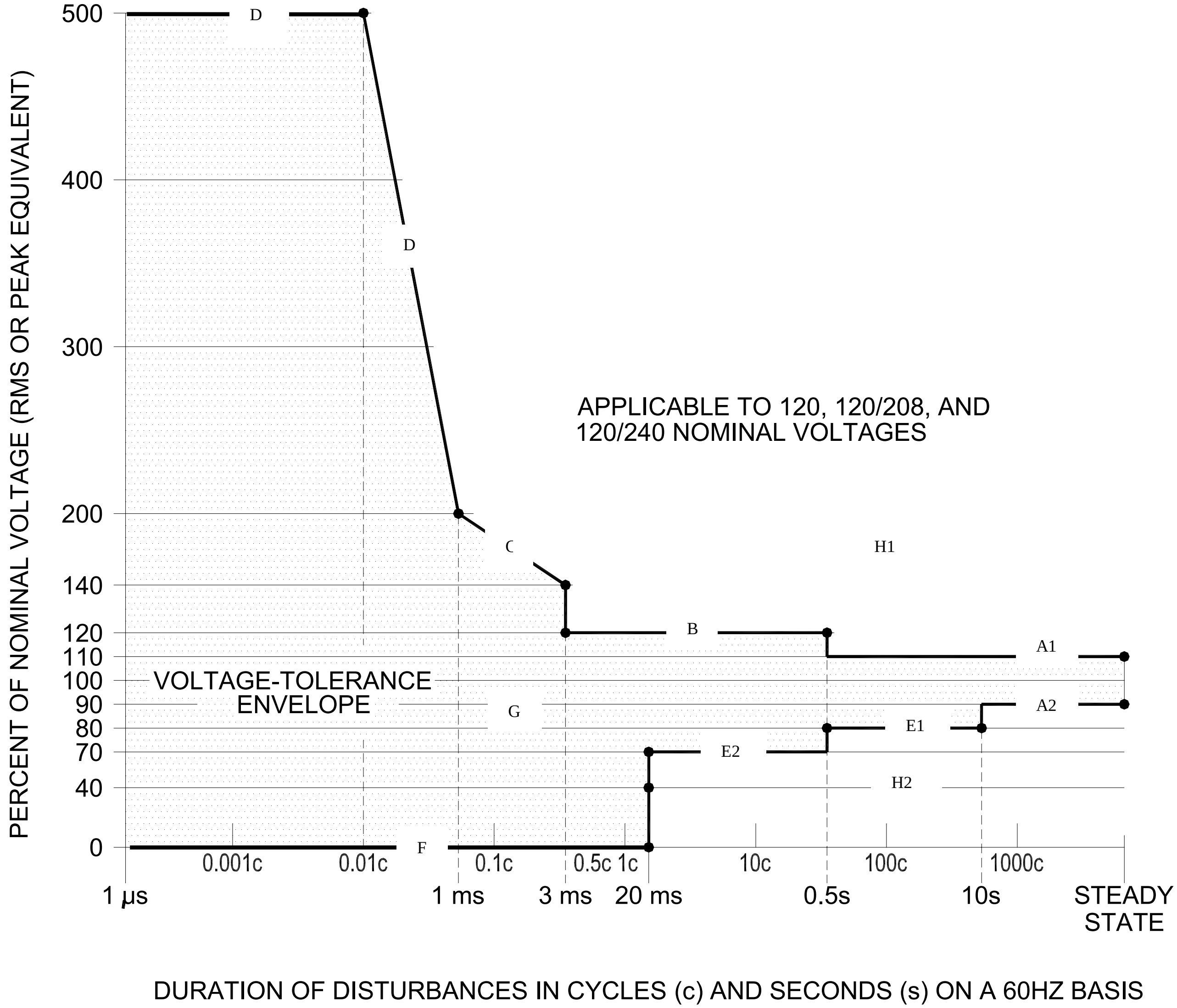
Standards – “Old CBEMA” Curve



NOTE: Newer data is expected to be included in next revision of IEEE Std 1100-1992.

Figure 3-4—Typical design goals of power-conscious computer manufacturers

Standards – "New CBEMA" Curve



Standards – "New CBEMA" Curve

Boundary A – These two lines define the acceptable steady-state voltage range. The range is +/- 10% of nominal voltage. Within this range, equipment should be able to tolerate this voltage continuously.

Boundary B – This boundary defines a voltage swell with a magnitude up to 120% of nominal voltage and duration up to 0.5 seconds. Such a voltage swell is generally the result of a significant reduction in load or when regulation is poor such as from alternate generation sources.

Boundary C – This boundary defines tolerance for typical low-frequency ringwaves such as utility capacitor switching. The frequency of the oscillation may range from 200 Hz to 5 kHz. This boundary includes transients that range from 140% (at 200 Hz) to 200% (at 5 kHz).

Boundary D – This boundary limits high frequency transients typically the result of induced effects from lightning or may be related to high frequency transients generated on the low voltage system. The waveforms characterized in this boundary are described by ANSI/IEEE C62.41-1991. The intent of the range covered by this boundary is to provide 80 Joule minimum transient immunity.

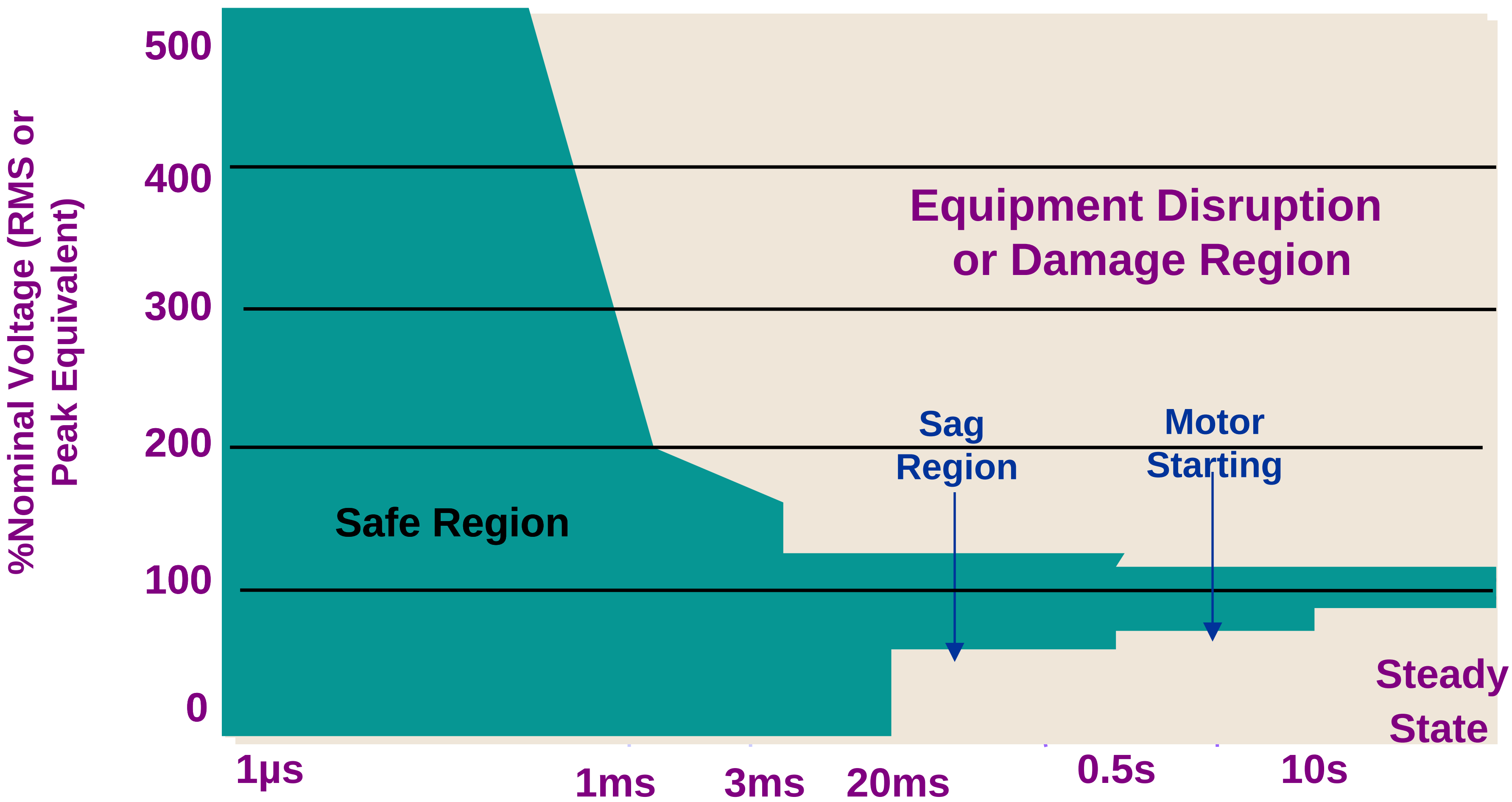
Boundary E – This boundary covers two different types of voltage sags. The first type of sag (E1) is related to application of large loads (motor starting, etc.). These sags are generally shallow (>80% retained voltage) but their duration is long (up to 10 seconds). The second type of sag (E2) is typically related to faults on the power system. This boundary is defined as a retained voltage of 70% and duration up to 0.5 seconds.

Boundary F – A complete loss of voltage is defined by this boundary. An interruption of up to 20 mS is acceptable. If a fault occurs on a power system, fast acting fuses or low voltage circuit breakers will clear a fault within this time and a very deep voltage sag near 0 V (retained voltage) may occur. In addition, reclosing operations that may occur on a power system will account for other occurrences of zero volts for this short period of time.

Region G – The shaded region inside all of the boundaries is the No Damage Region. Within these boundaries, normal operation of information technology equipment (ITE) is expected.

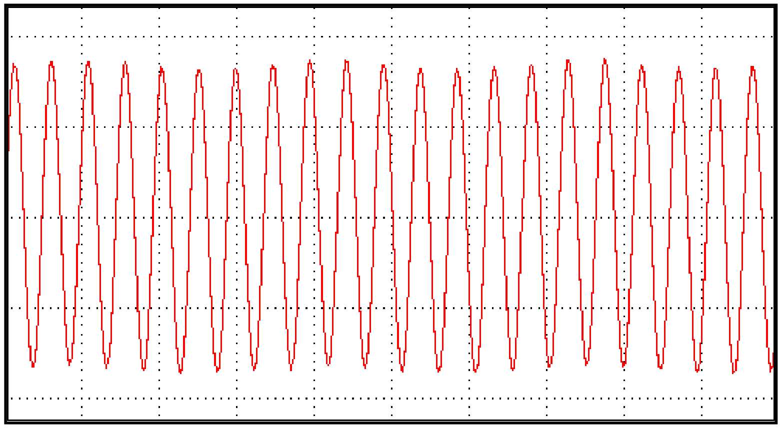
Region H – The Prohibited Regions are the areas outside Boundaries A-F. H1 defines the area above boundaries A1, B, C, and D and Region H2 defines the area below Boundaries A2, E1, E2, and F.

ITIC Curve: Voltage-Tolerance Envelope

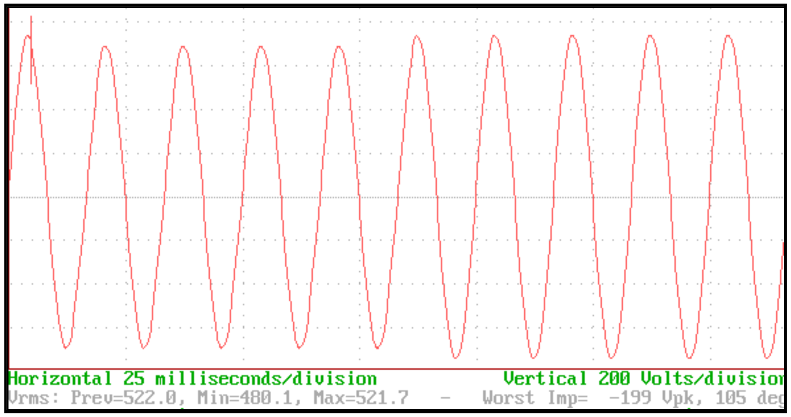


Definitions

Flicker – A repetitive variation of input voltage sufficient in duration to allow visual observation of a change in electric light source intensity.



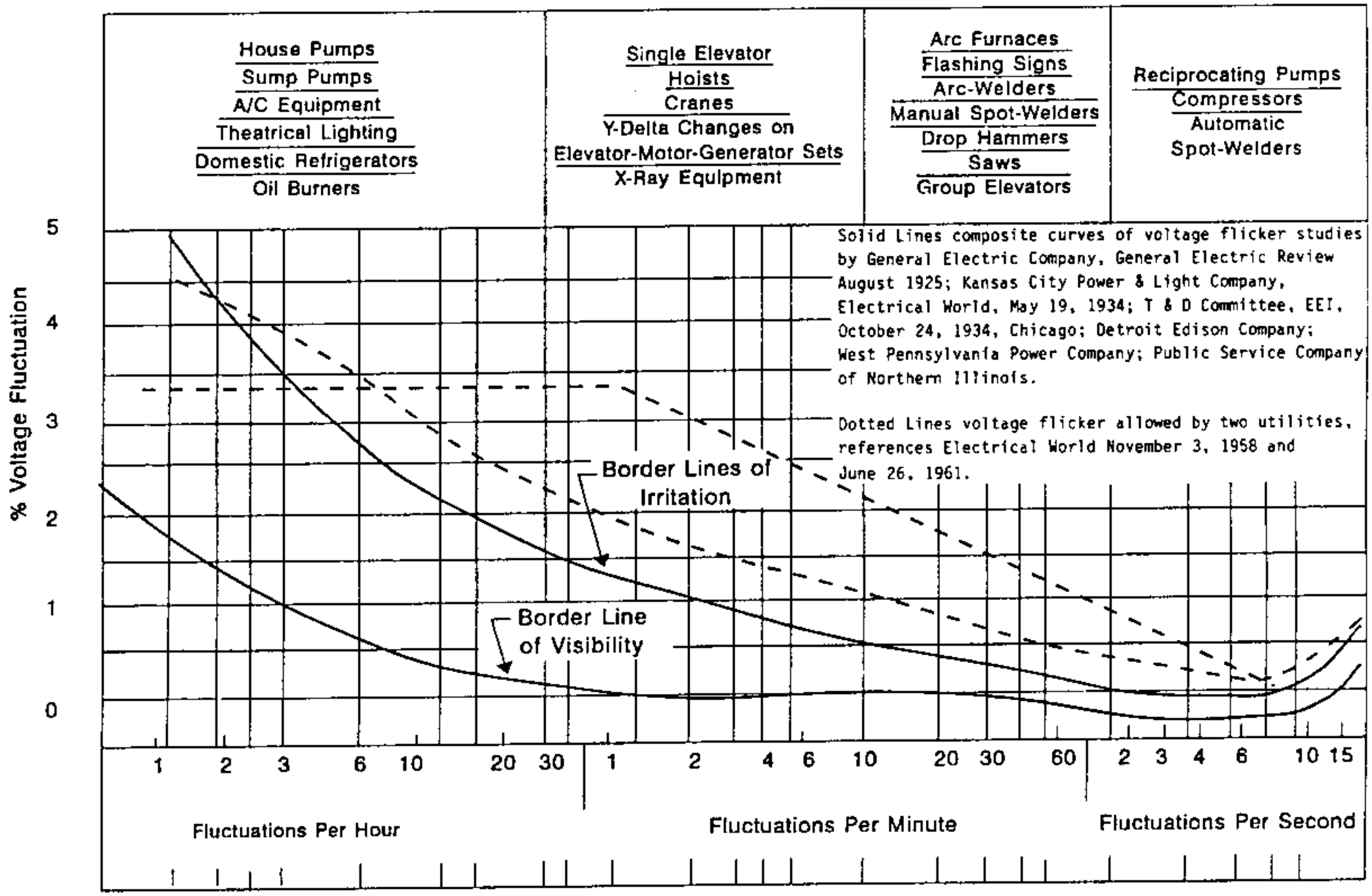
Flicker - 3% 8.5 Hz
Fundamental is 60 Hz



Circuit Breaker Test Set
45000 A Primary Injection Test

(Input Voltage Dropped from 522.0 V to 480.1 V During Test)

Voltage Flicker



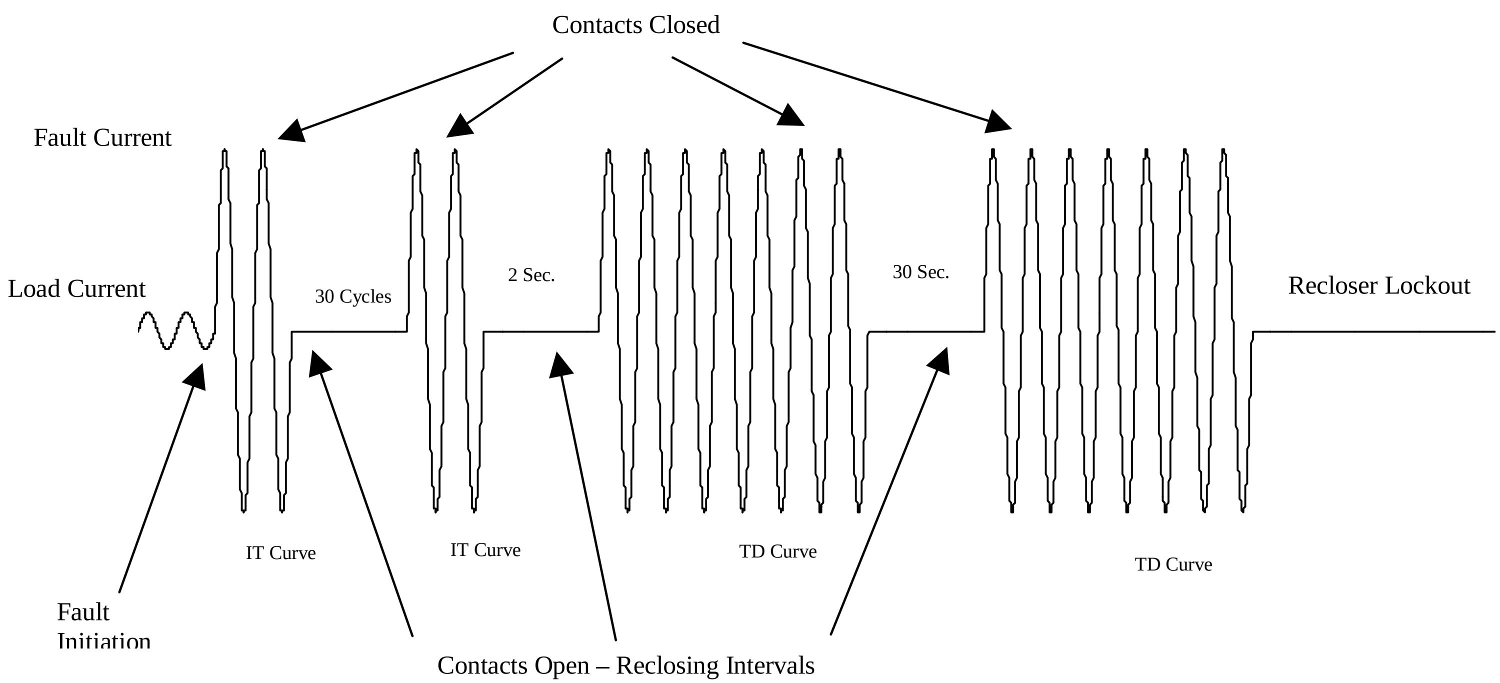
Definitions

Brownout – A reduction of voltage by utility for long duration (hours)

- Often a problem in developing countries or where utility is overloaded

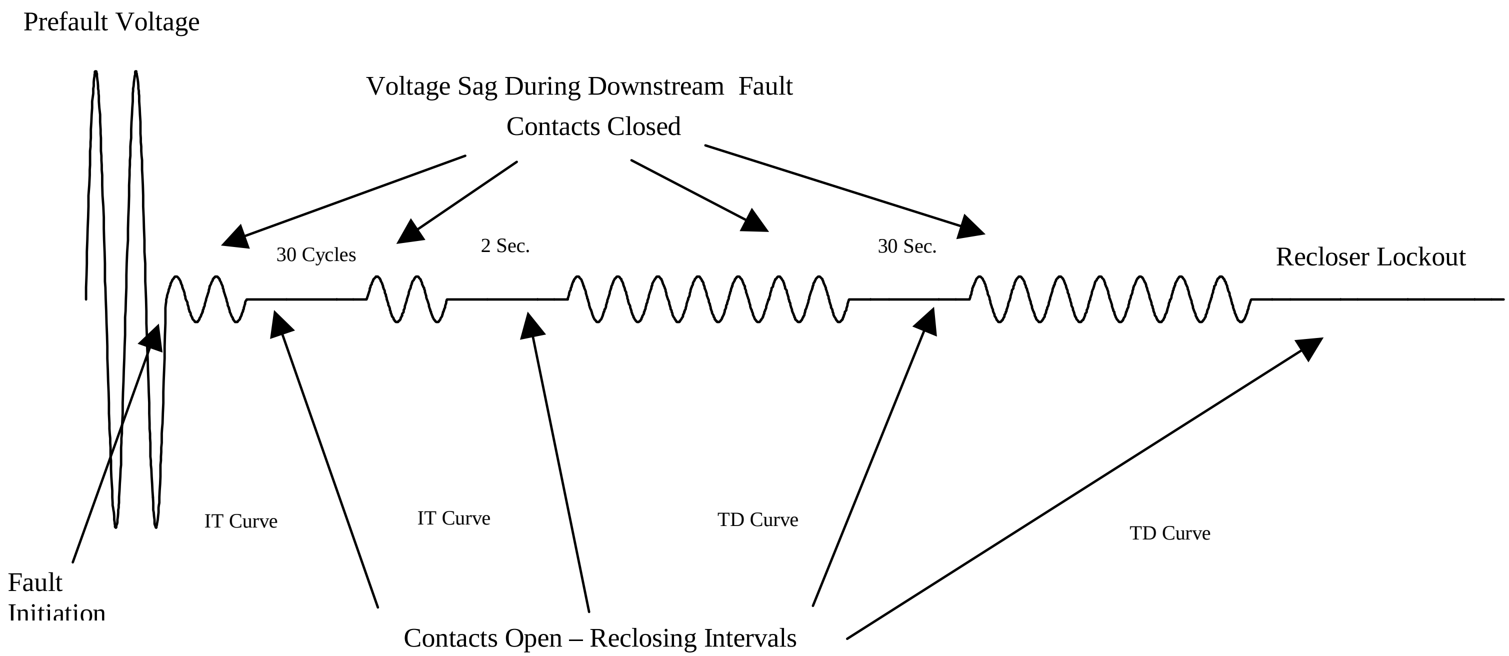
- Utilities will admit that with deregulation, they will push the +/- 10% limits

Recloser Operation



Line Current during a Fault

Recloser Operation



Faulted Circuit Voltage During Fault

Transients

Impulse Transient - a sudden, non-power frequency change in the steady-state voltage or current, which has a unidirectional polarity.

- Typical duration is nsec to msec.
- Often associated with lightning strikes.
- Because of the high frequencies involved, these types of transients are not conducted very far.
- Impulse transients have been known to excite the natural frequency of the power system and produce oscillatory transients.

Transients

Oscillatory Transient - sudden, non-power frequency change in the steady-state voltage or current, that includes both positive and negative polarity values.

- Typical duration can range from 5 usec to 3 msec
- Divided into three types by frequency of the primary frequency component.

– High frequency - primary component over 500 kHz - usually the result of a system response to an impulse transient.

– Medium frequency - primary component between 5 kHz and 500 kHz - often the result of cable switching or back-to-back capacitor bank switching.

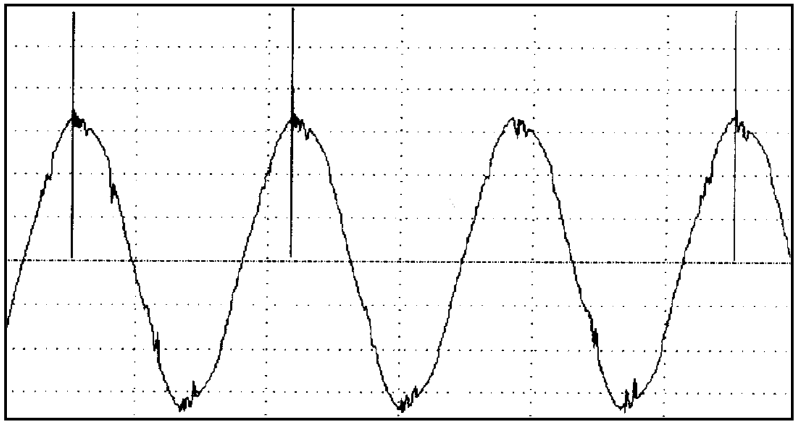
– Low frequency - primary component less than 5 kHz - usually the result of capacitor bank switching on a distribution or sub-transmission system.

Transients

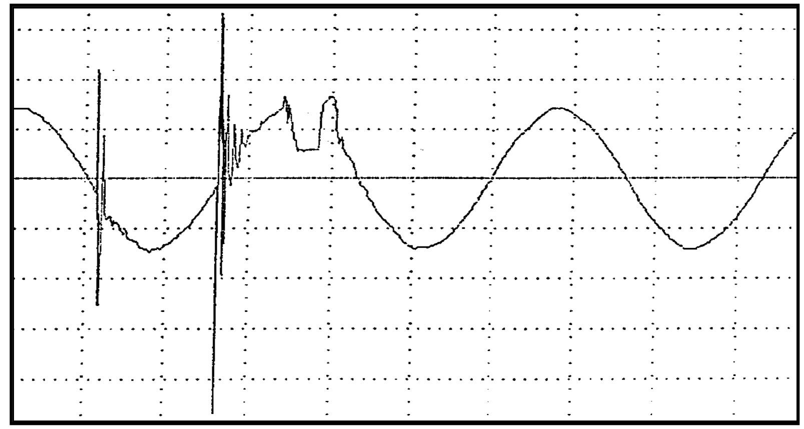
Low Frequency Oscillatory Transient - sudden, non-power frequency change in the steady-state voltage or current, that includes both positive and negative polarity values – usually caused by utility capacitor switching.

- Distribution capacitor switching will typically produce a transient between 300 Hz and 900 Hz.
- Many utility distribution systems will have a common "ring" frequency due to fact that many utilities reuse construction details such as structure type, conductor type, etc.
- In theory the peak magnitude can be 2.0 p.u., but in reality it tends to fall between 1.3 p.u. and 1.8 p.u. with a duration between 0.5 to 3 cycles. 1.4 p.u. is a typical value.
- Transients below 300 Hz are generally the result of transformer energization or ferroresonance.

Transients – Impulsive and Oscillatory

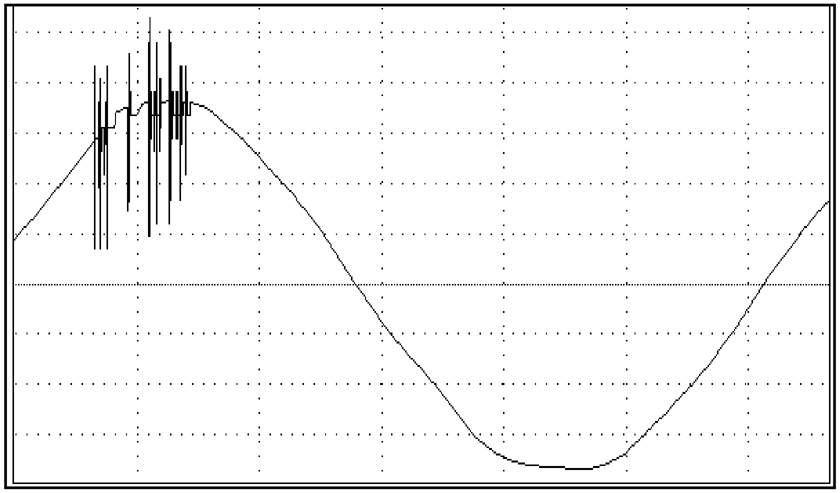


Example of repetitive impulsive transient caused by SCR load

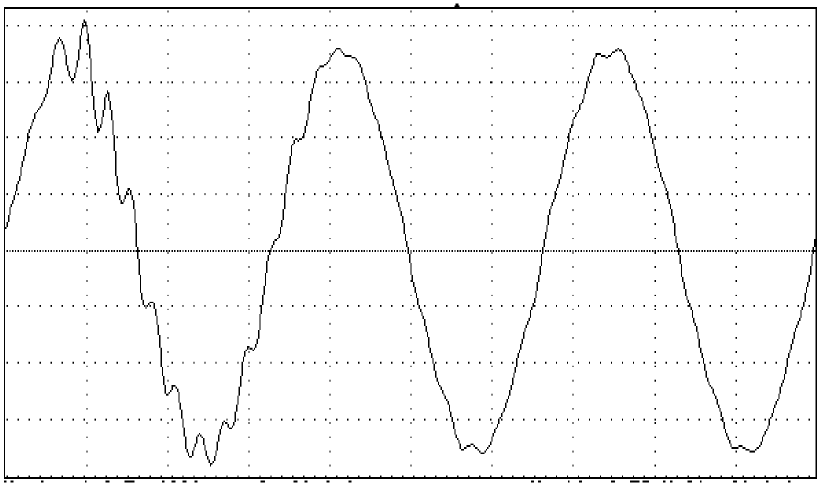


Example of high frequency oscillatory transient

Transients – Impulsive and Oscillatory

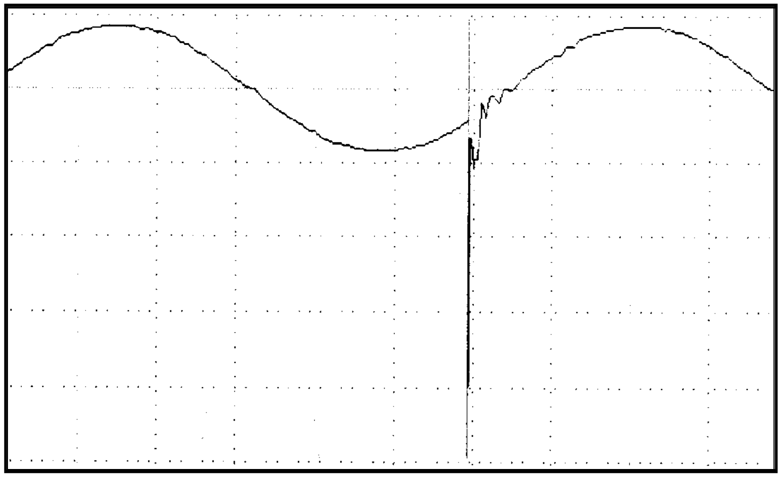


Example of repetitive oscillatory transients caused by arcing during contactor bounce

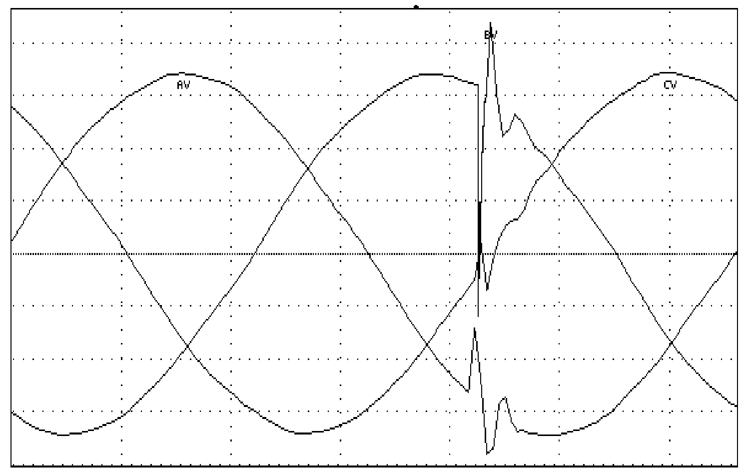


Example of low frequency oscillatory transient caused by utility capacitor switching

Transients – Impulsive and Oscillatory



Impulsive (induced) voltage transient resulting from nearby lightning strike



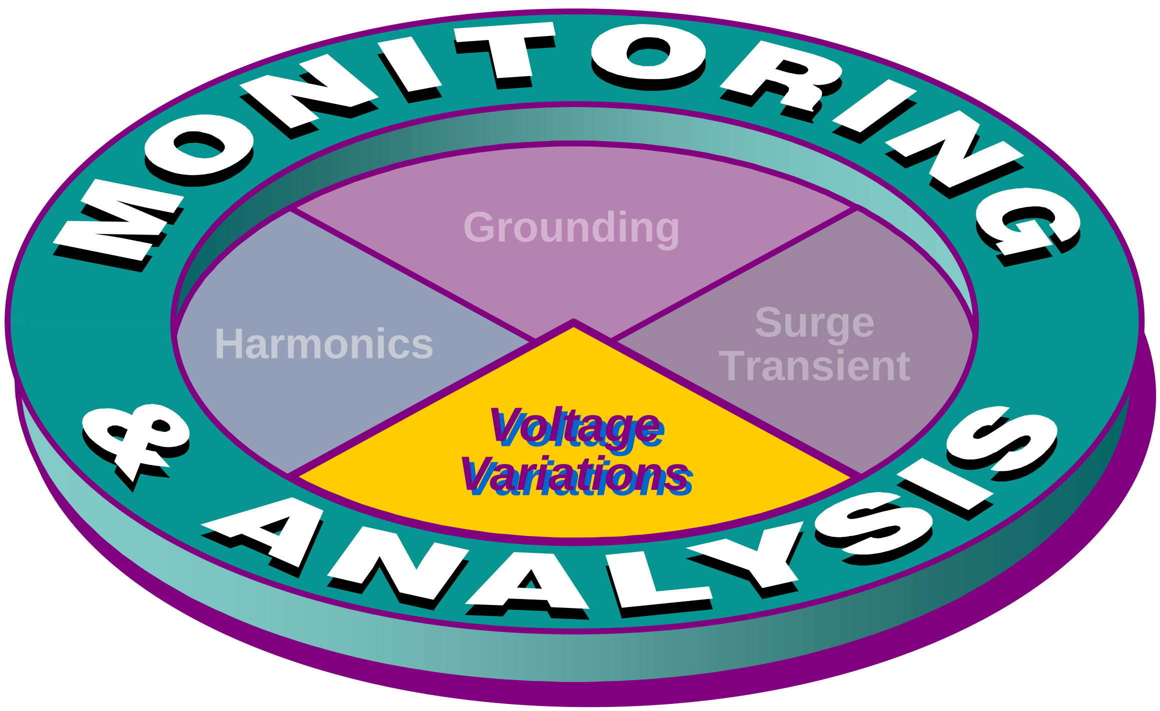
Three phase MV capacitor bank switching with significant damping

Outline

- Introduction
  - Describing a Power Quality Waveform
  - Sample PQ Monitoring Videos
  - Sample PQ Waveforms
- Monitoring Equipment
- PQ Definitions
- Power Quality Issues and Expected Waveforms
  - Voltage Variations
  - Transients
  - Harmonics
  - Wiring and Grounding Considerations
- Power Quality Lab Overview
- Final Exam

Multi-Cycle Voltage Variations

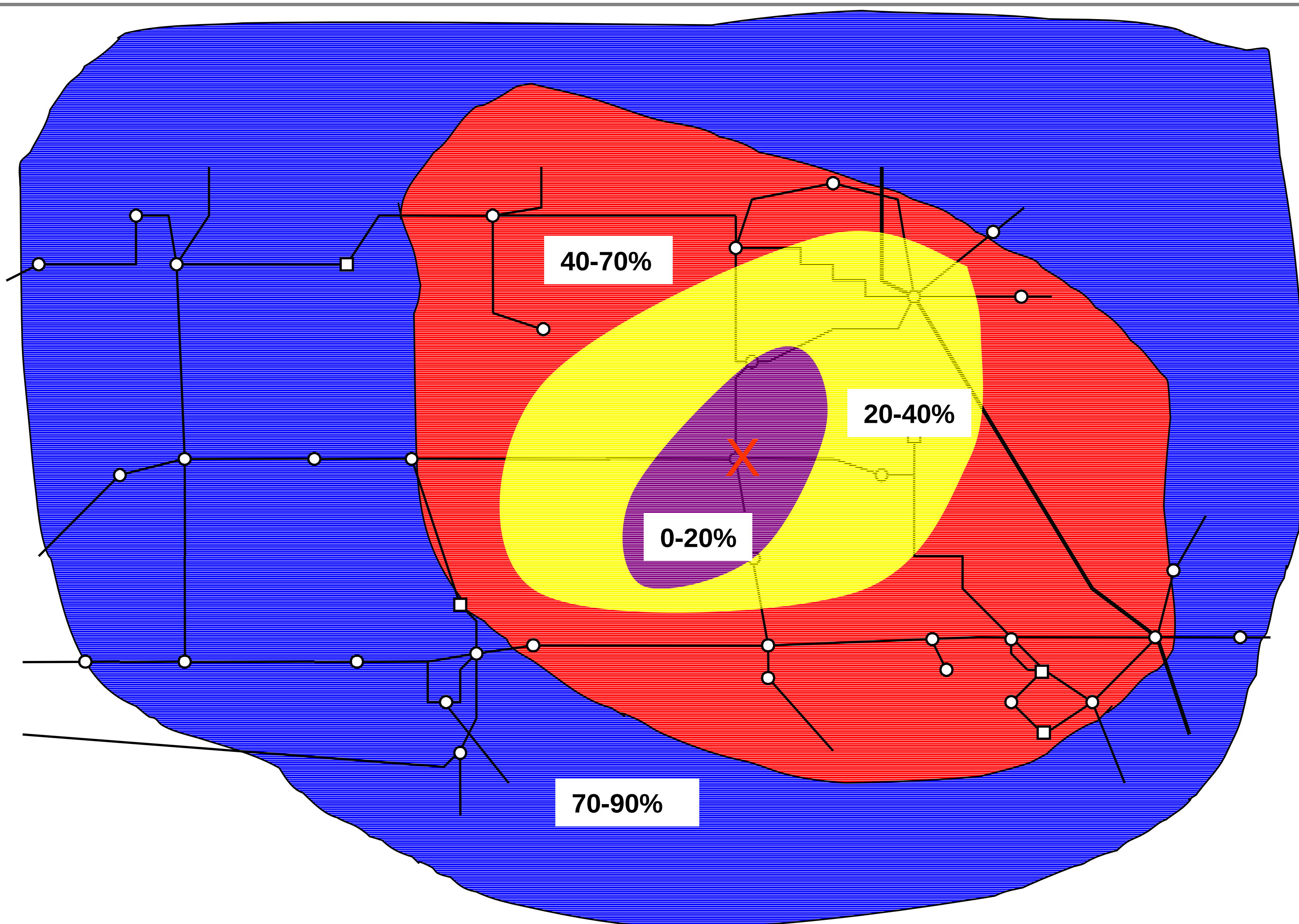
- Sags are responsible for a majority of upsets and nuisance trips of sensitive electrical equipment



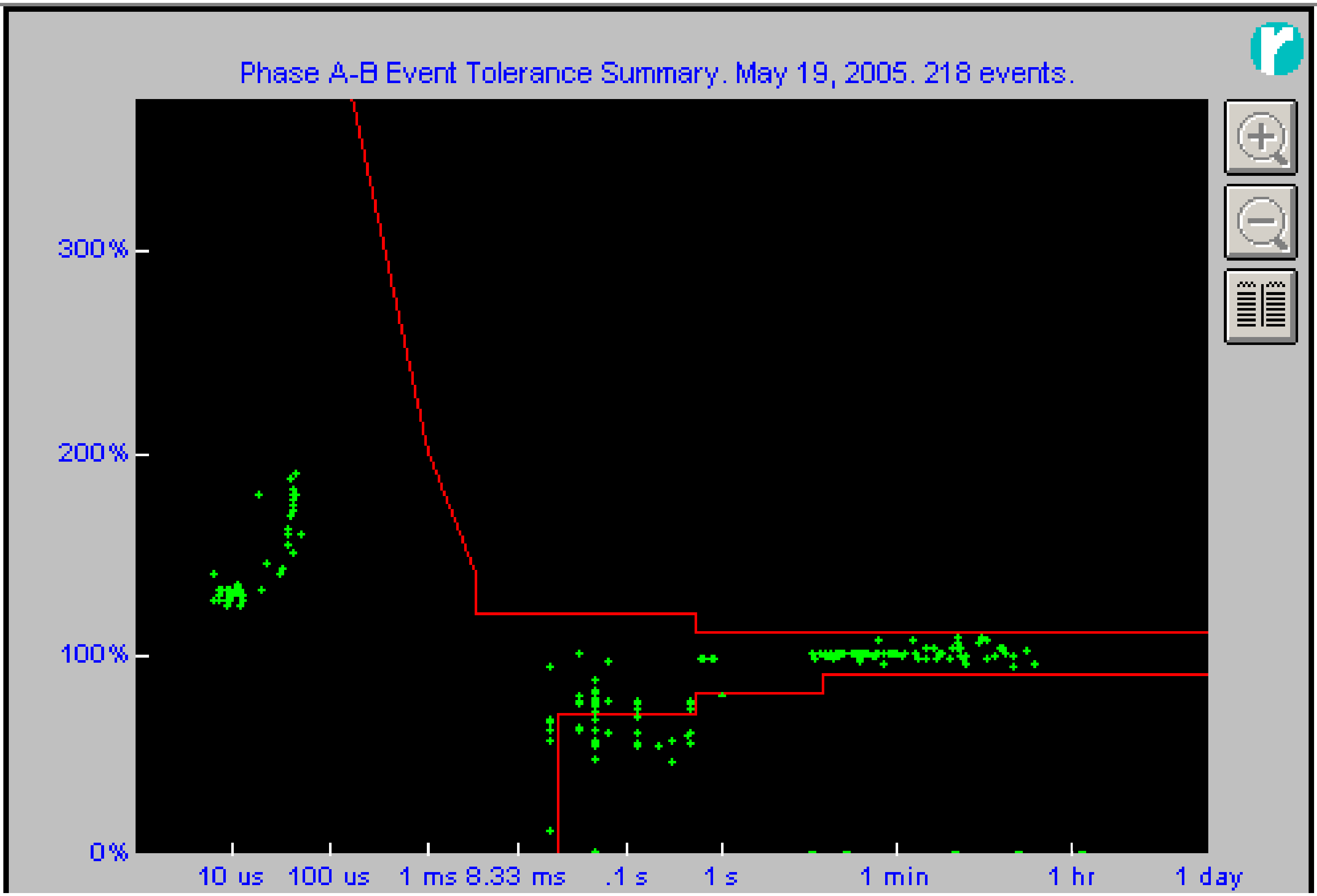
Where Do Sags Come From???

How can you prevent that???

Area of Vulnerability

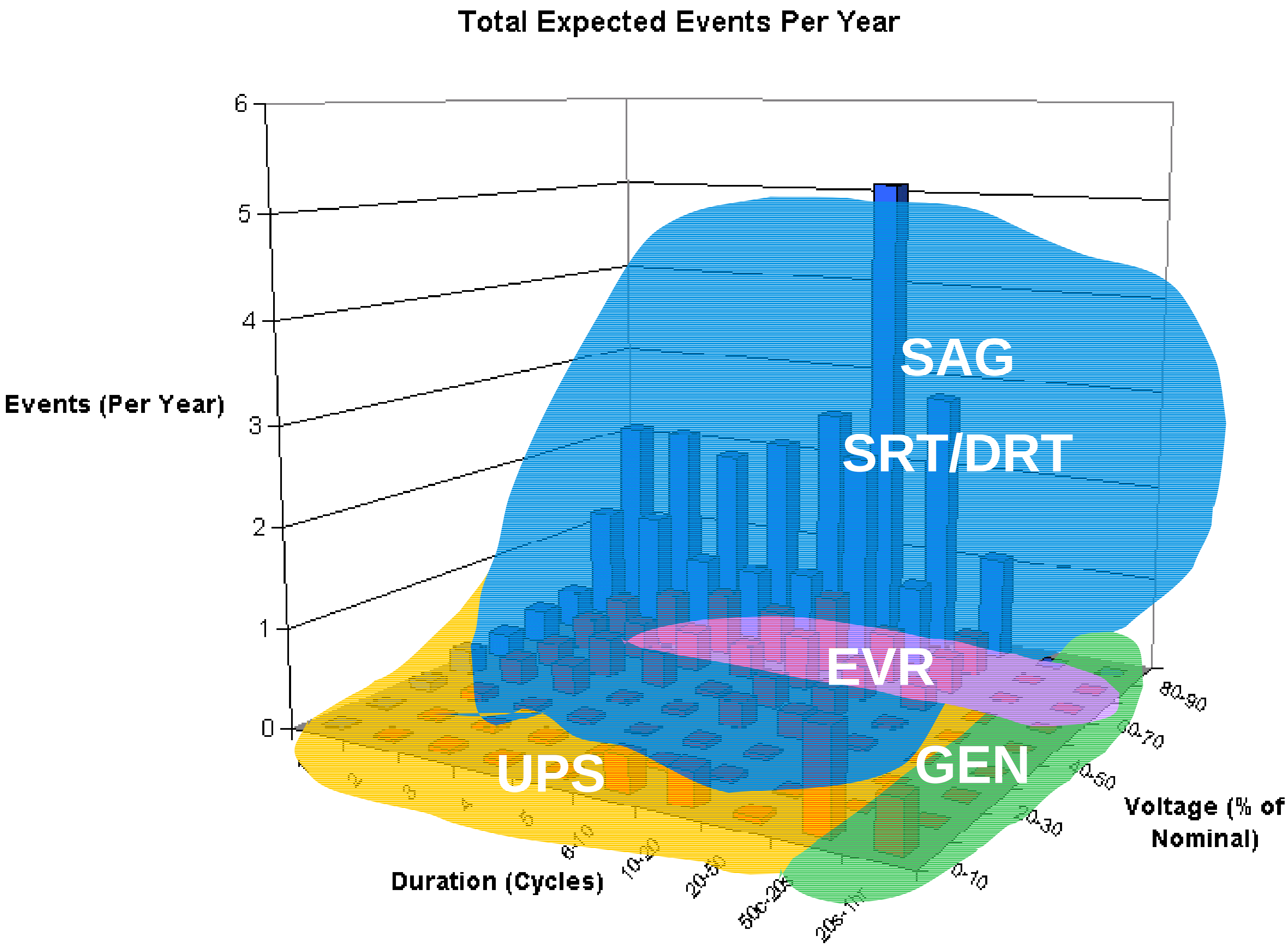


Field Data

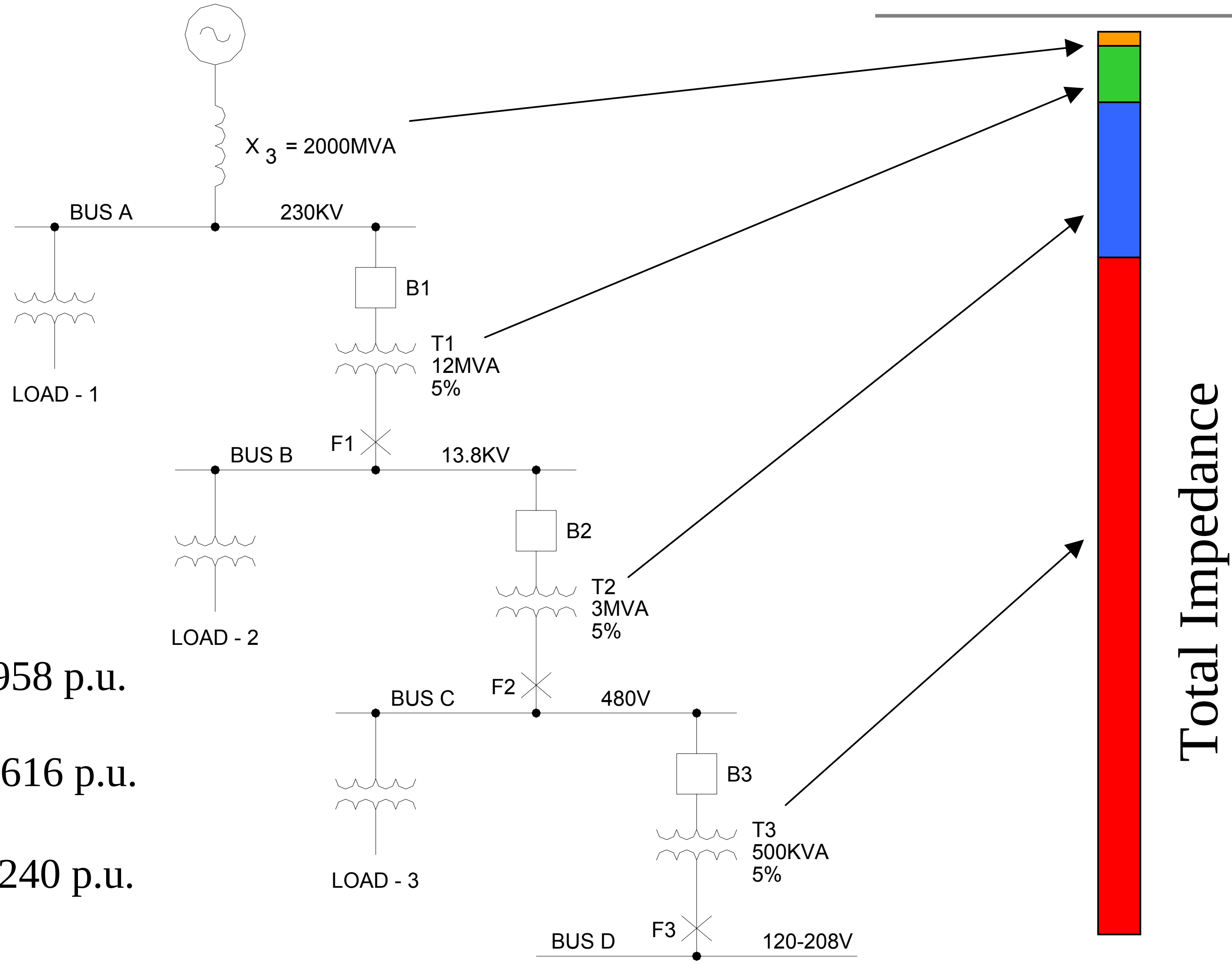


Phase A-B Event Tolerance Summary. May 19, 2005. 218 events.
300%
200%
100%
0%
10 us
100 us
1 ms
8.33 ms
.1 s
1 s
1 min
1 hr
1 day

Which Solution Will Work?



Voltage Sag Calculation



For a fault at F3

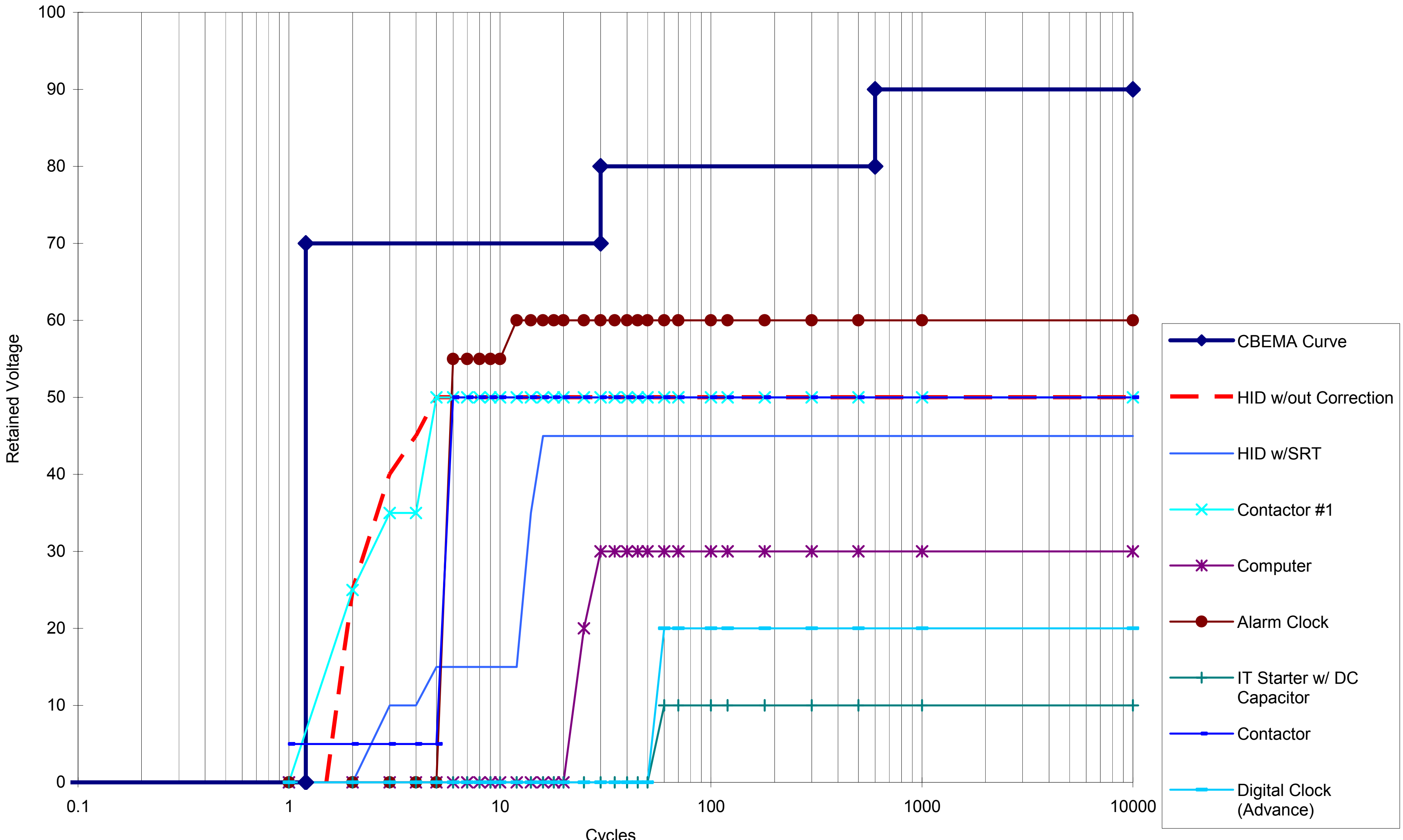
$V_{\text{Load1}} = V_A = 0.9958$ p.u.

$V_{\text{Load2}} = V_B = 0.9616$ p.u.

$V_{\text{Load3}} = V_C = 0.8240$ p.u.

$V_{\text{Bus D}} = V_D = 0$ p.u

Equipment Susceptibility to Sags



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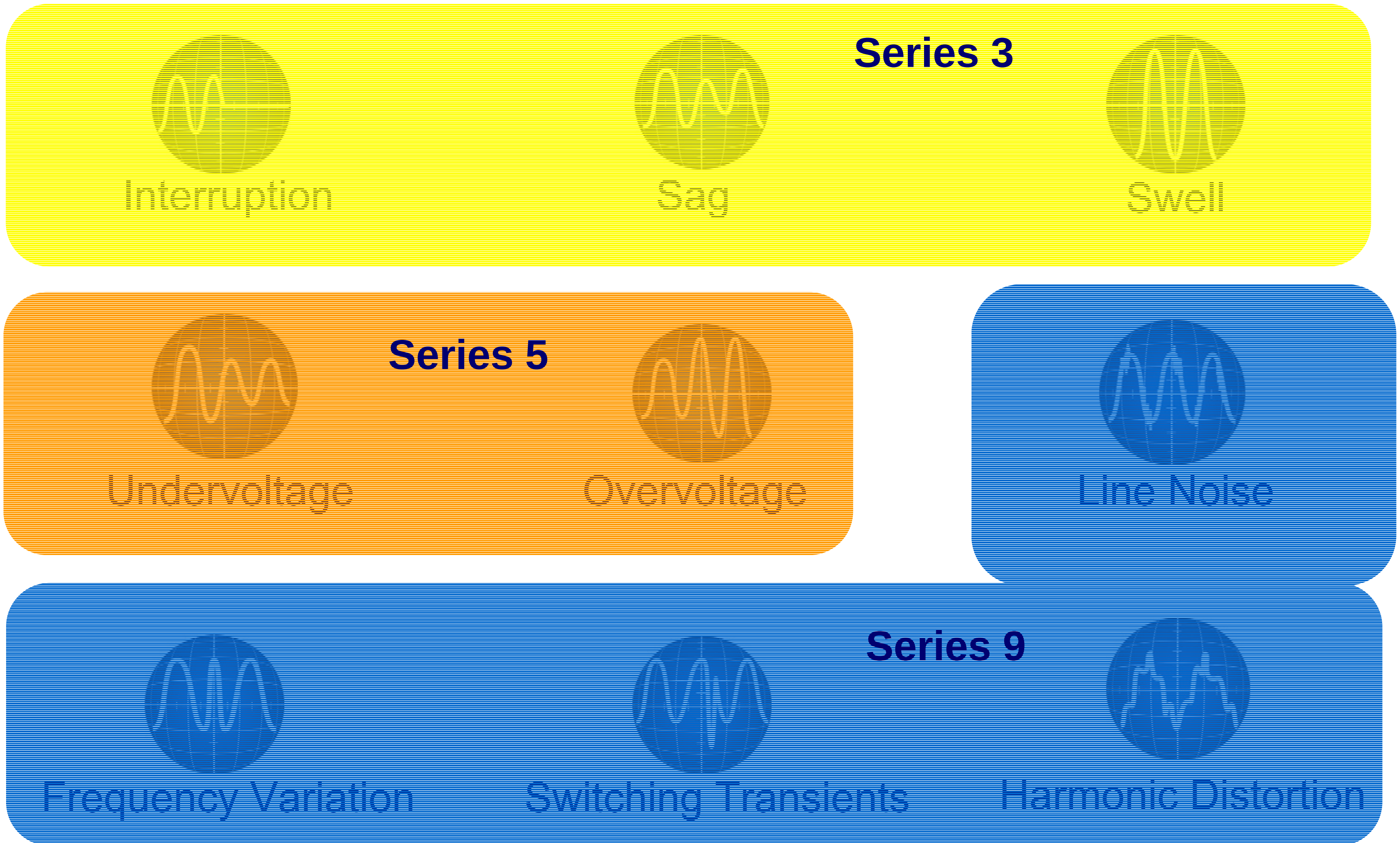
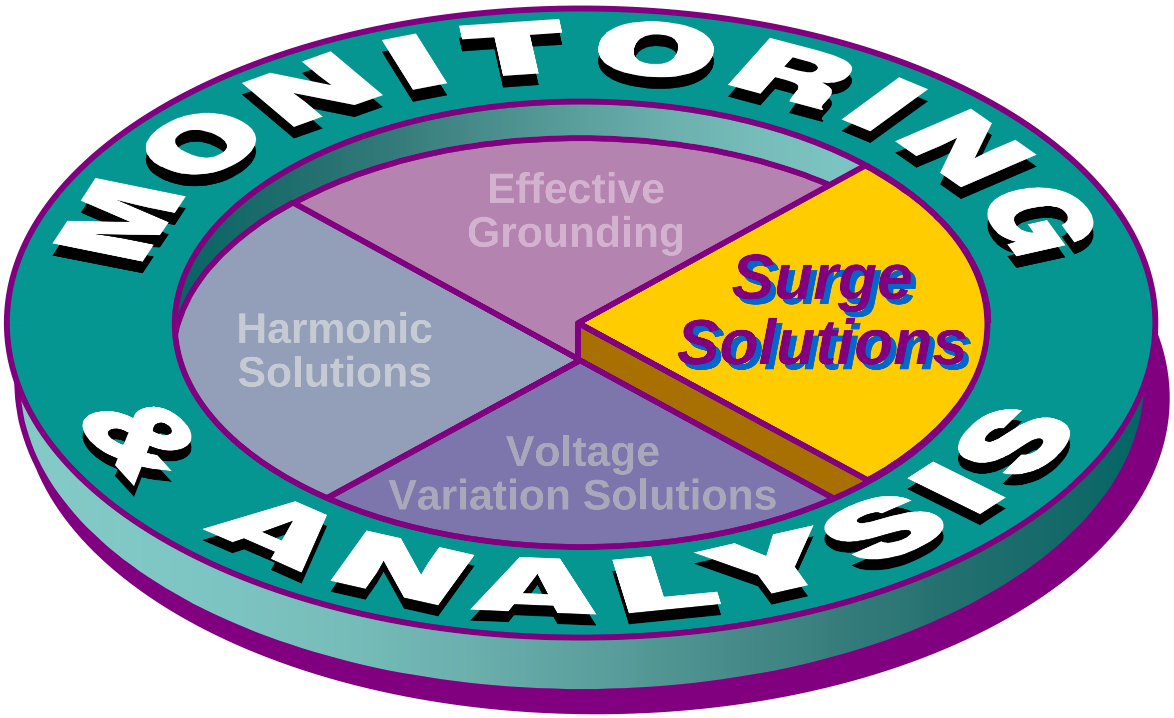
The 9 Common Power Problems



Surges and Transients



The two sources of surges/transient overvoltages that account for the majority of all events are switching and lightning

Monitoring Transients - Outline

- Monitoring Techniques for Surges and Transients.
- Explore the capabilities of the various meters to capture transients.
- Quantify the protection afforded by surge protective devices (SPDs).
- Investigate the affect of lead length on let-thru voltage of the SPD.

Sources of Surge Voltages

Common External Sources

- Lightning
- Capacitor switching
- Short circuits

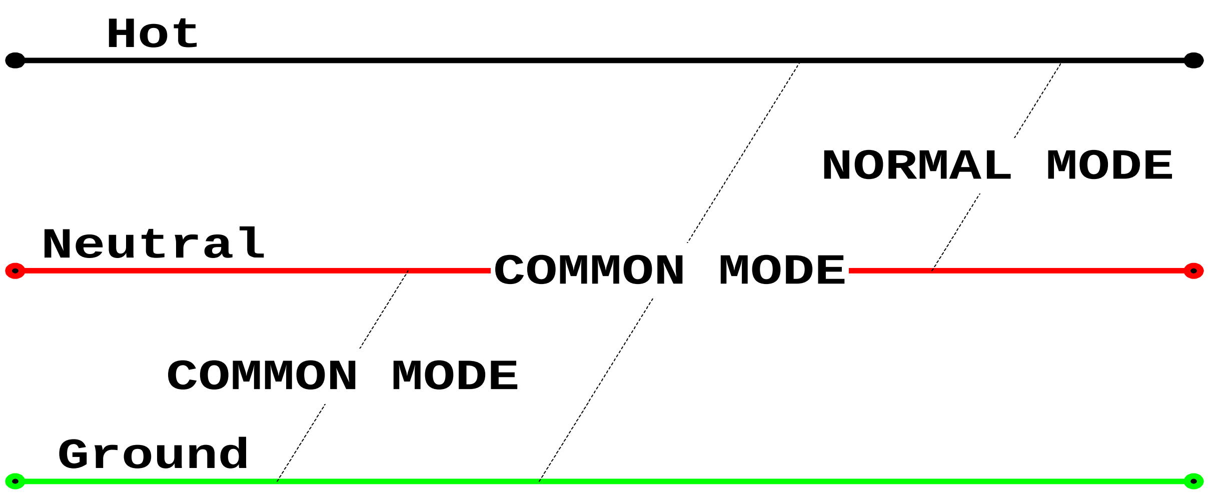
Common Internal Sources

- Load switching
- Short circuits
- Capacitor switching
- Imaging equipment operation
- Variable speed drive operation
- Arc welders
- Light dimmers

Transient Modes

Engineers may categorize transients that occur in a three-phase system with a separate neutral according by their mode. This is popular with many Transient Voltage Surge Suppressors (TVSS) manufacturers.

- Common Mode - Transient between line or neutral and ground.
- Normal Mode - Transient between line and neutral.



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Capacitor Switching Transients

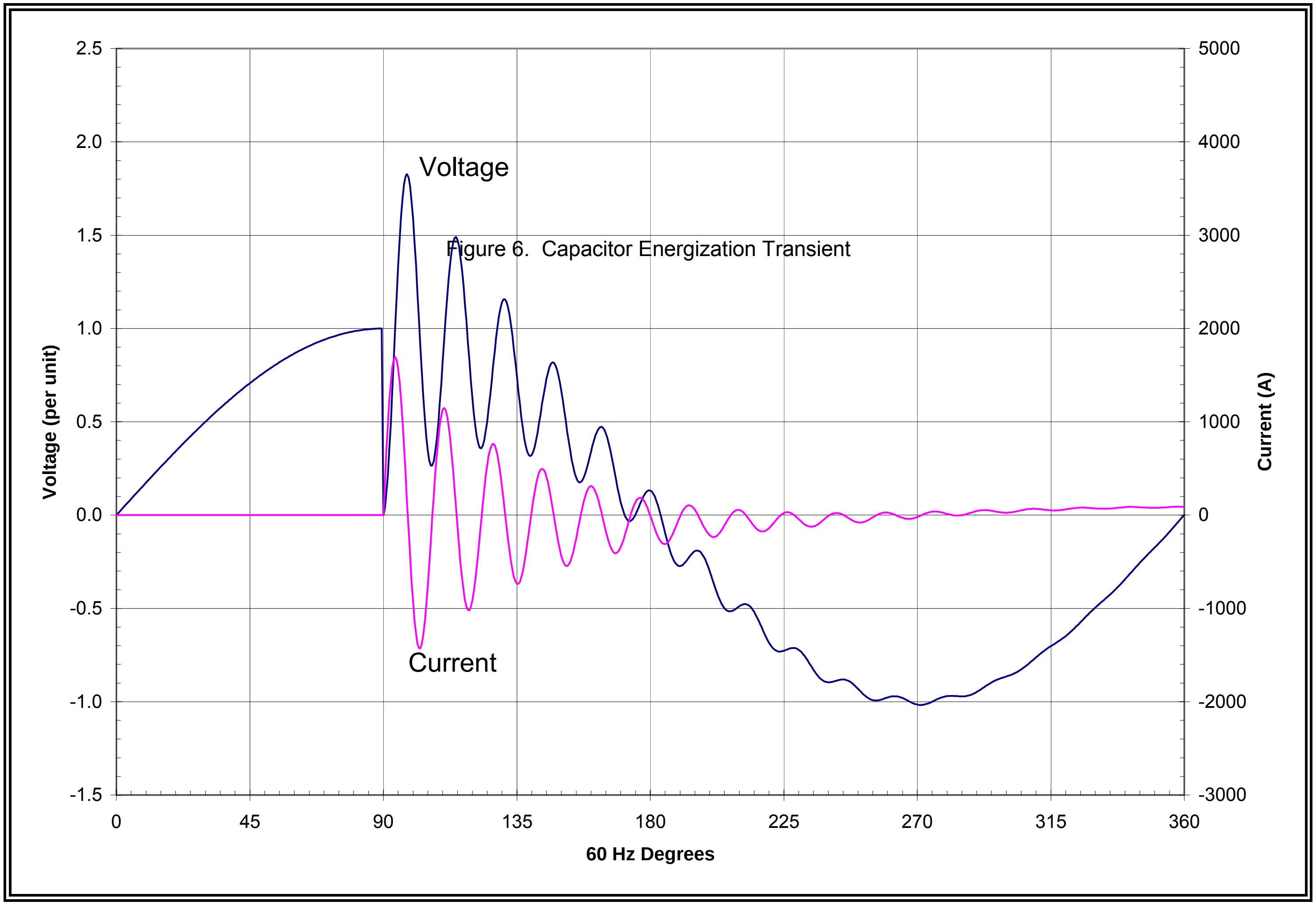
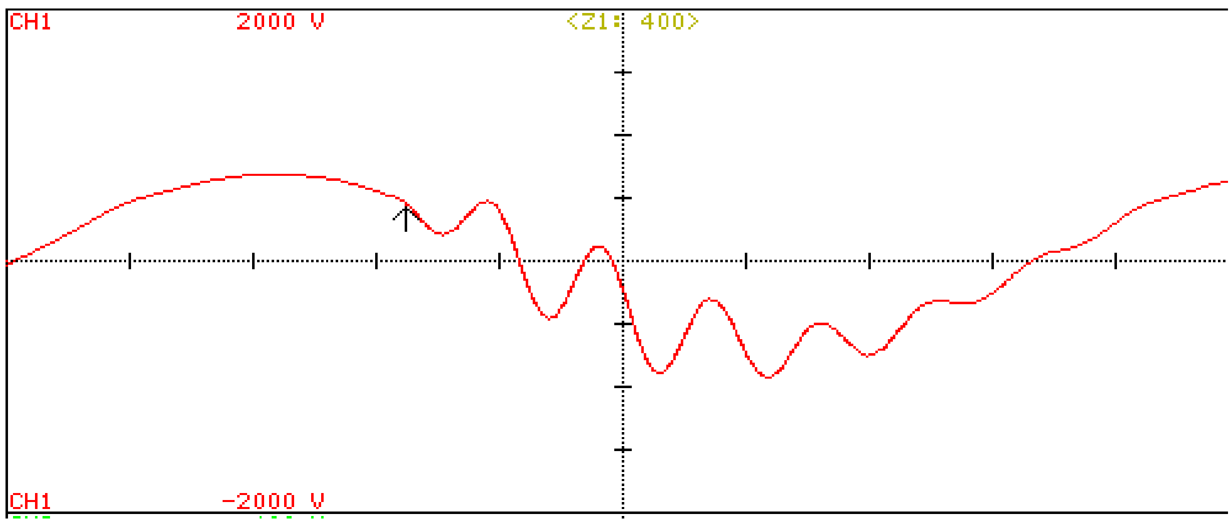


FIGURE 6. CAPACITOR ENERGIZATION TRANSIENT

Transients - Capacitor Switching

- Frequency
- Phase Angle Variations (Phase Shifting Transformers)



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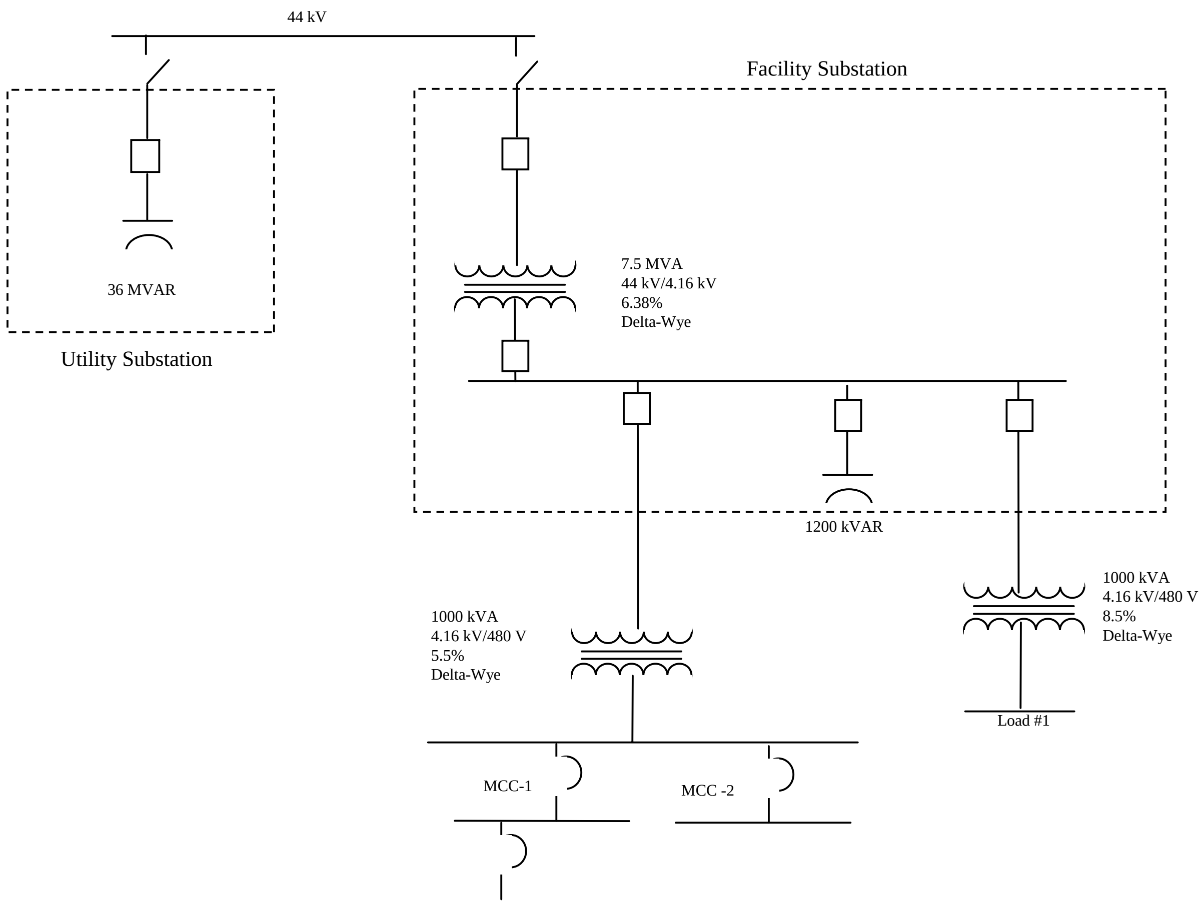
Capacitor Switching – Voltage Magnification

- Oscillatory transients approaching 2.0 p.u. will not generally cause insulation damage. Transients can be magnified if the conditions are right on the low voltage side to between 3.0 to 4.0 p.u.
- Voltage magnification can occur if the low side resonant frequency closely matches the switching frequency of the capacitor bank.

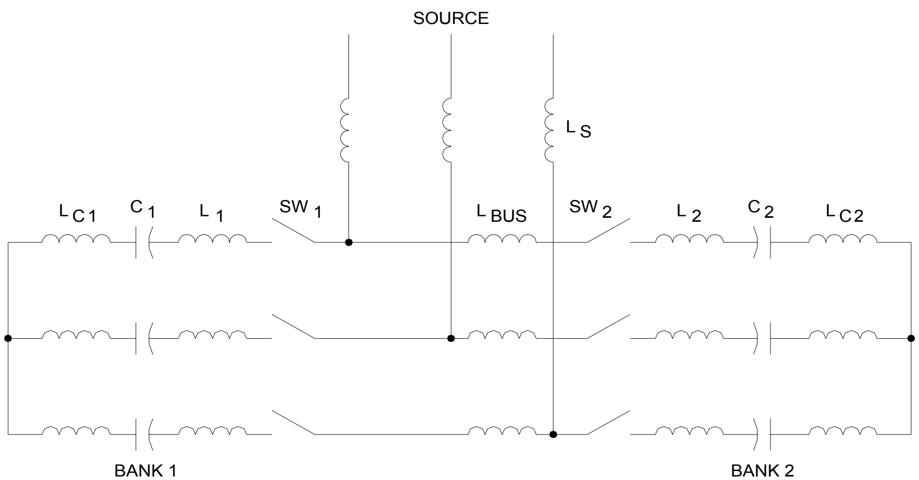
Capacitor Switching – Voltage Magnification

The following example shows the amplification of a voltage transient initiated by the switching of a 44 kV capacitor on the utility distribution system (see the simplified single-line diagram below). Unfortunately for this facility, the switching transient caused by the energization of the 36 MVAR bank was amplified at the 4160 V level when the 1200 kVAR capacitor was on-line and was also amplified at the 480 V bus when the 120 kVAR bank was on-line.



Capacitor Switching – Back-to-Back

The figure below was taken from the ANSI/IEEE C37.012 – 1979 Application Guide. This diagram is used to show the effect of back-to-back capacitor switching. Once the first bank is energized, a "sympathetic inrush" occurs and some of the energy required to initially charge the second bank comes from the first bank. If no intentional reactance (i.e. L1 and L2) is placed between the banks, very large transient overvoltages and transient currents will occur. The frequency of these transients is much higher than the typical single capacitor bank switching transient frequency.



Where,
Ls is the source reactance
LC1 and LC2 are the individual
L1 is L2 are the reactors betweer
Lbus is the reactance of the bus between the circuit breakers
Example:

Maximum recorded, single bank energization current during tests was 4,000A peak at 794Hz
Maximum recorded back-to-back switching peak current was 9,640A peak at 2940Hz

Capacitor Switching Transients

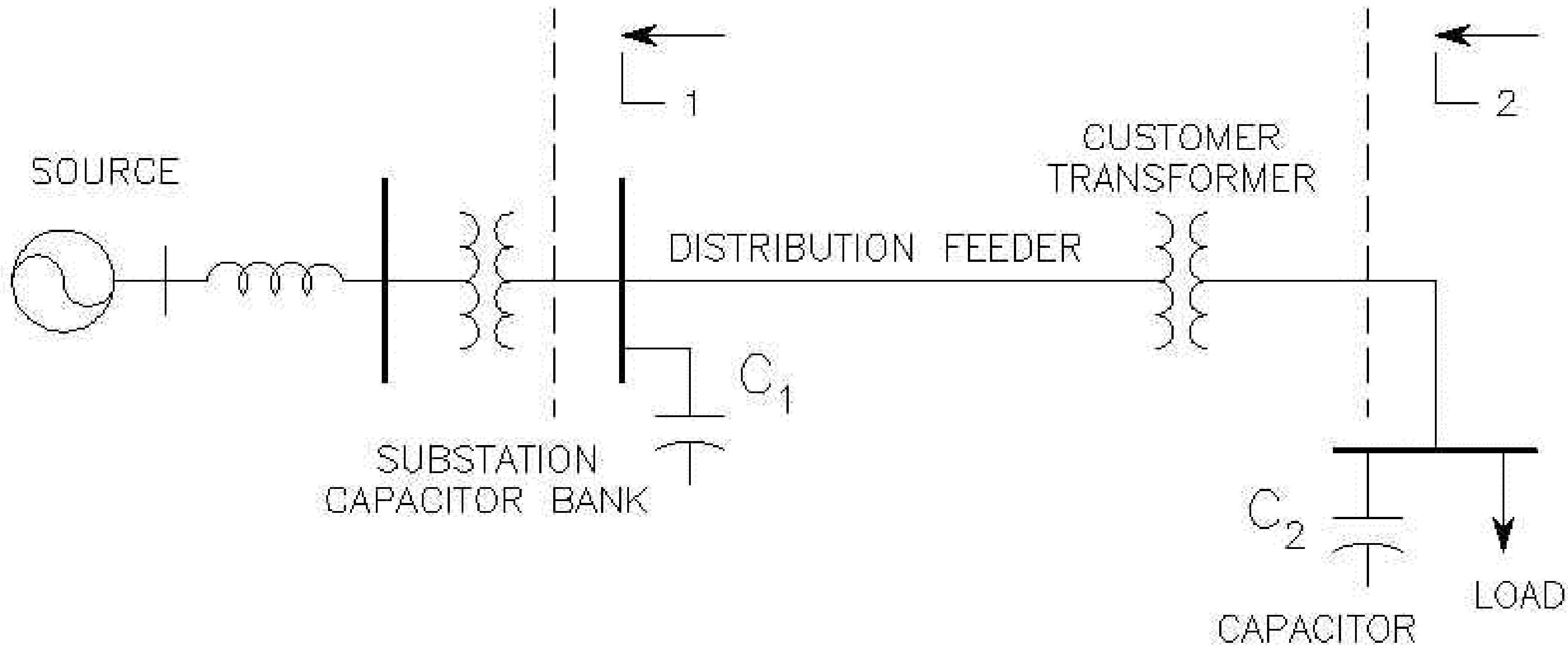


FIGURE 8. VOLTAGE MAGNIFICATION CIRCUIT

Capacitor Switching Transients

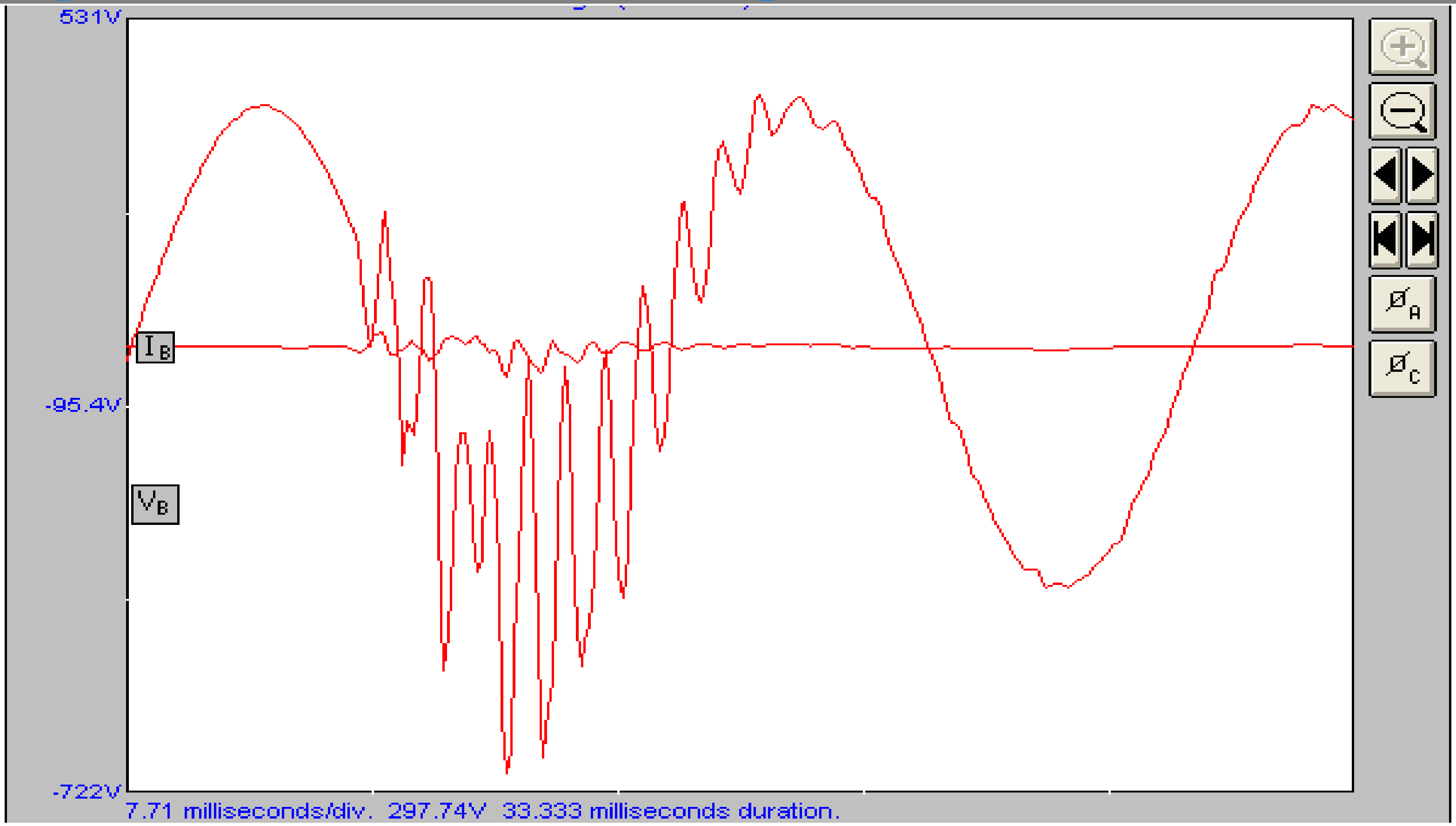


FIGURE 9. UTILITY CAPACITOR ENERGIZED WITH LV CAPACITOR ENERGIZED: VOLTAGE MAGNIFICATION AT 480 V BUS

Capacitor Switching Transients

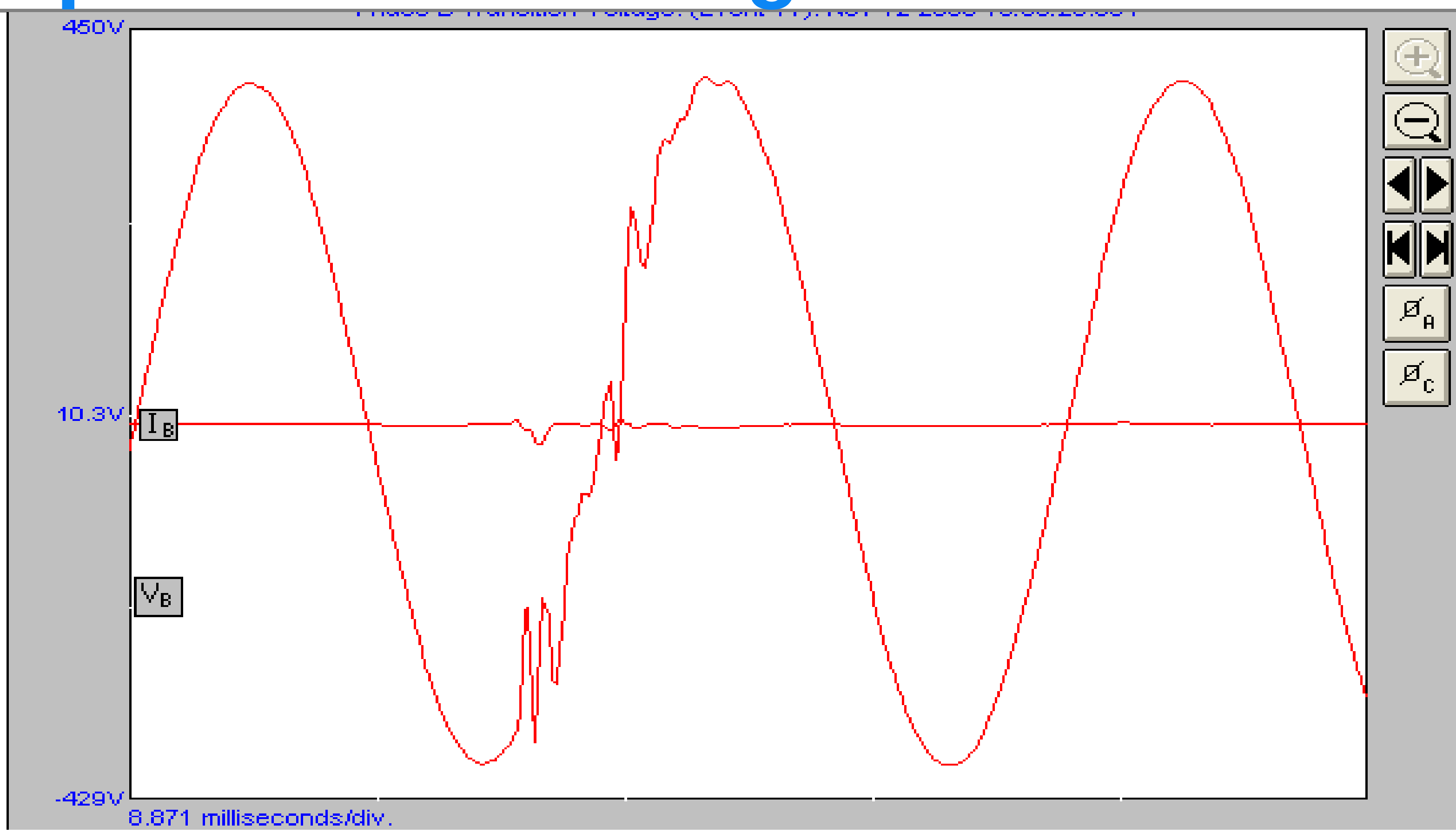
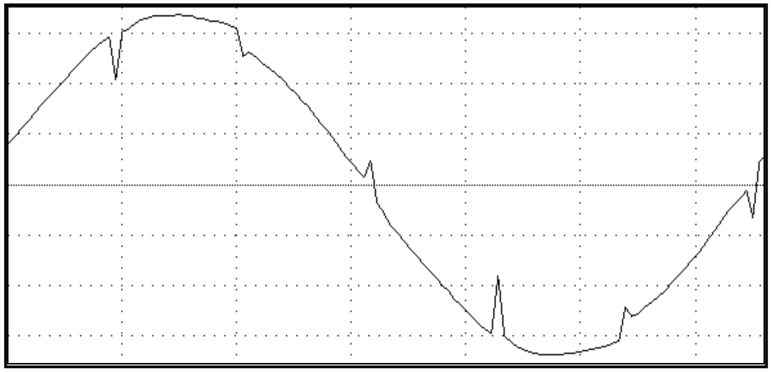


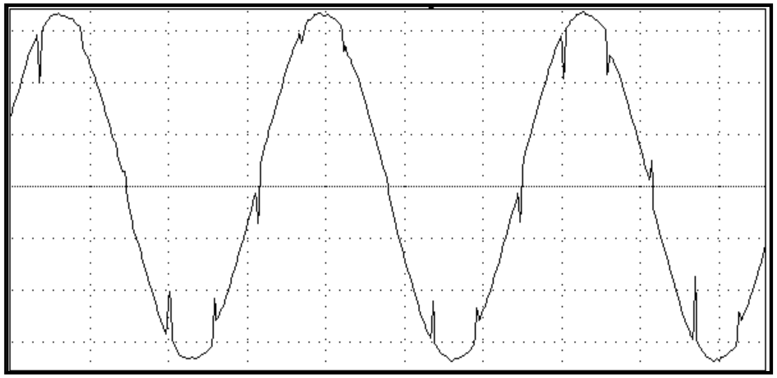
FIGURE 10. UTILITY CAPACITOR ENERGIZED WITHOUT LV CAPACITOR ENERGIZED: NO VOLTAGE MAGNIFICATION

Transients – Voltage Notching

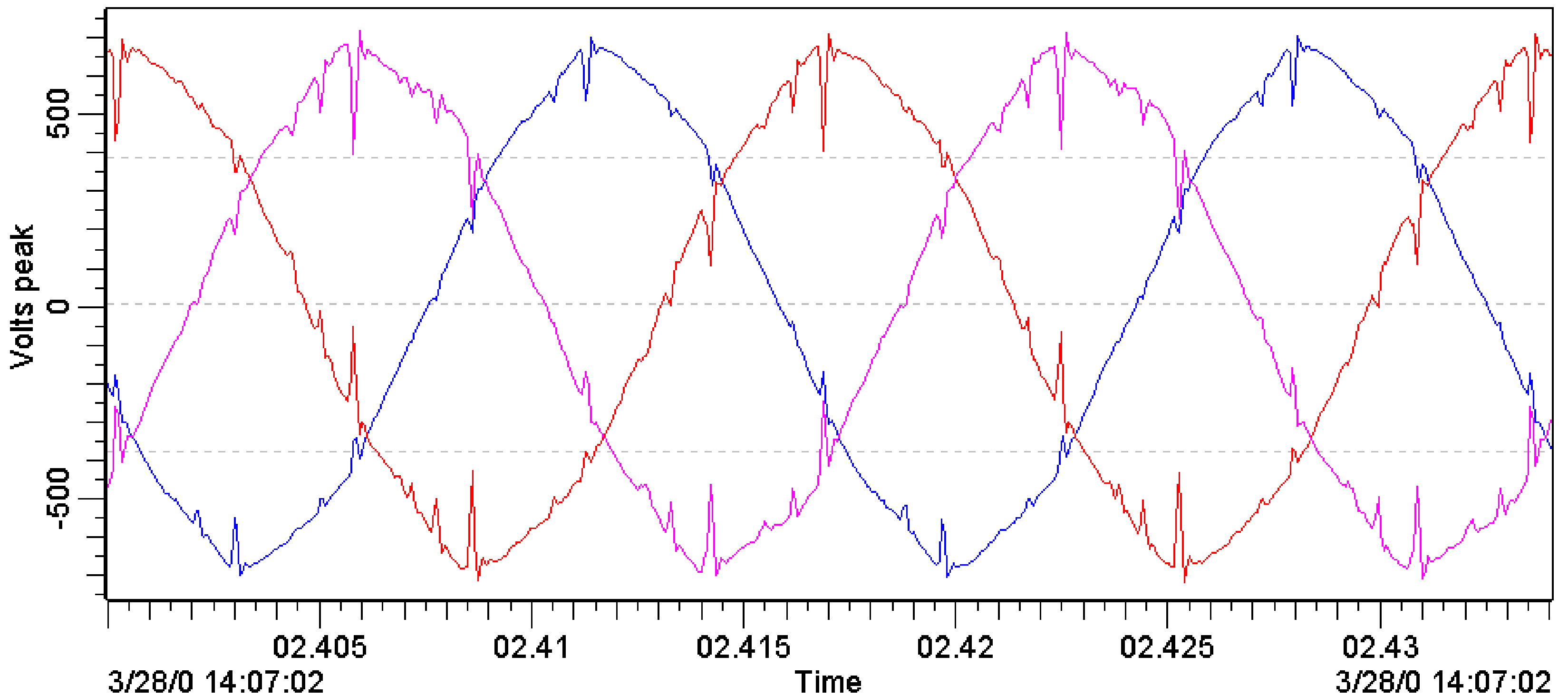
Notching - a switching (or other) periodic disturbance of the normal power voltage waveform, lasting less than a half-cycle. This disturbance is initially the opposite polarity of the normal waveform and is thus subtractive from the normal waveform in terms of the peak value of the disturbance voltage. A complete loss of voltage for up to a half-cycle is also considered notching.

The duration of the notch, called the commutation period, is determined by the source inductance to the drive and the current magnitude. Most of the source inductance is in the step-down or isolation transformer in front of the drive. If the notch depth is severe, inserting a series inductor in the ac supply circuit to the drive can reduce the depth of the notch. A typical inductance size is 3% based upon the drive rating.



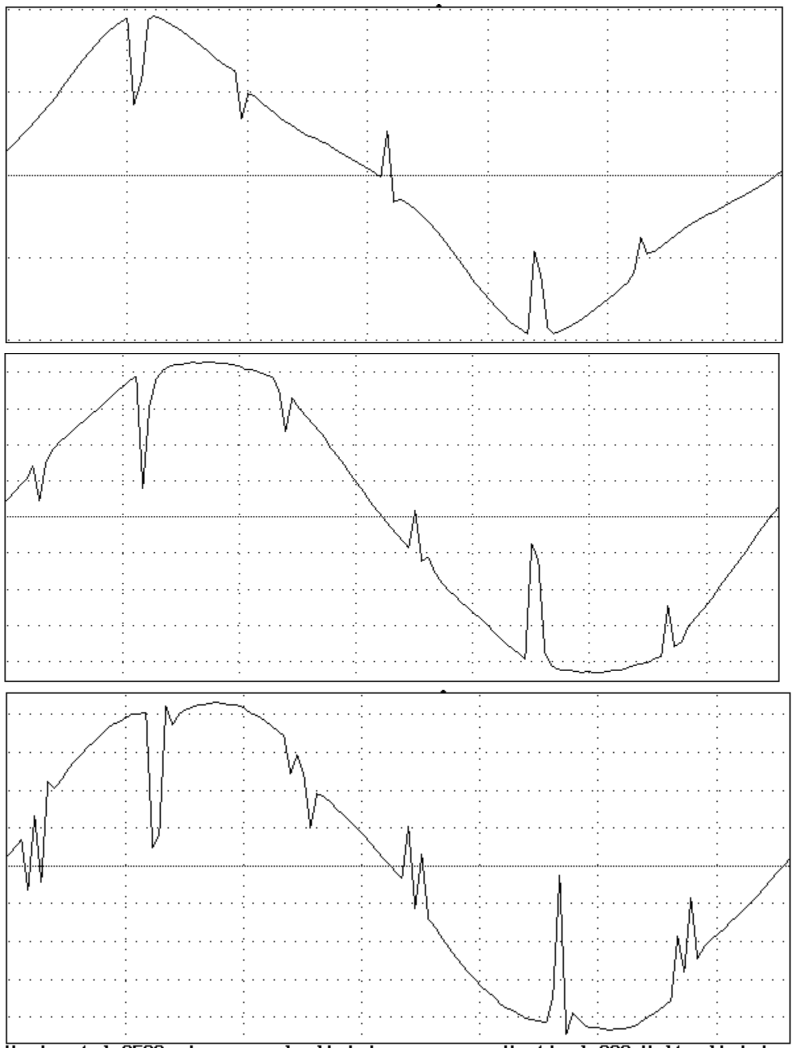


Severe Voltage Notching



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

Severe Voltage Notching

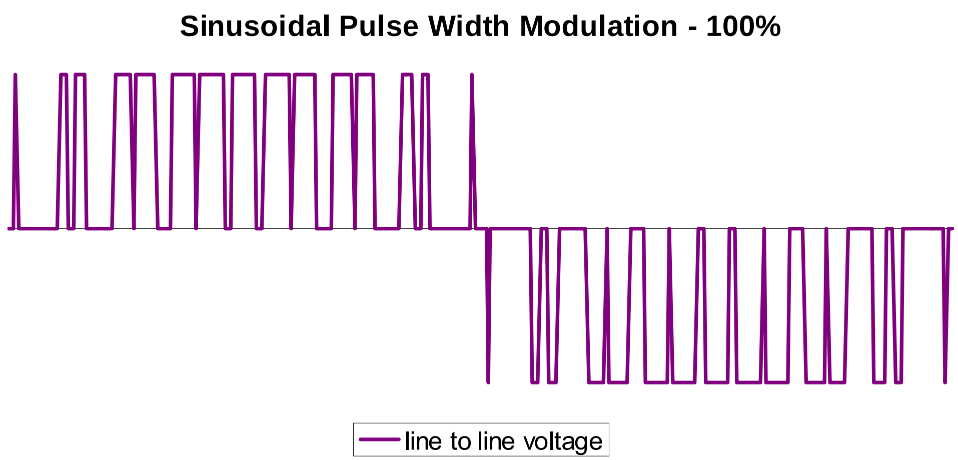


PWM Drives

Pulse Width Modulation (PWM) Drives

The output waveshape of the line-to-line voltage of a PWM drive is very dependent on the number of pulses per cycle. A typical waveshape is shown below for 15 pulses per cycle. Each pulse consists of a leading edge transient and a falling edge transient. These high frequency pulses may couple into communications cables and may "confuse" communication equipment because the coupled voltages appear as real signals on the communication lines.

THD	72%
1	100.0%
5	2.8%
7	1.1%
11	1.4%
13	27.2%
17	30.6%
19	4.3%
23	1.2%
25	2.4%
29	27.3%
31	22.3%
35	5.2%
37	3.6%
41	16.0%
43	9.6%
47	8.6%
49	13.9%



Surge Protection Demonstration

With Protection

Without Protection

ANY QUESTIONS?????

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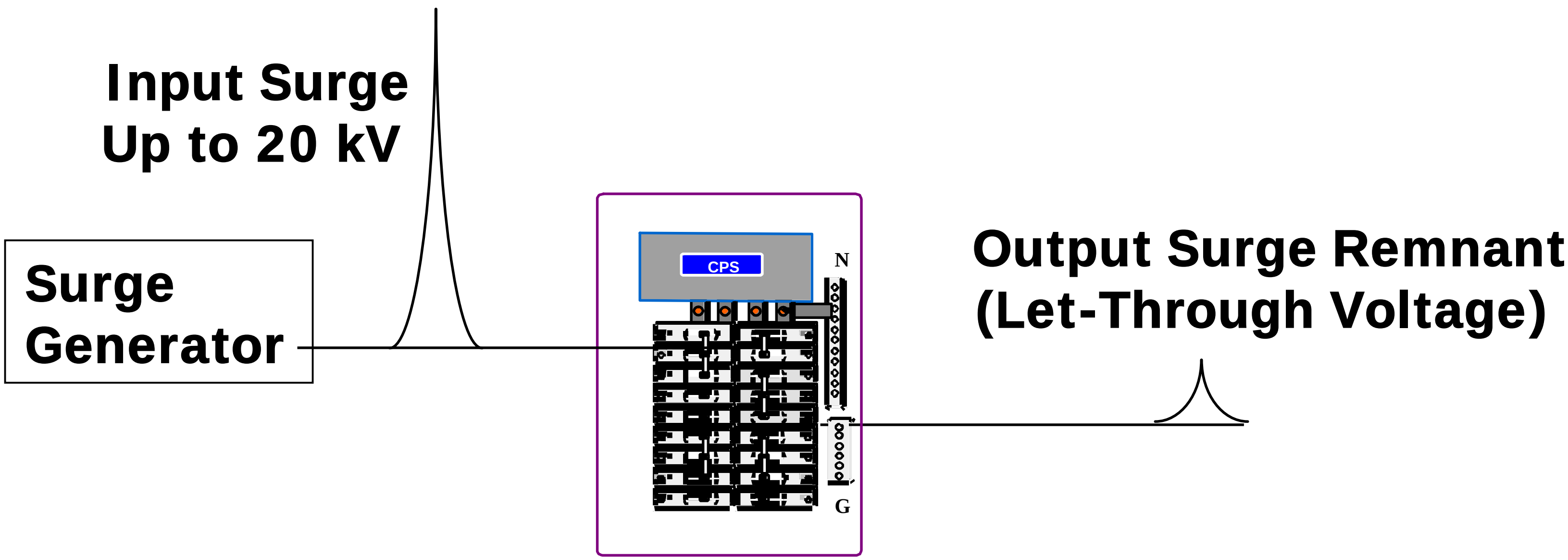
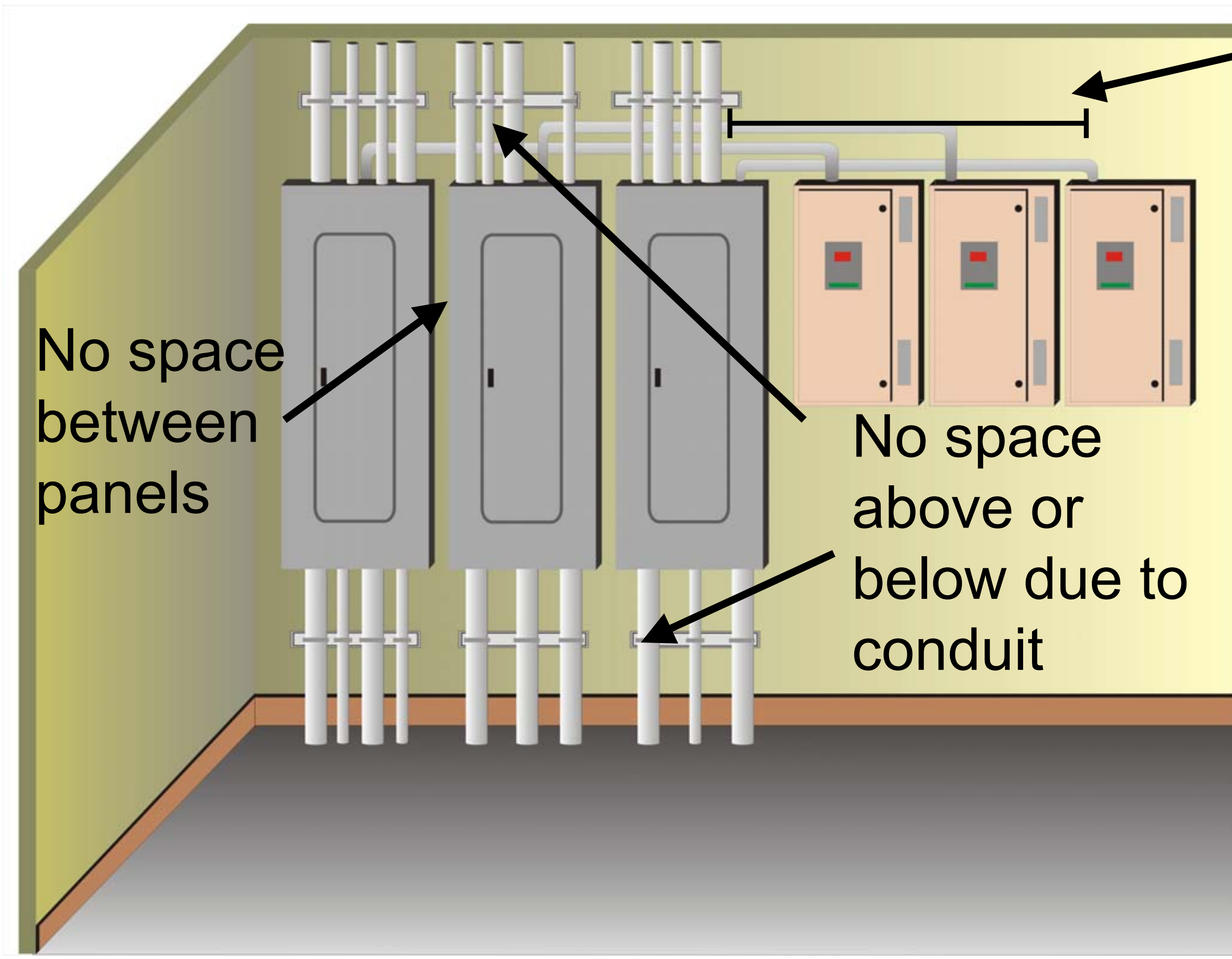
How Does a SPD Work?



SPD Reduces Voltage and Surge Current to protect downstream loads.

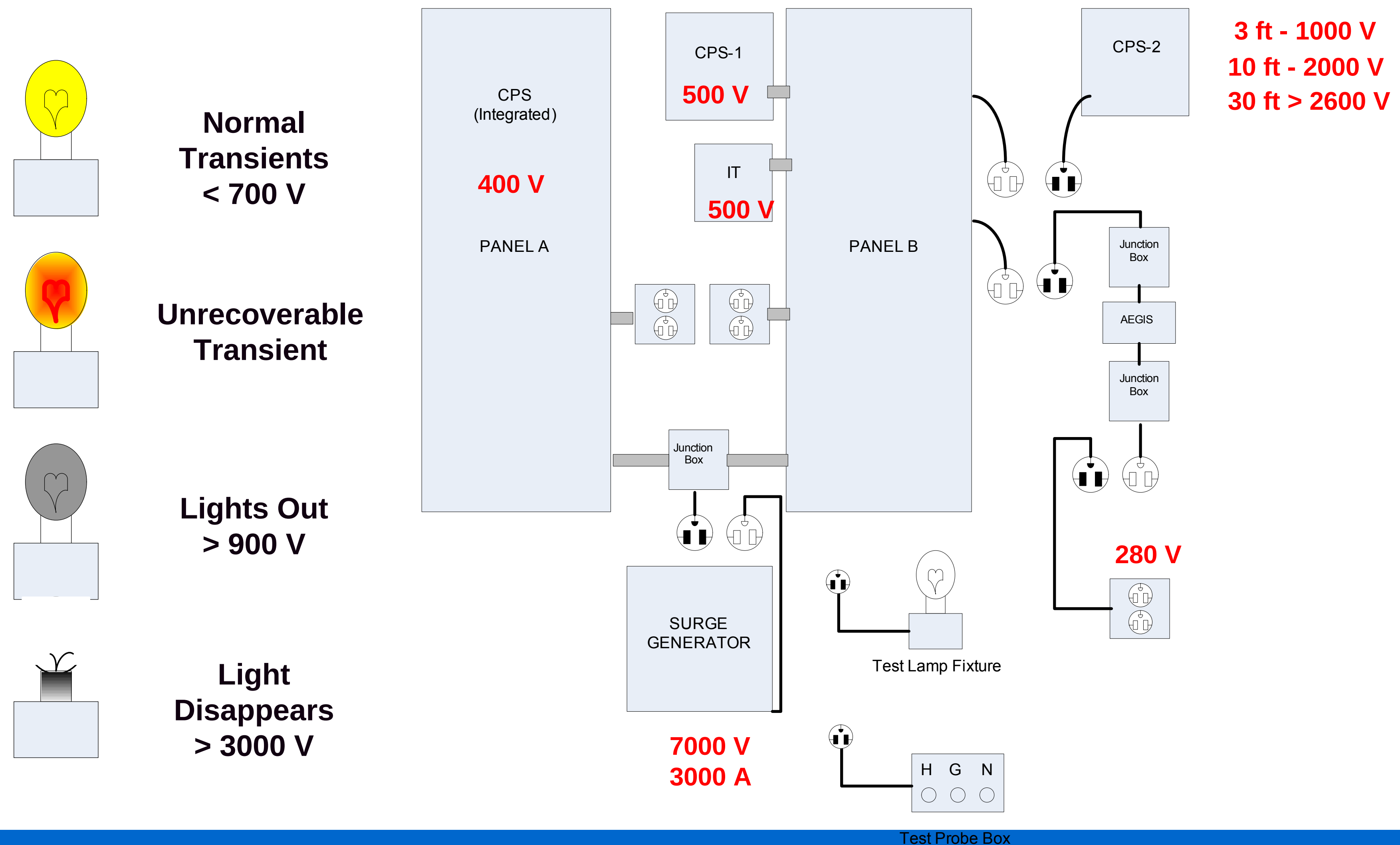
Side Mounted SPD's Can Not Be Mounted Next To Panel



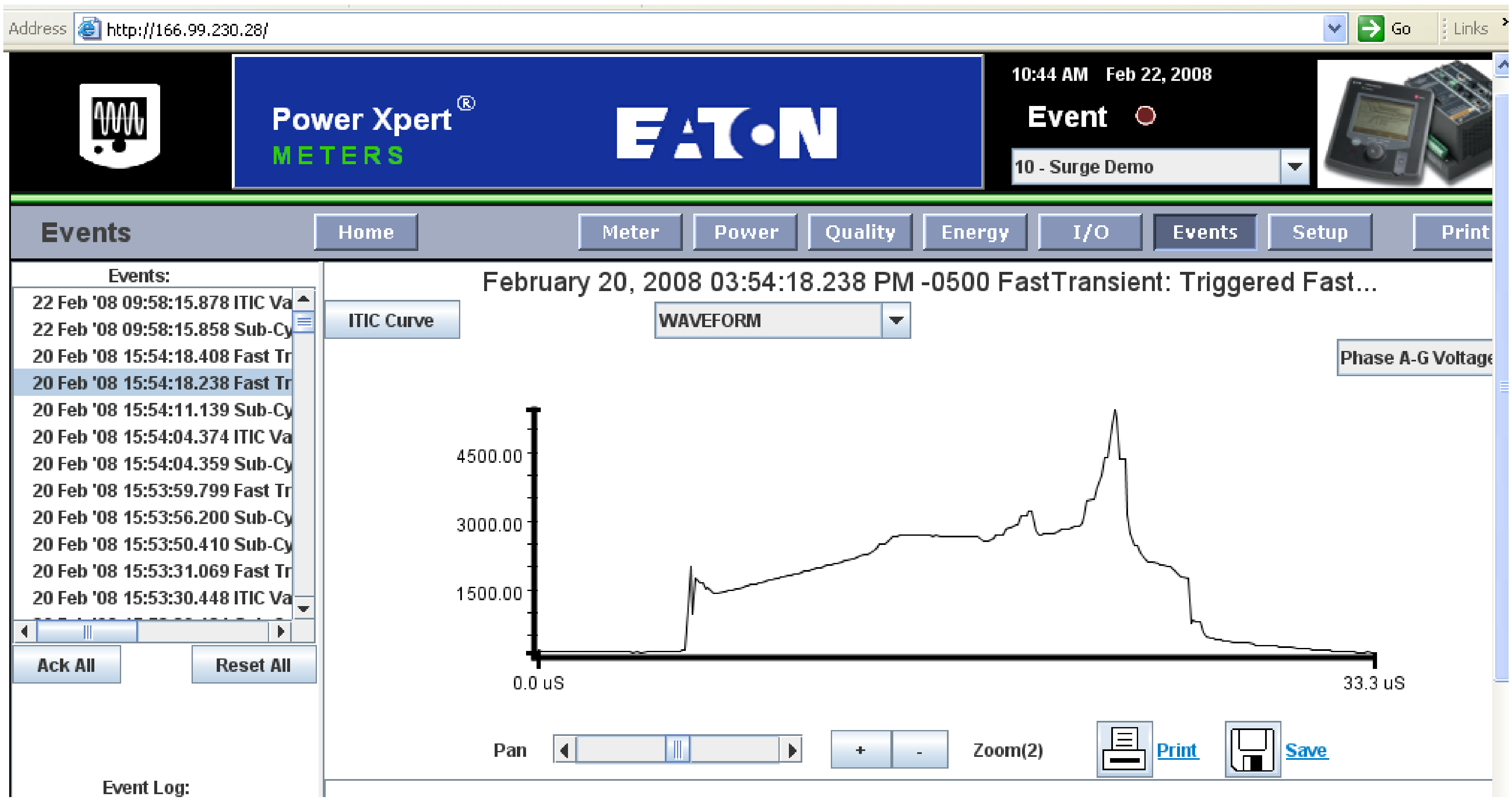
Lead length = 6 - 10 feet

Increased let-through voltage can be 100's of volts!

Surge Protection Demonstration

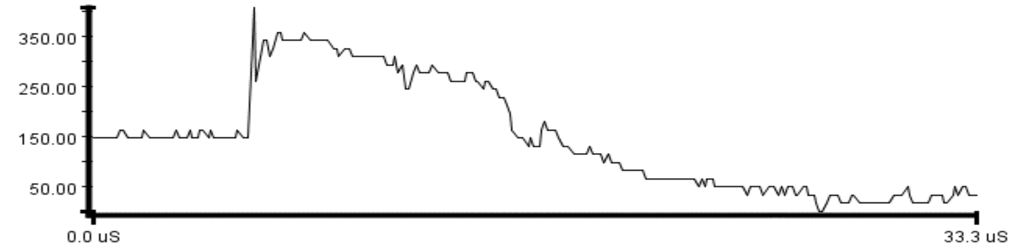


Surge Protection Demo – No Protection

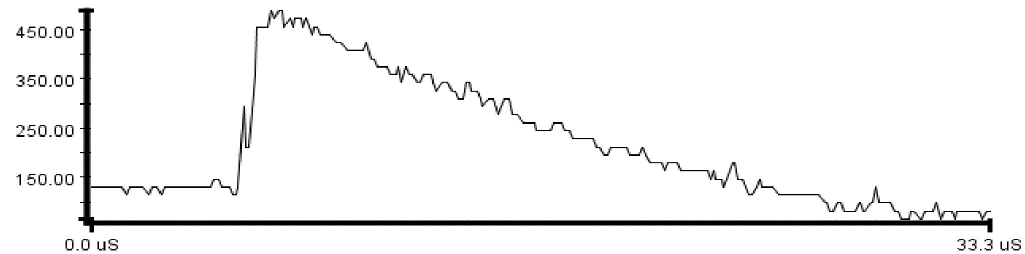


Surge Protection Demonstration

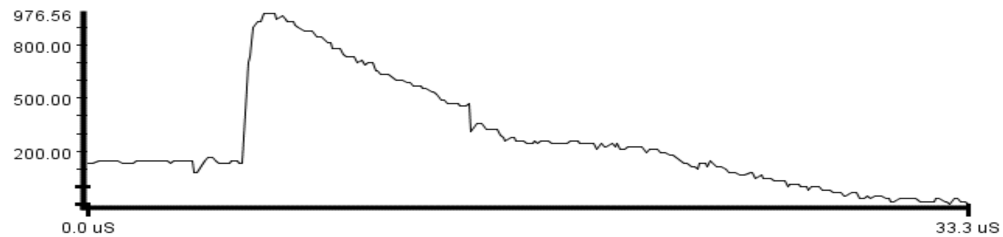
Integrated SPD
400 V Peak



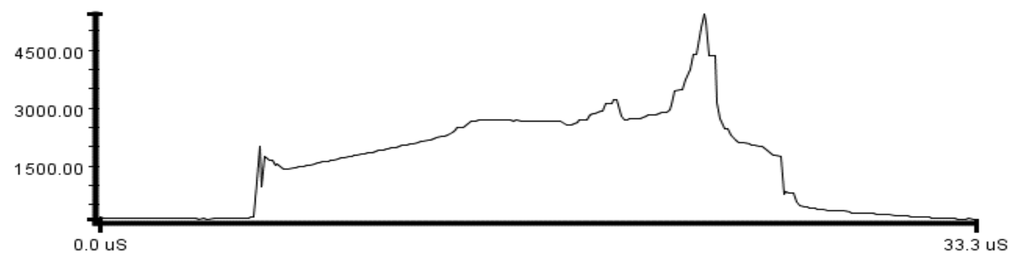
SPD w/12 inch lead length
500 V Peak



SPD w/36 inch lead length
1000 V Peak



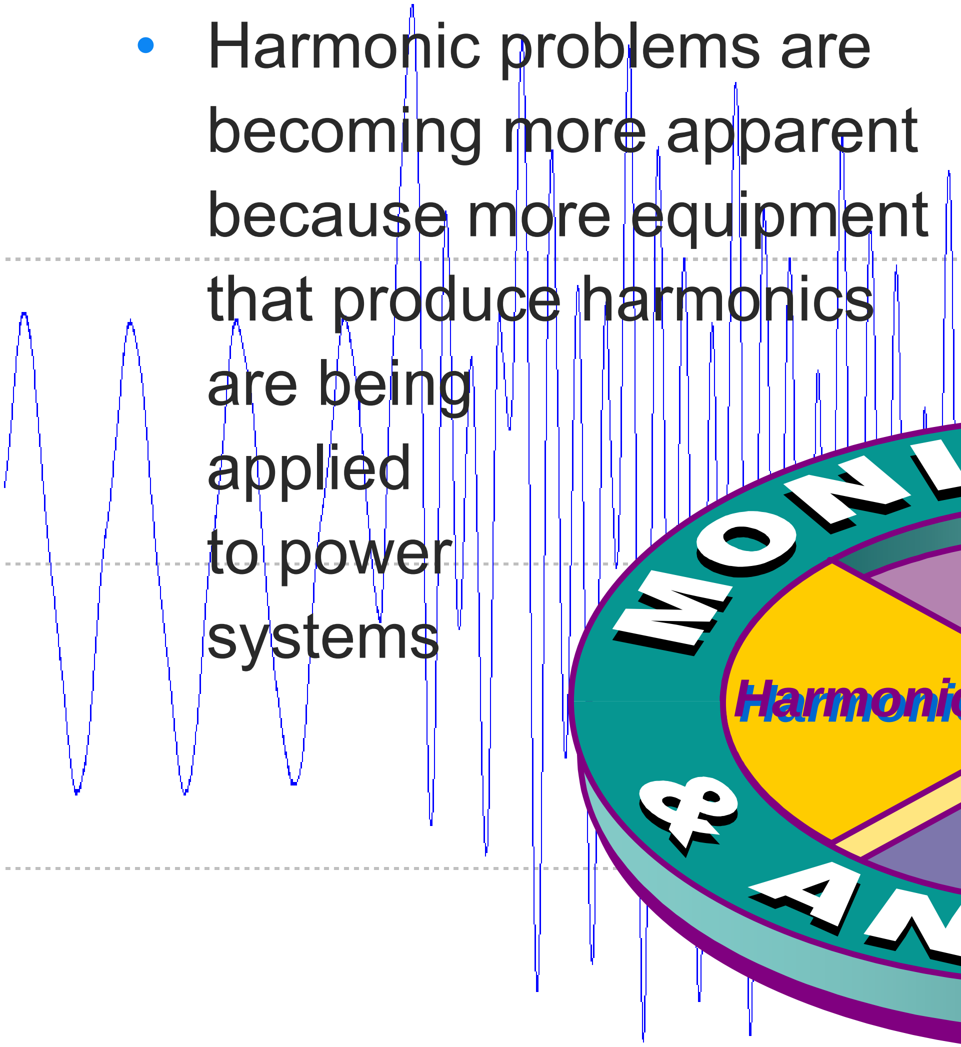
No protection

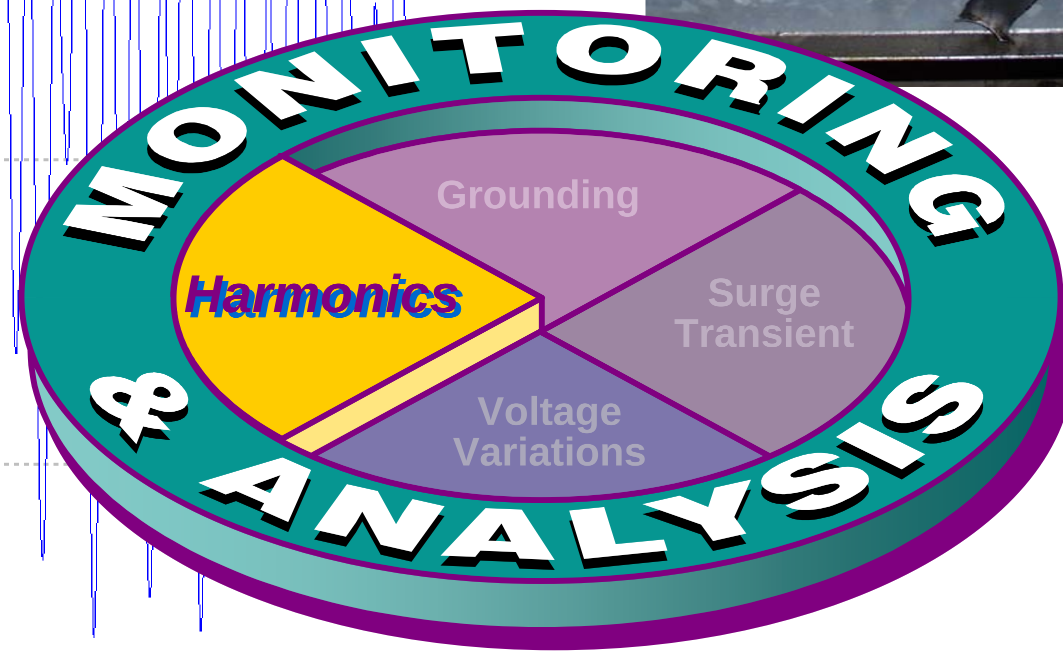


(Sampled at 6MHz)

Harmonic Distortion

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





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Specific Conditions to Consider

- Power factor correction capacitors
- Harmonic filter that may be out of service
- Shunt capacitors on the utility supply
- Alternate sources from the utility or a utility transformer out of service
- Different load combinations
- Nearby facilities with significant harmonic generation
- Monitor long enough to cover one complete “business” cycle

Which came first?.....

Voltage Distortion **Current Distortion**

- In this case…the Egg!
  - **Current distortion causes Voltage distortion**
  - **Voltage distortion is created by pulling <u>distorted current</u> through an impedance**
  - **Amount of voltage distortion depends on:**
    - **System impedance**
    - **Amount of distorted current pulled through the impedance**
    - **If either increases, V_{THD} will increase**

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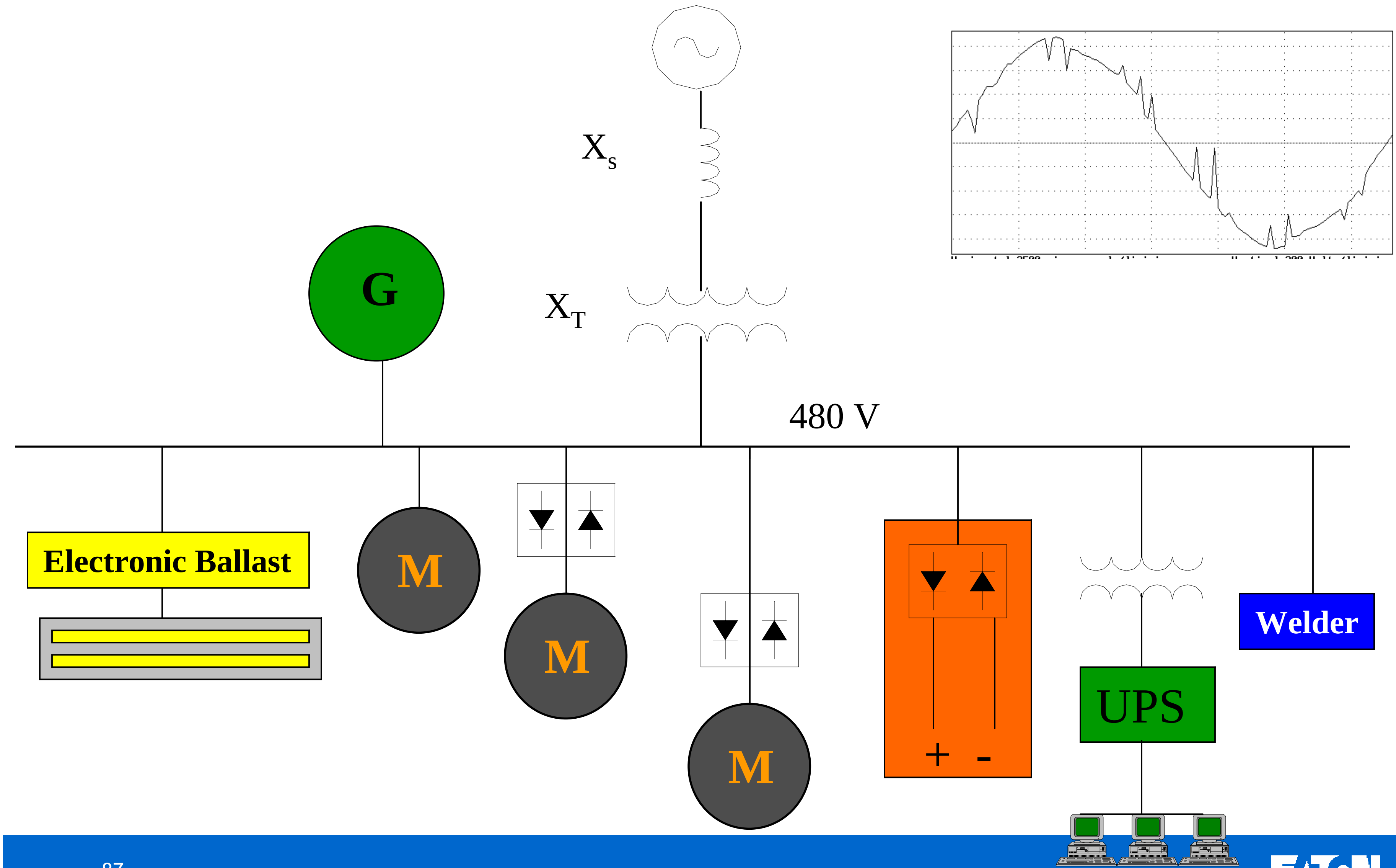
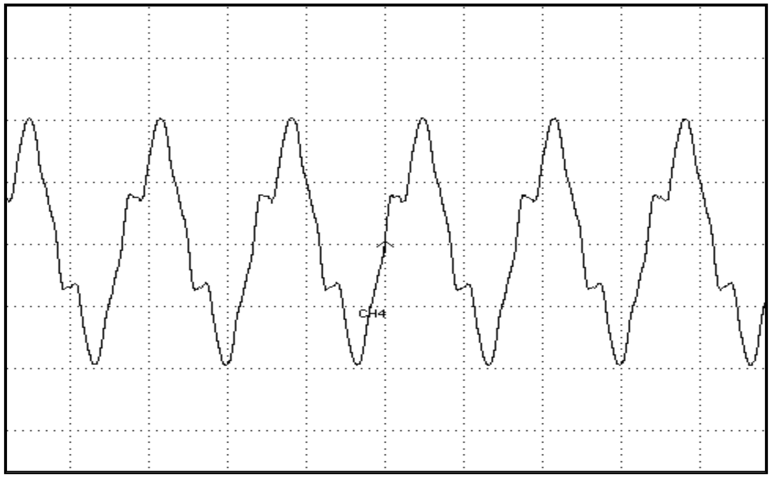
Harmonics Today

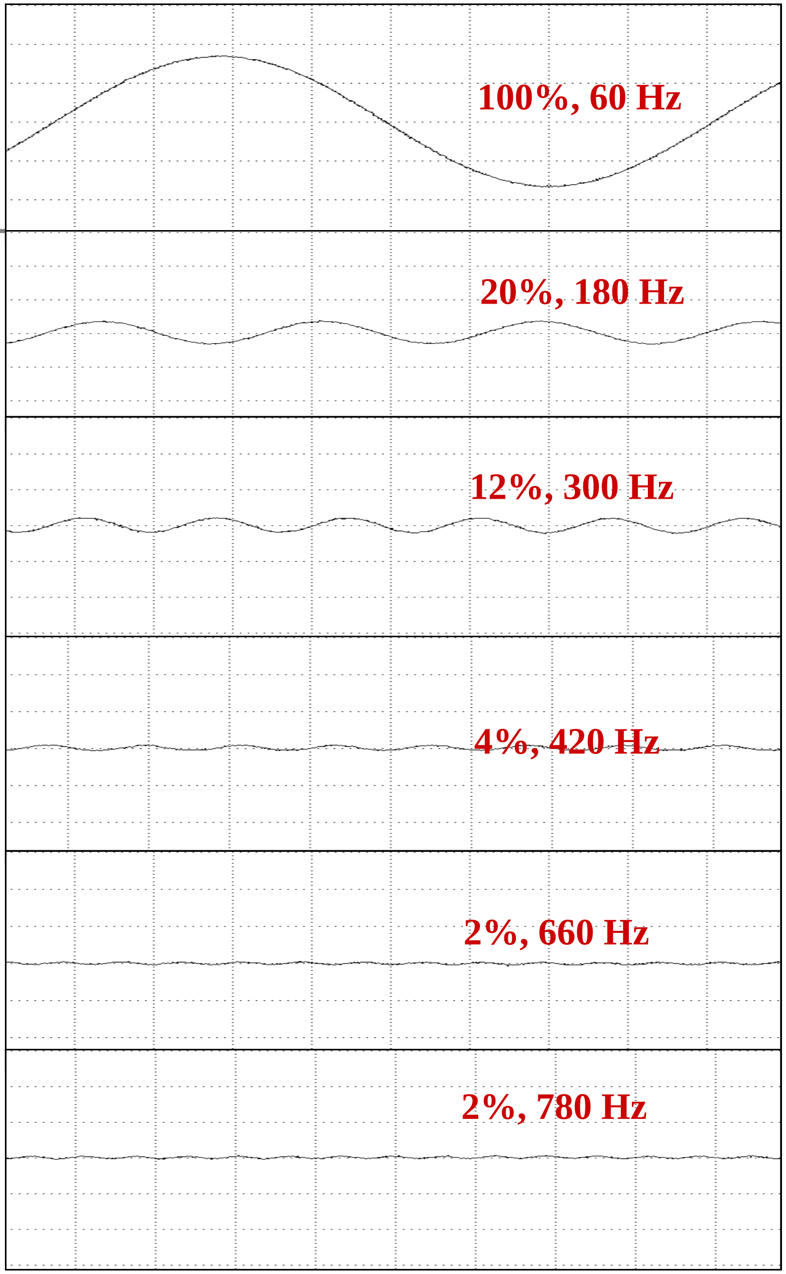


Harmonics

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

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





Expected Harmonics

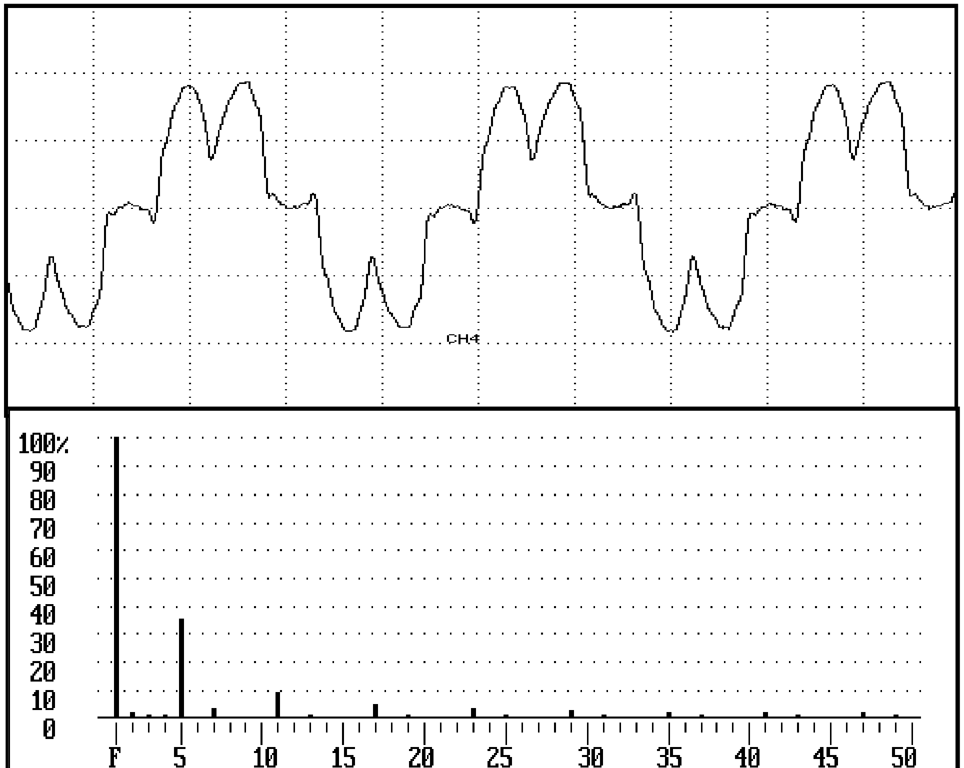
Source	Typical Harmonics*
6 Pulse Drive/Rectifier	5, 7, 11, 13, 17, 19…
12 Pulse Drive/Rectifier	11, 13, 23, 25…
18 Pulse Drive	17, 19, 35, 37…
Switch-Mode Power Supply	3, 5, 7, 9, 11, 13…
Fluorescent Lights	3, 5, 7, 9, 11, 13…
Arcing Devices	2, 3, 4, 5, 7...
Transformer Energization	2, 3, 4

* Generally, magnitude decreases as harmonic order increases

H = NP+/-1

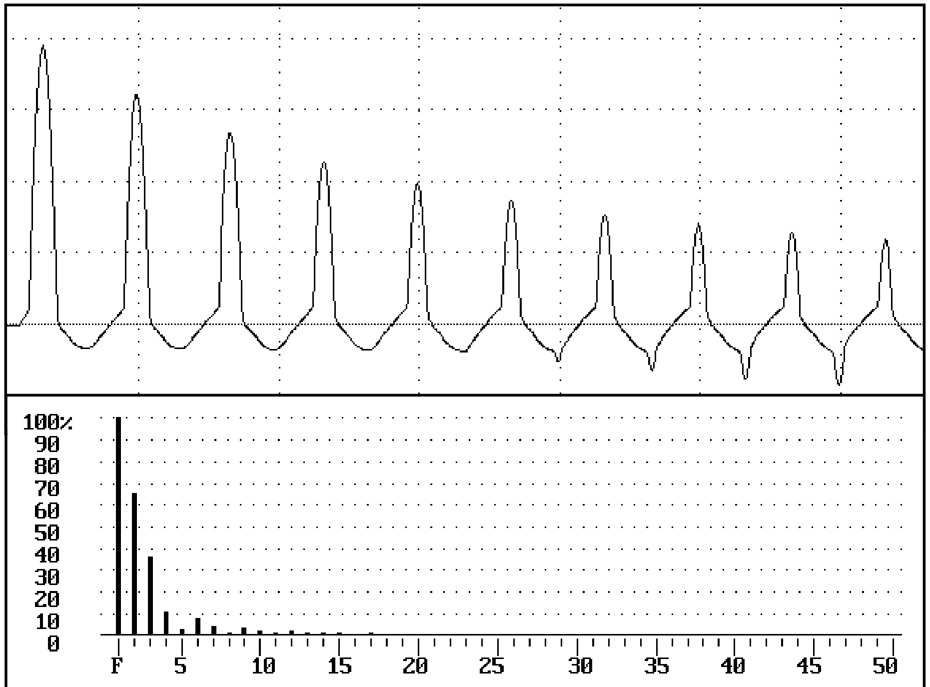
i.e. 6 Pulse Drive - 5, 7, 11, 13, 17, 19,…

Harmonic Sources – VFDs



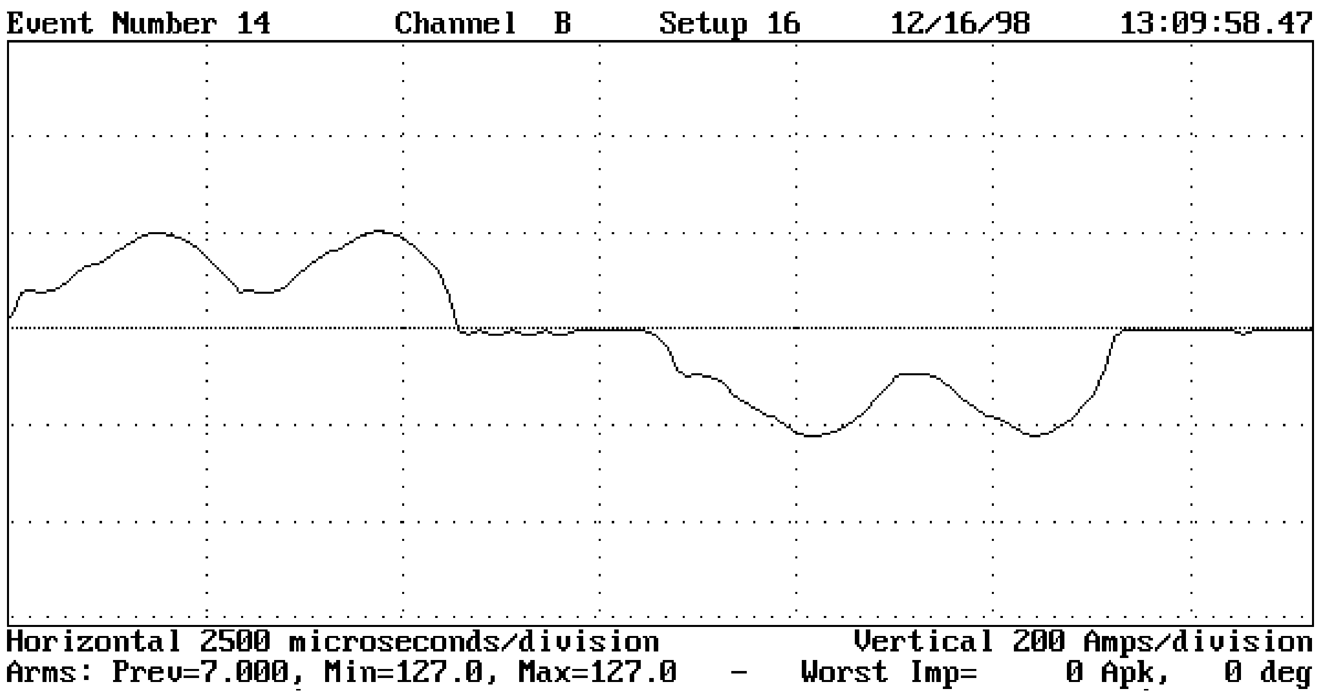
Fnd:	212.30A	291	deg	18th:	0.2%	298	deg	35th:	1.9%	75	deg
2nd:	2.1%	31	deg	19th:	1.2%	222	deg	36th:	0.2%	250	deg
3rd:	1.0%	73	deg	20th:	0.3%	327	deg	37th:	1.1%	137	deg
4th:	1.1%	118	deg	21st:	0.1%	8	deg	38th:	0.2%	266	deg
5th:	35.6%	208	deg	22nd:	0.1%	30	deg	39th:	0.2%	278	deg
6th:	0.4%	313	deg	23rd: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

Harmonic Sources – Transformer Inrush



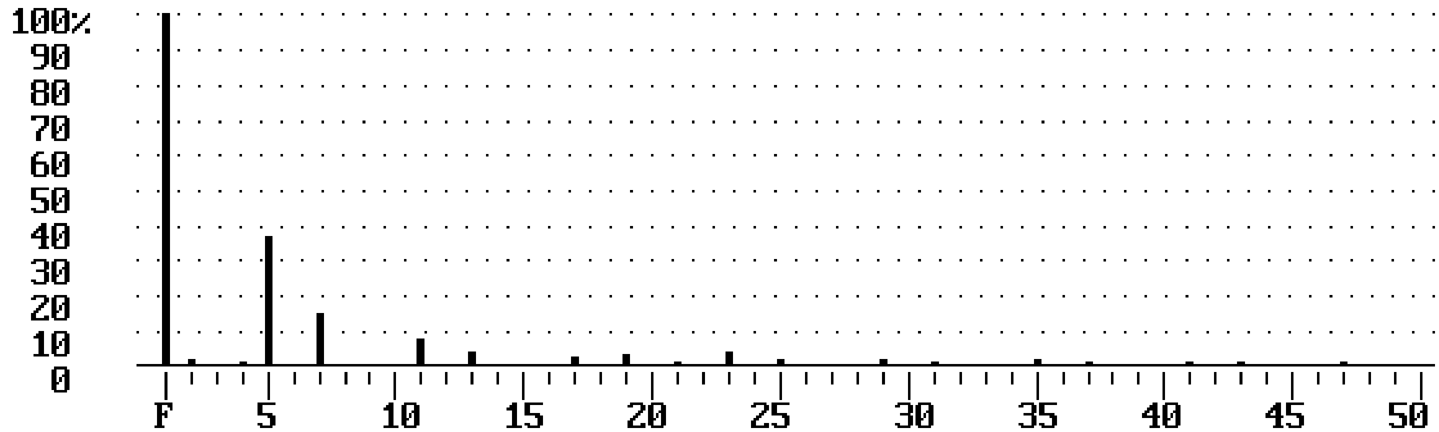
Fnd:	224.13A	165 deg	18th:	0.5%	39 deg	35th:	0.1%	66 deg
2nd:	65.4%	342 deg	19th:	0.6%	149 deg	36th:	0.3%	31 deg
3rd:	36.4%	144 deg	20th:	0.6%	9 deg	37th:	0.2%	37 deg
4th:	10.3%	325 deg	21st:	0.4%	48 deg	38th:	0.1%	53 deg
5th:	2.4%	330 deg	22nd:	0.5%	112 deg	39th:	0.2%	18 deg
6th:	7.9%	113 deg	23rd: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

Waveform Display



Harmonic Spectrum

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



HARMONIC NUMBER:	50	5th:	36.7%	Phase: 155 degrees
TOTAL HARMONIC DISTORTION:	41.2%	7th:	15.1%	Phase: 342 degrees
ODD CONTRIBUTION:	41.2%	11th:	7.9%	Phase: 127 degrees
EVEN CONTRIBUTION:	2.2%	13th:	3.9%	Phase: 16 degrees

Horizontal: Harmonic Number Vertical: % of Fundamental

Frequency: 60.0 Hz

Text and Phase Angle

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

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

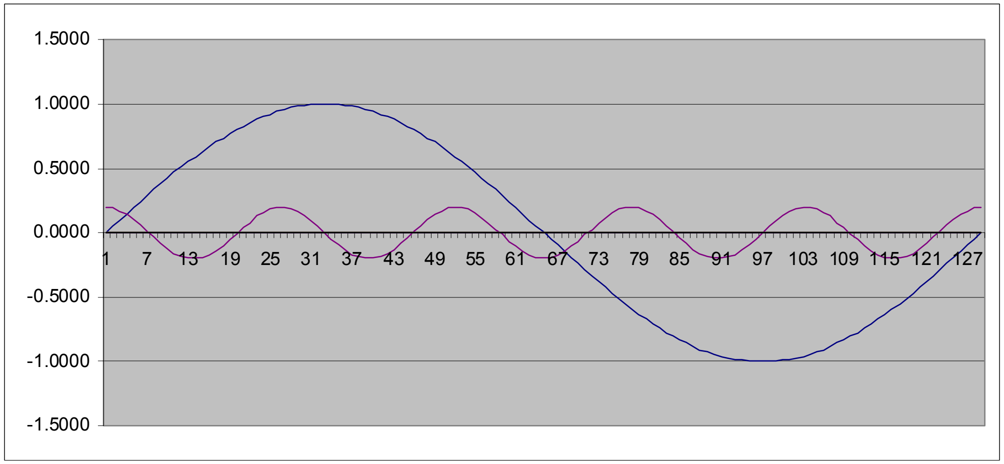
T.H.D.: 41.2% ODD CONTRIB.: 41.2% EVEN CONTRIB.: 2.2%

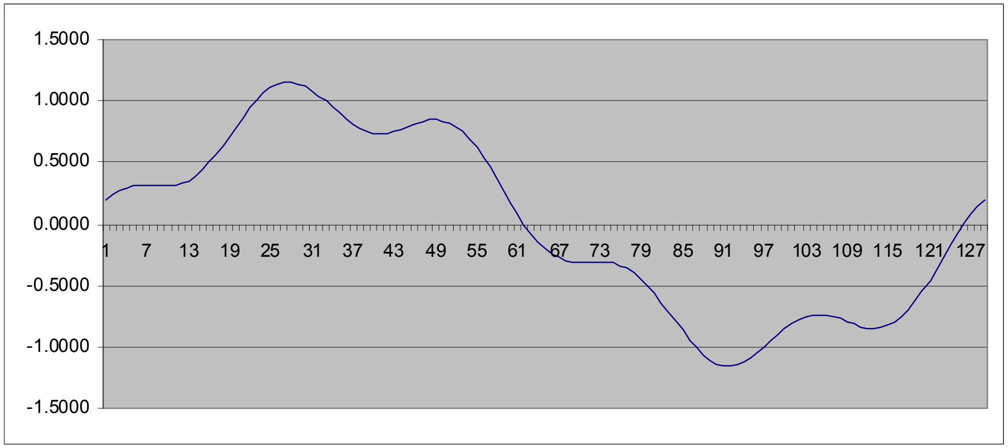
Frequency: 60.0 Hz

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

Phase Angle

20% 5th harmonic at 90 degrees

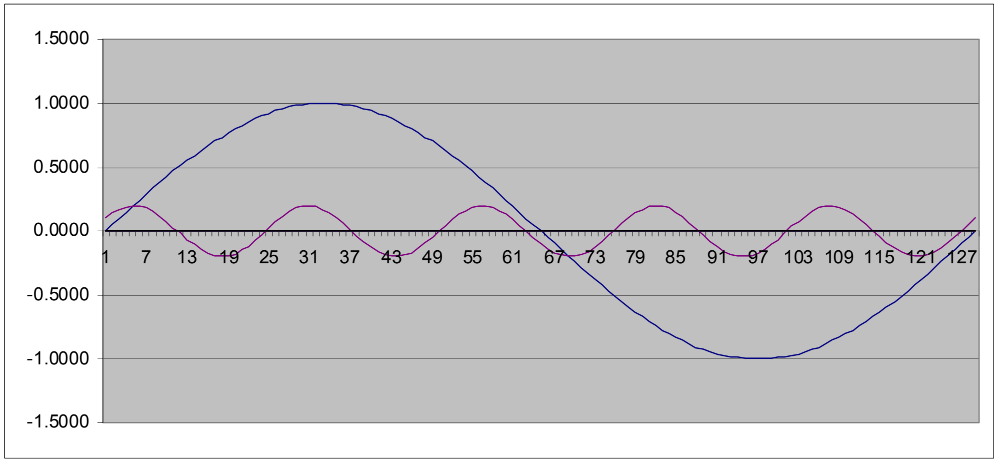


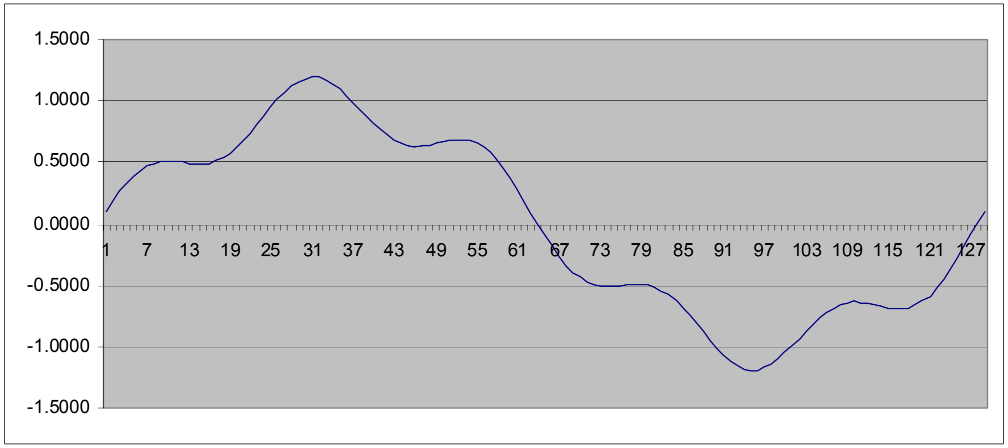


Phase Angle

20% 5th harmonic at 30 degrees

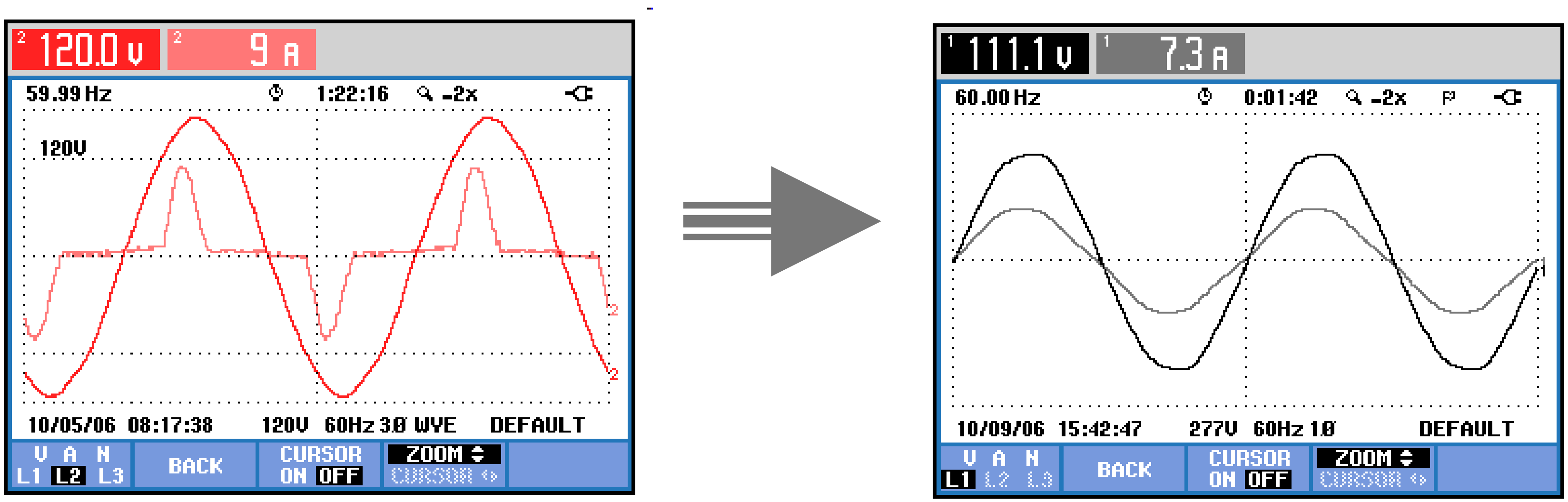
Phase Angle is very important if you plan to model the harmonic loads.





Harmonics – Who Cares!

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



Industry driven toward component (load) solutions

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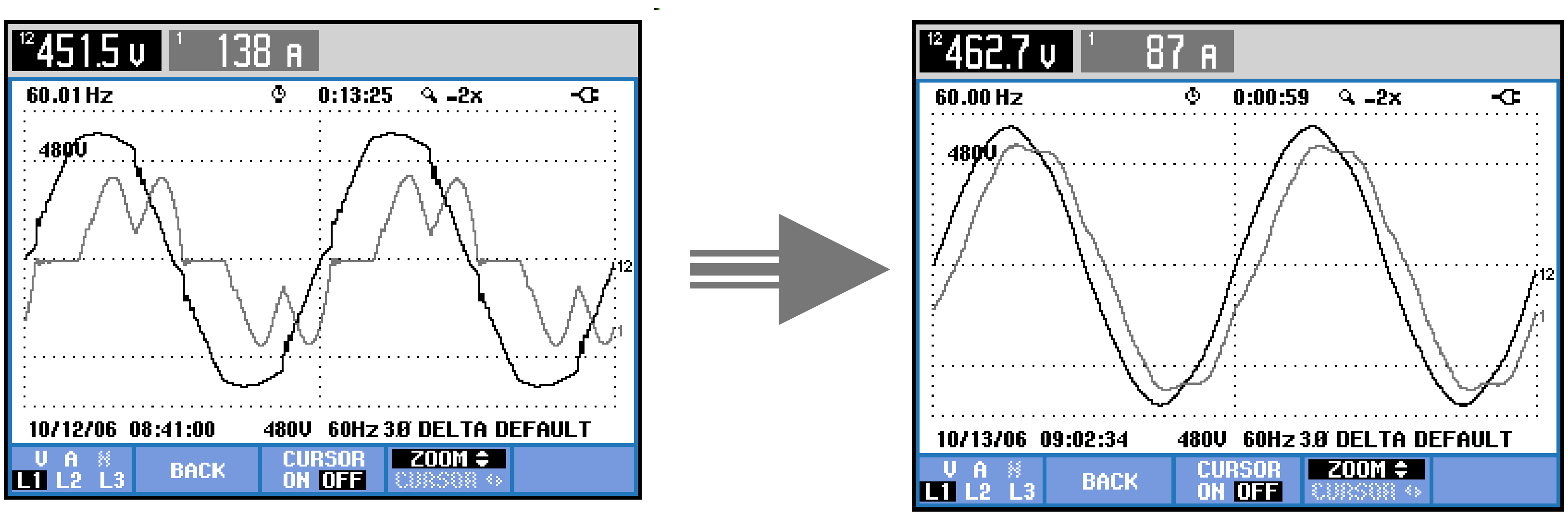
Harmonics – Who Cares!

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

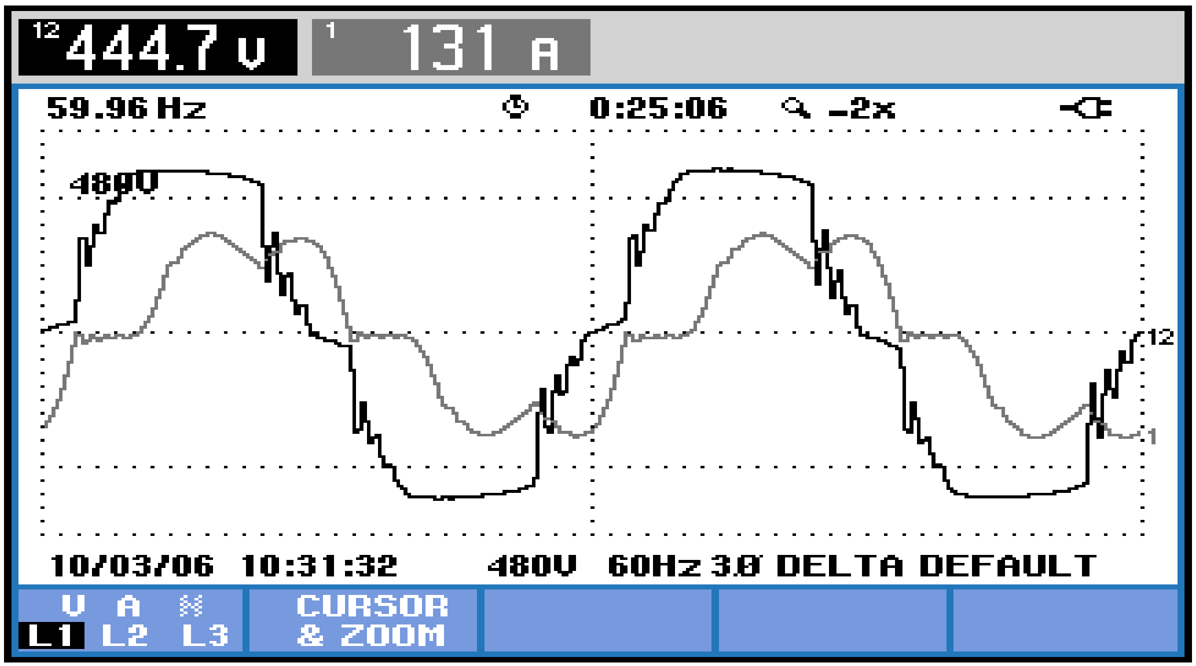


Industry driven toward component (load) solutions

Harmonics – Who Cares!

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

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



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Harmonics – Case Studies

Case Studies

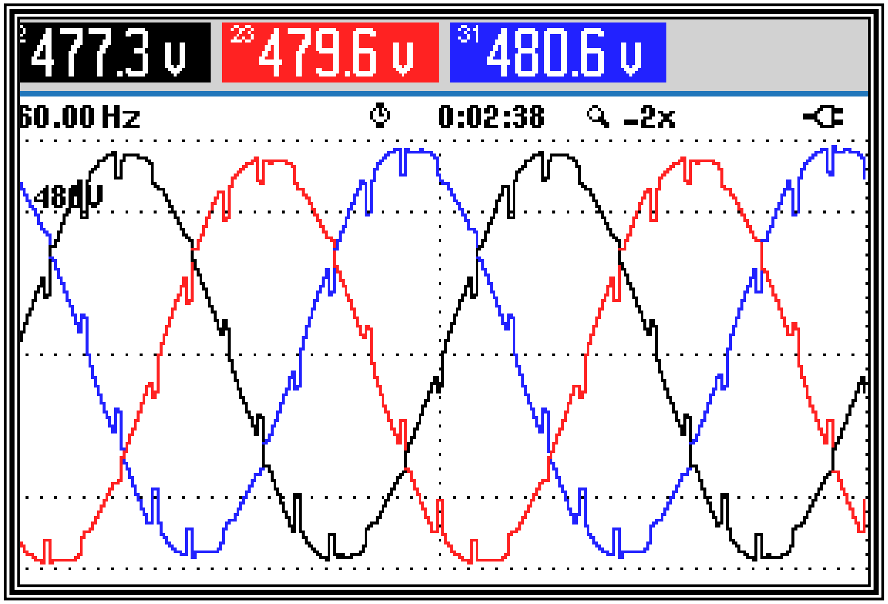
- Case 1 – Generator Sync Failure
- Case 2 – Transfer Switch Frequency Sync Check Failure
- Case 3 – Small Single-Phase Examples
- Case 4 – Ferroresonance Example
- Case 5 – UPS Filter Parallel Resonance

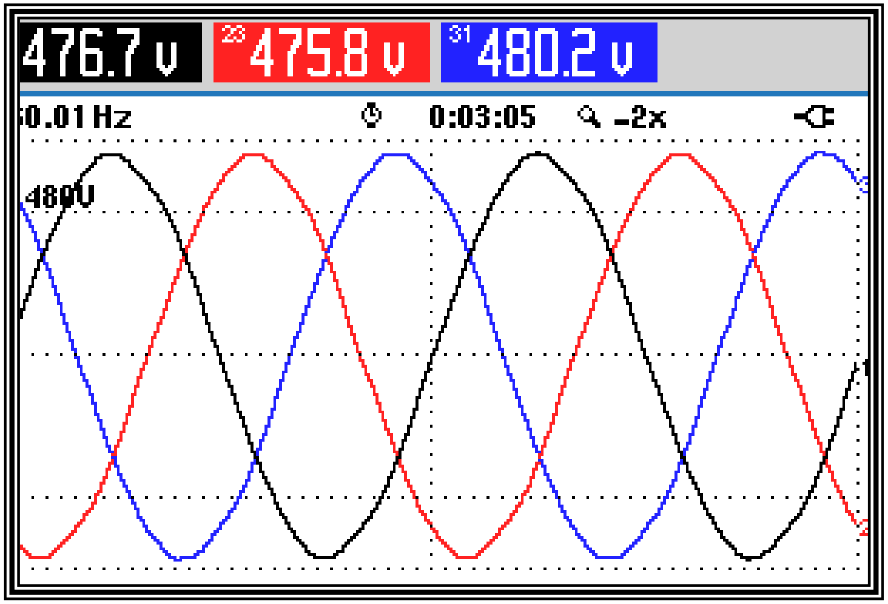
Harmonics – Case Studies

Case 1 – Generator Sync Failure

- Generator 1 (Loaded)

Generator 2 (Unloaded)





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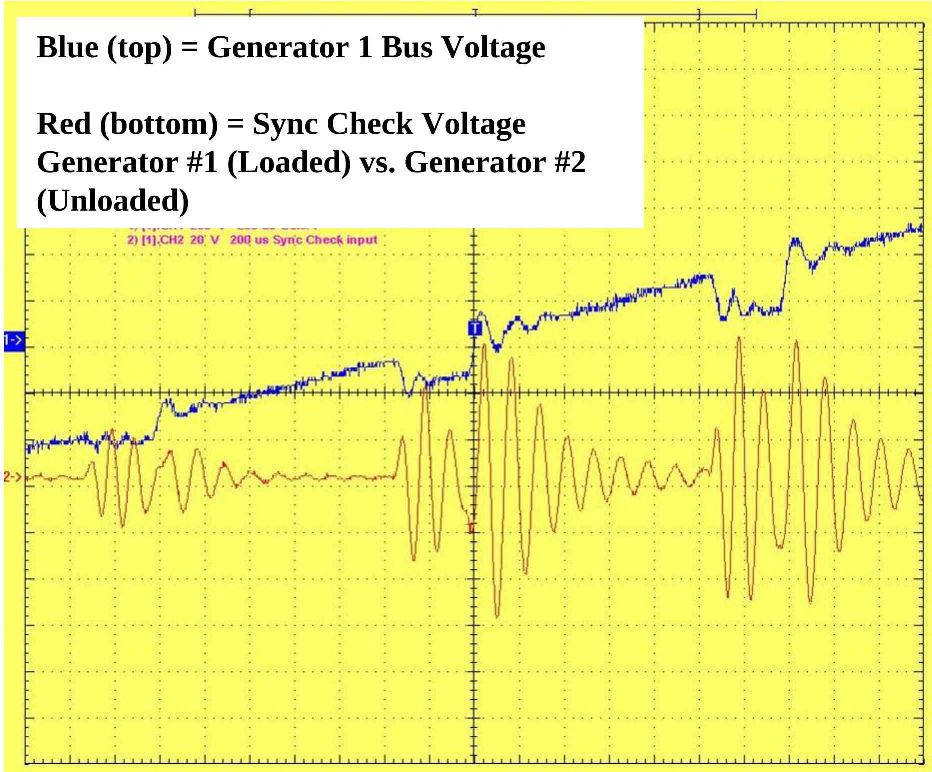
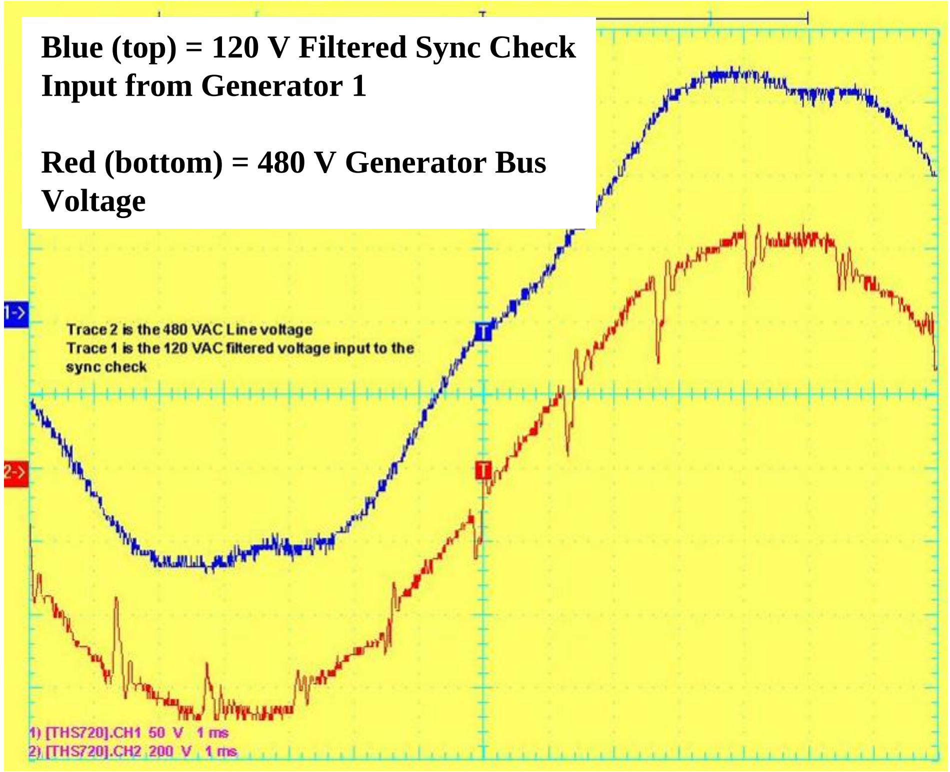
Harmonics – Case Studies

Case 1 – Generator Sync Failure





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Harmonics and Generators – Case 2

- Generator Filter – UPS Filter On/Off

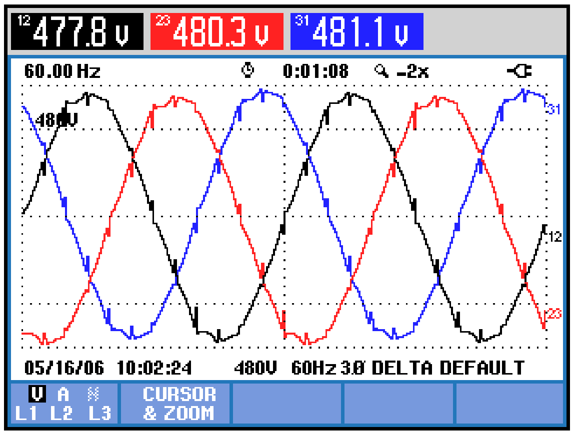
Utility Source

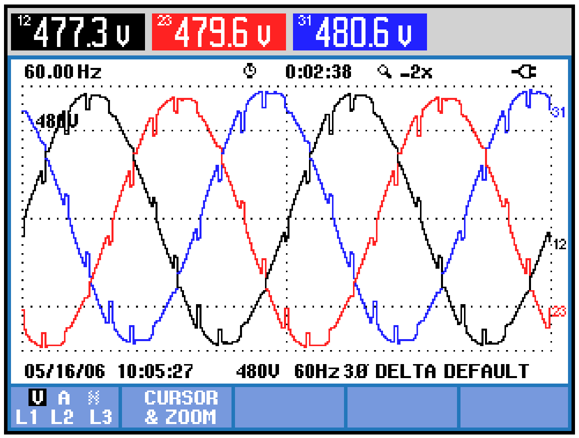
Harmonic Filter ON

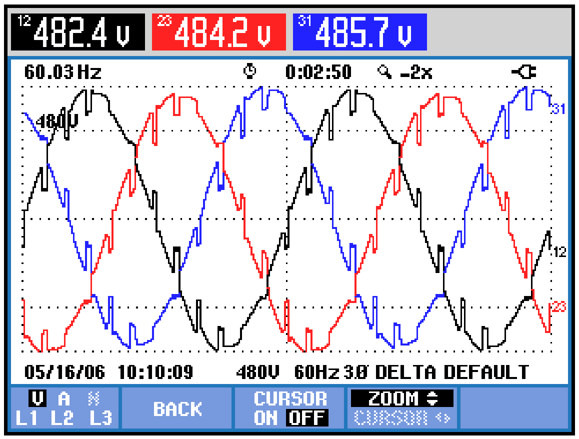
Generator Source

Harmonic Filter ON

Harmonic Filter OFF

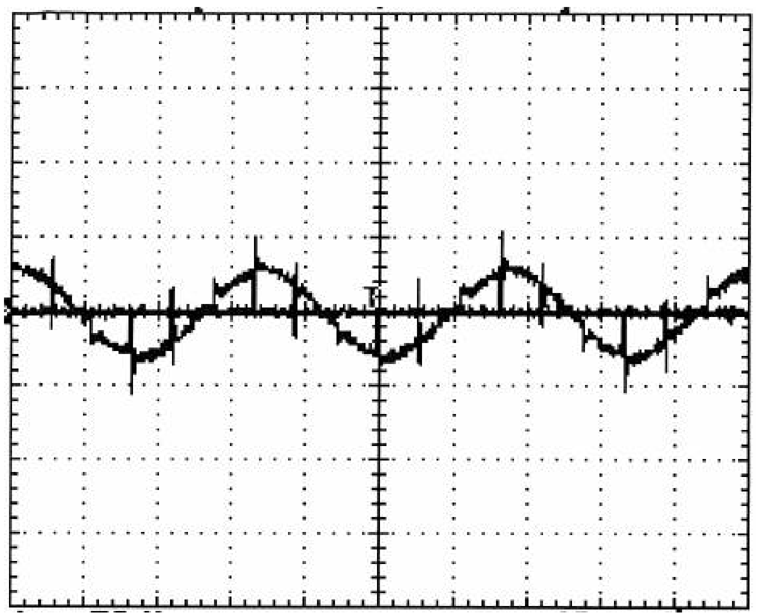






Harmonics – Case Studies

Case 2 – Transfer Switch Frequency Sync Check Failure



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

Solution: (Temporary) Disable over-frequency check

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

Harmonics – Case Studies

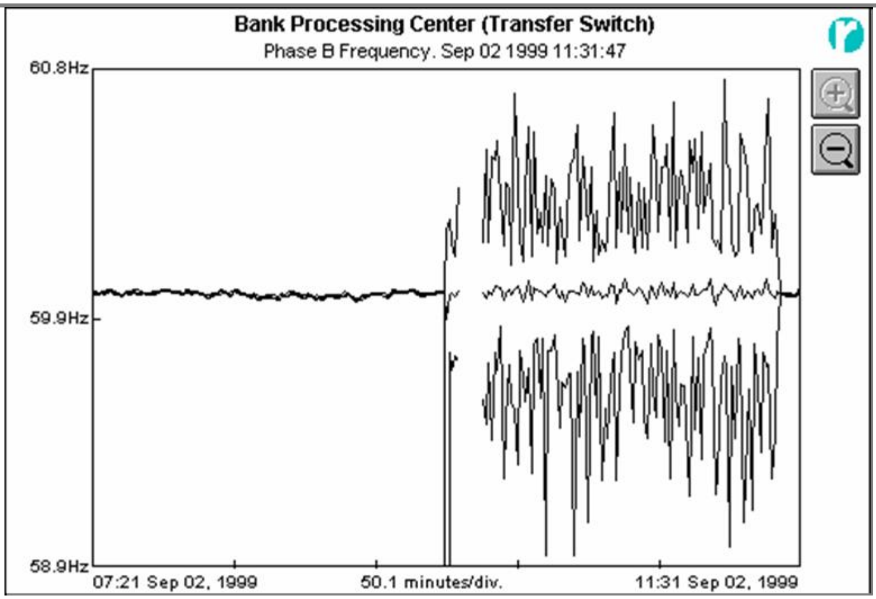
Case 3 – Small UPS System Examples

- Reference:
  - Applying Uninterruptible Power Supplies: System Compatibility Issues
  - Thomas M. Blooming – Eaton Electrical
  - Presented: Power Quality 2001, Chicago, IL
  - 6 Case Study Examples
- Many cases, the UPS will not synchronize or switch back upon utility return – draining batteries and causing system failure

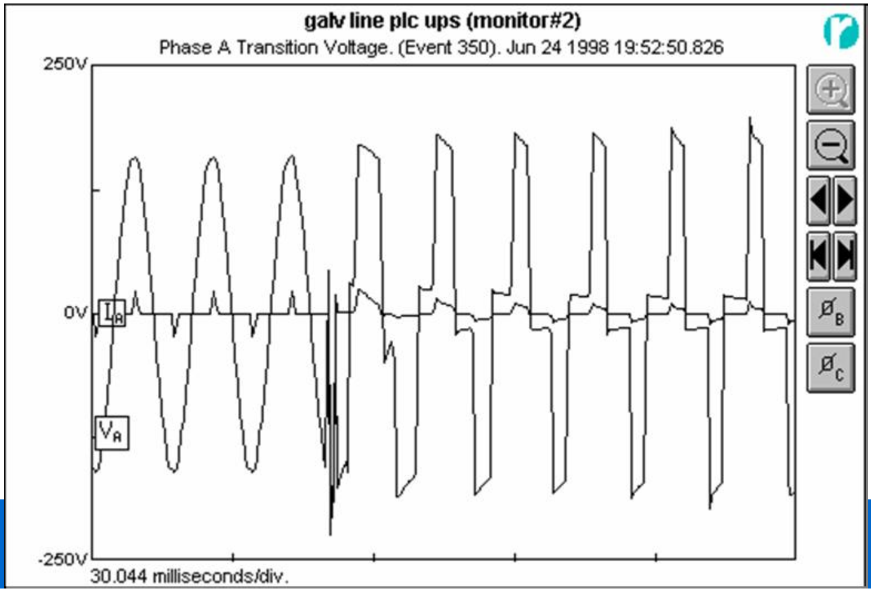
Harmonics – Case Studies

Case 3 – (Samples)

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



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



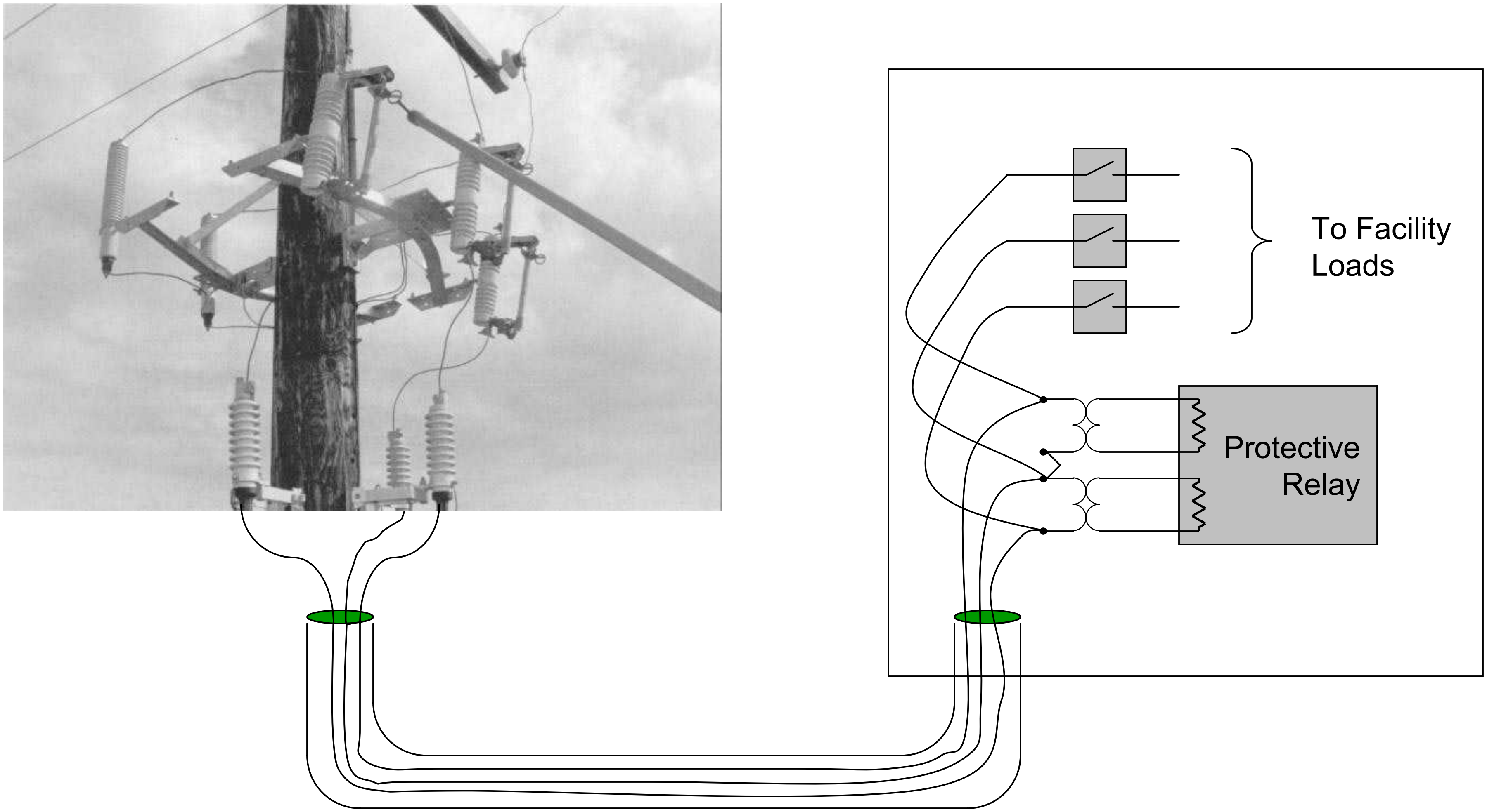
Harmonics – Case Studies

Case 4 – Resonance (ferro-resonance)

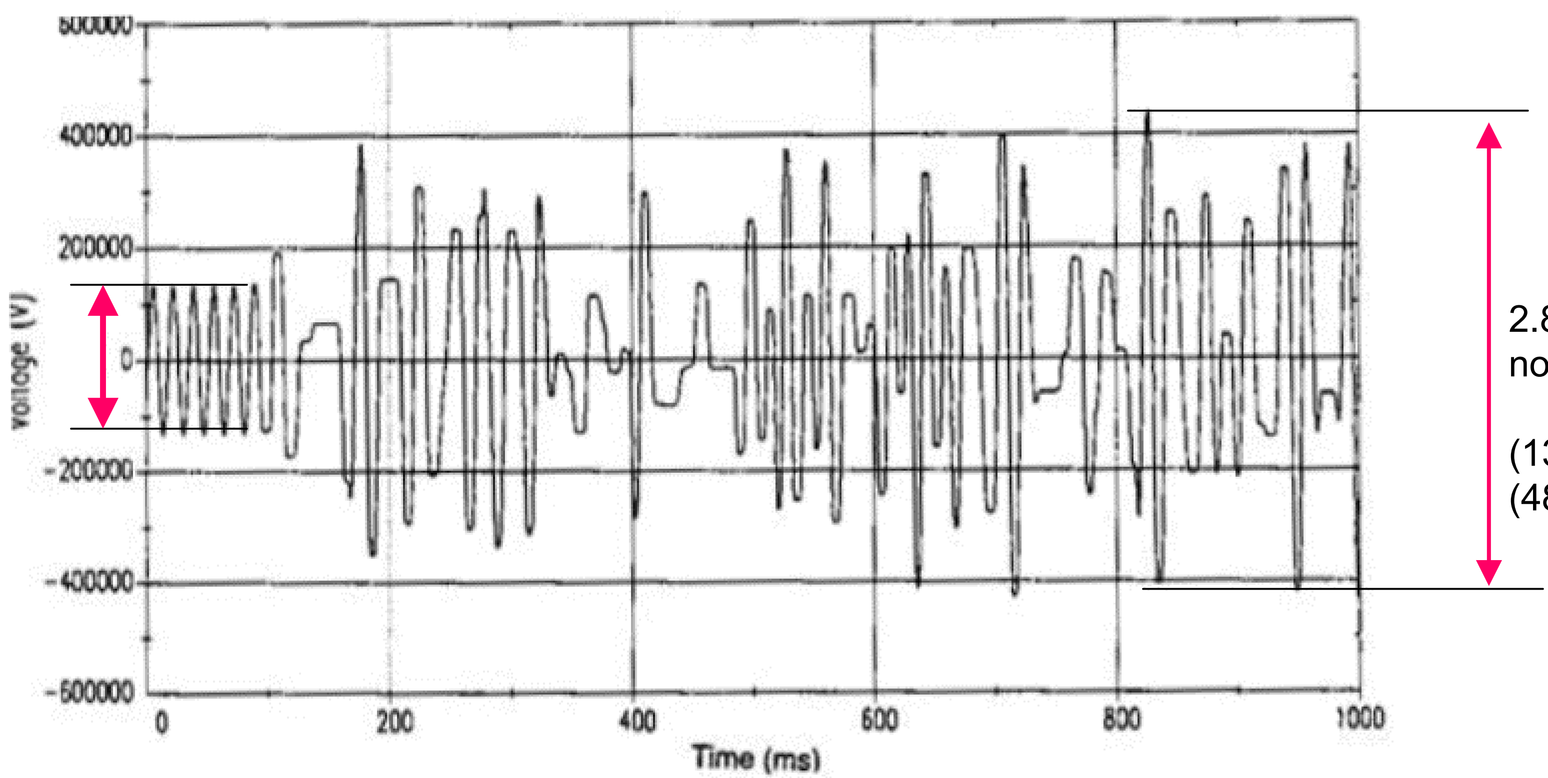
- Mission Critical Site
  - 6 MW Diesel Gen Backup Power (3 x 2MW)
  - 13.2 kV service
  - Underground service from pole ~300' to riser and pole mounted cut-outs (1ϕ switching)
- Single-Phase condition fed to site
  - Generator switchgear malfunctioned
  - Root Cause: Ferroresonance within system

Harmonics – Case Studies

Case 4 – Resonance (ferro-resonance)



Harmonics – Case Studies

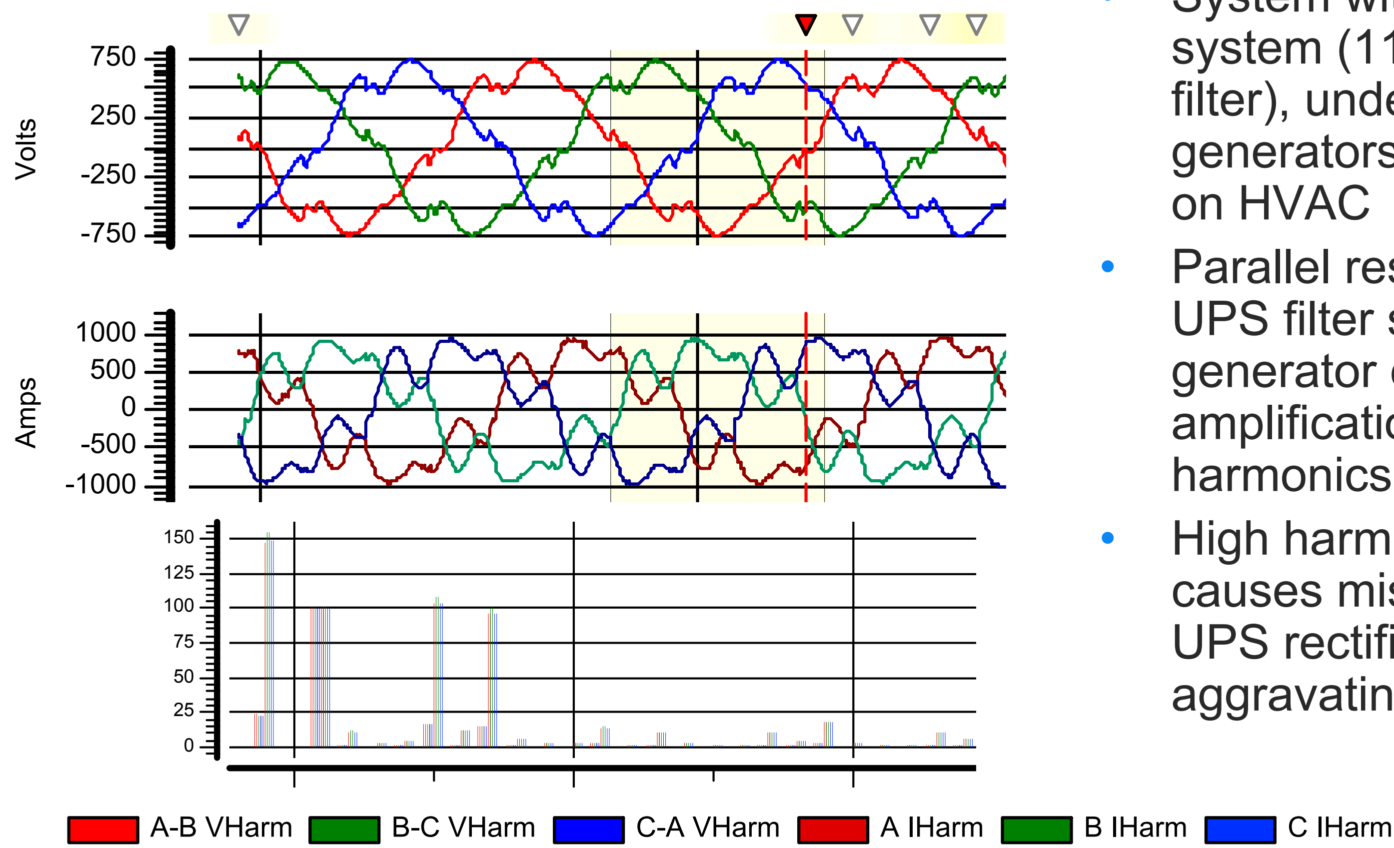


2.8 times
nominal voltage

(13.2 kV ► 37.7 kV)
(480 V ►1371 V)

Harmonics – Case Studies
Softstart on Generator

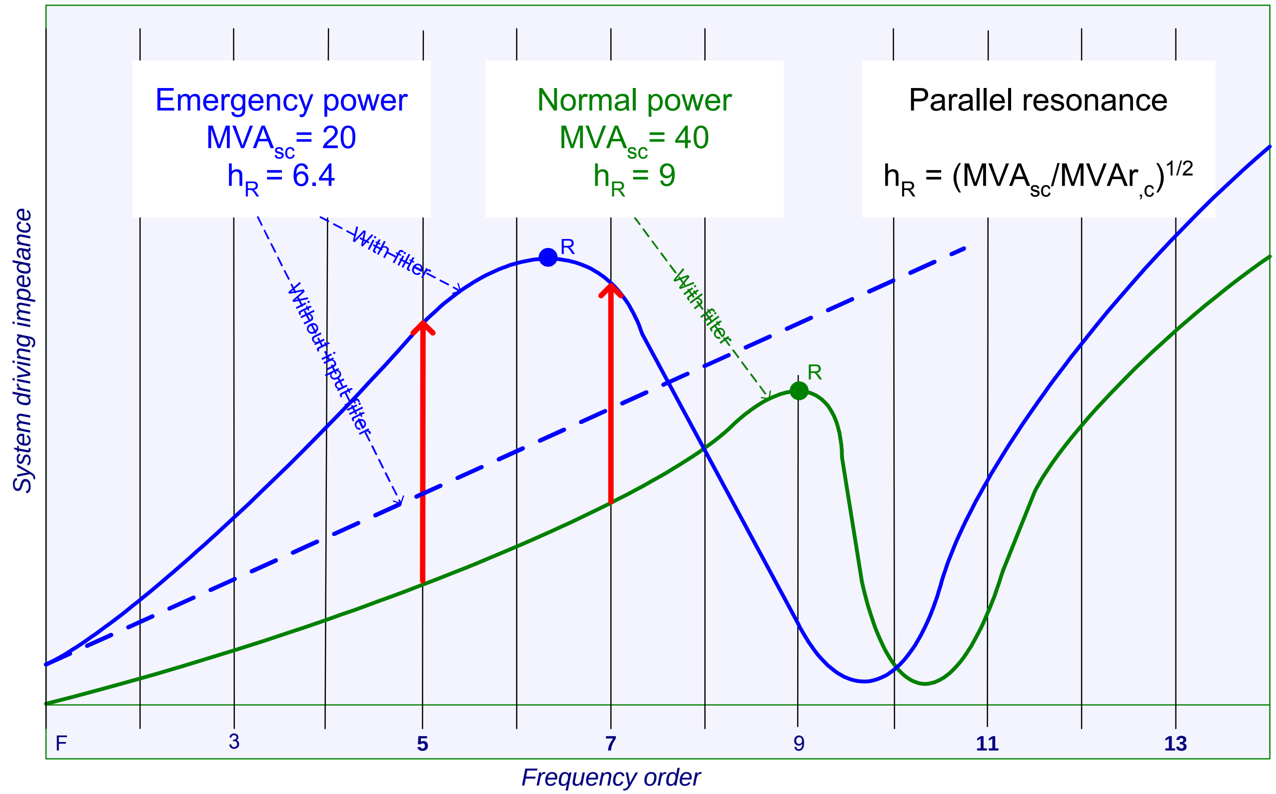
Case 5 – Parallel Resonance



	AV	BV	CV	A-BV	B-CV	C-AV	AI	BI	CI
RMS	273.53	273.95	273.33	472.52	475.10	474.01	629.26	611.21	634.59
FND	N/A	N/A	N/A	100.00	100.00	100.00	100.00	100.00	100.00
DC	510.53	312.04	-850.55	0.17	1.04	-1.23	1.56	-0.62	-1.13
THD	64491.80	64359.01	65019.52	23.28	22.99	22.89	148.08	154.73	148.24

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

Harmonics – Case Studies
Softstart on Generator



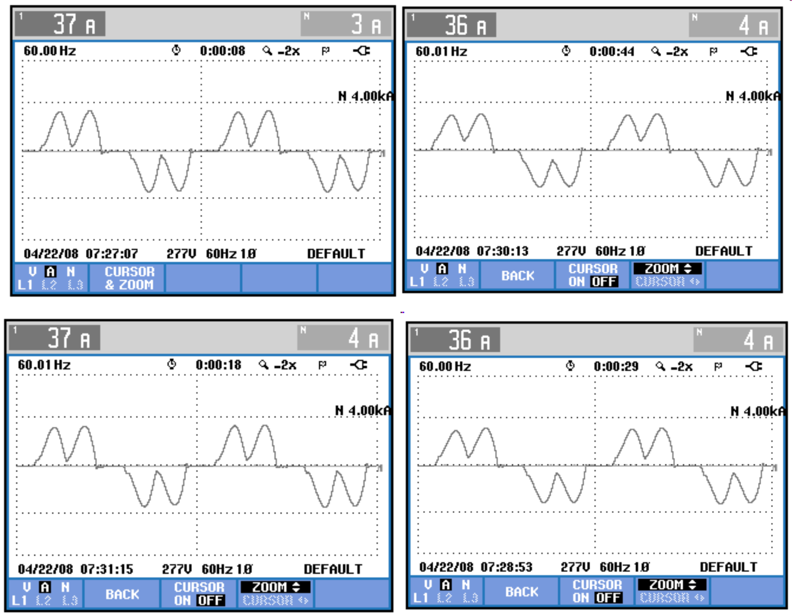
Solution: (Temporary) Disable UPS Filter(s)

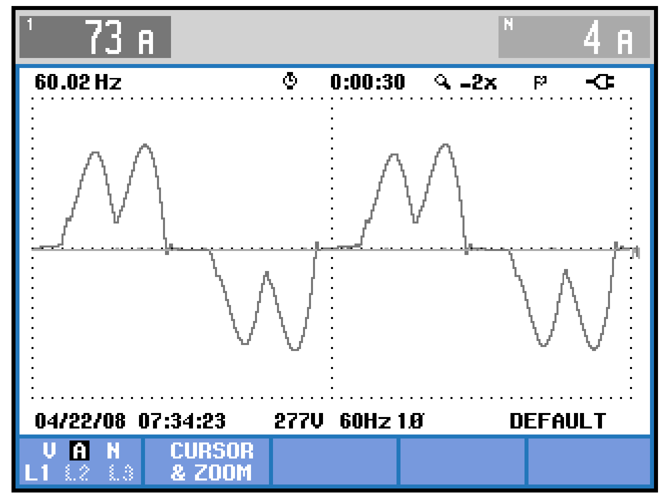
Solution: (Permanent) Replace w/Active Filter(s)

Harmonics and Cancellation

Drive 1

Drive 2





One Running   Two Running

Individual Drives

Summation of Both Drives

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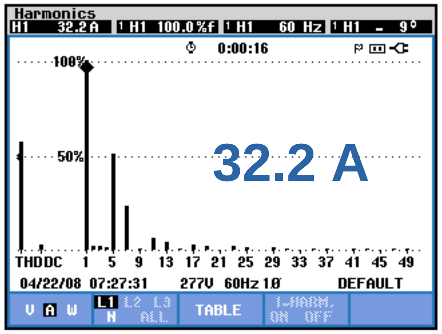
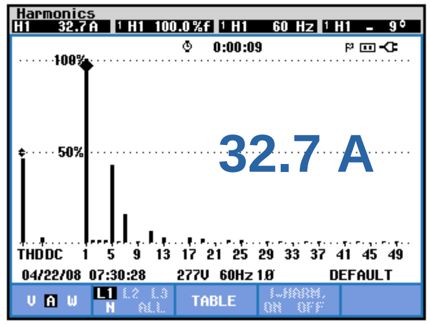
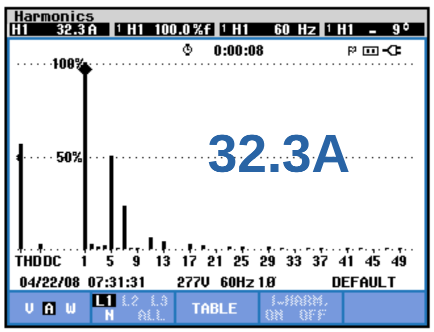
Harmonics and Cancellation – 60 Hz

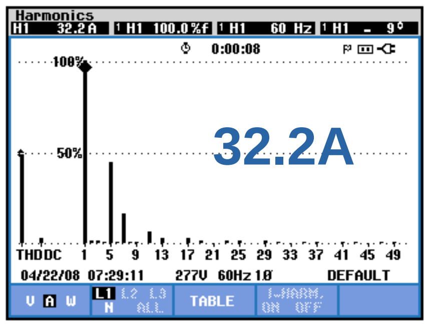
Drive 1

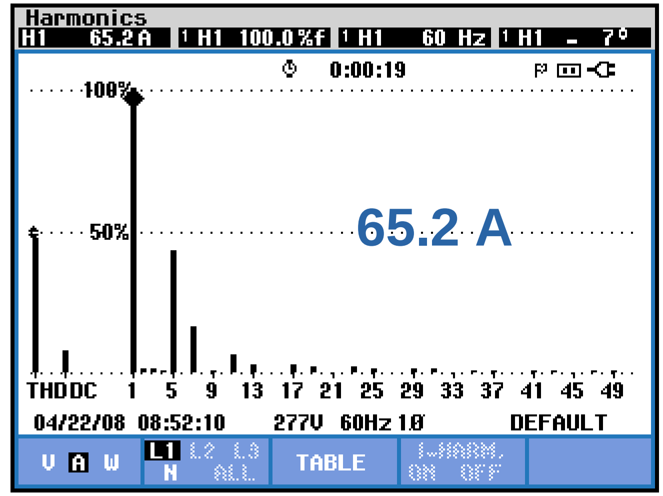




Drive 2







One Running   Two Running   Summation of Both Drives

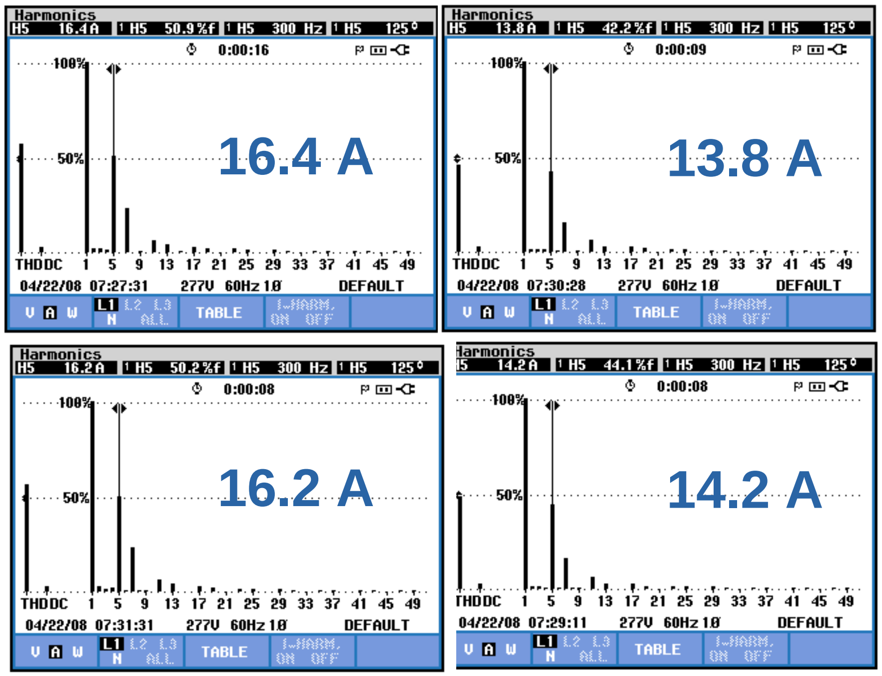
Individual Drives

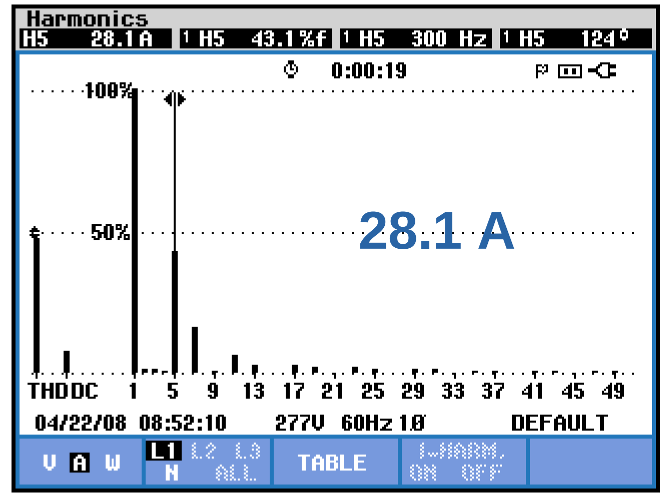
60 Hz currents add as this is the power doing the work

Harmonics and Cancellation – 5th Harmonic

Drive 1

Drive 2





One Running Two Running Summation of Both Drives

Individual Drives

Total 5th harmonic is the sum of two running drives (not the individual sum of one drive running at a time). More drives running on a common source increases the load per impedance ratio – like adding a larger (%) reactor

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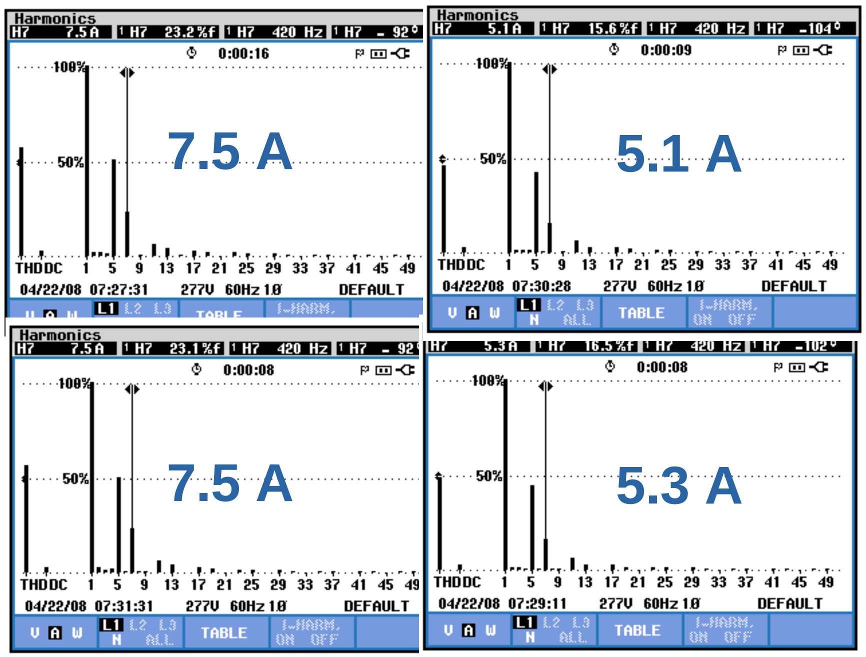
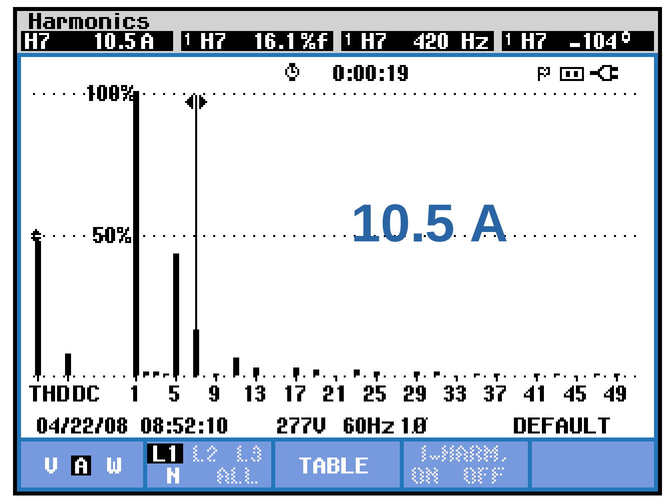
Harmonics and Cancellation – 7^{th} Harmonic

Drive 1

Drive 2





One Running Two Running Summation of Both Drives

Individual Drives

Total 7^{th} harmonic is the sum of two running drives (not the individual sum of one drive running at a time). More drives running on a common source increases the load per impedance ratio – like adding a larger (%) reactor

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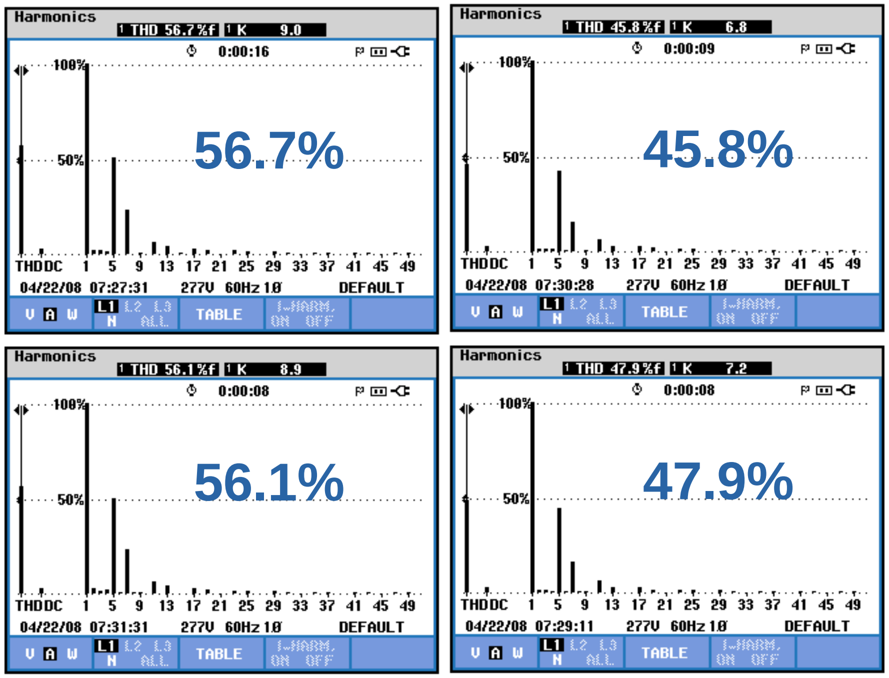
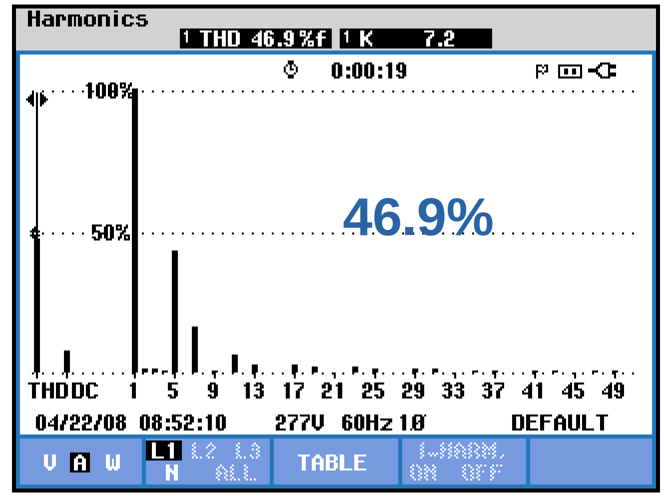
Harmonics and Cancellation

Drive 1

Drive 2





One Running Two Running Summation of Both Drives

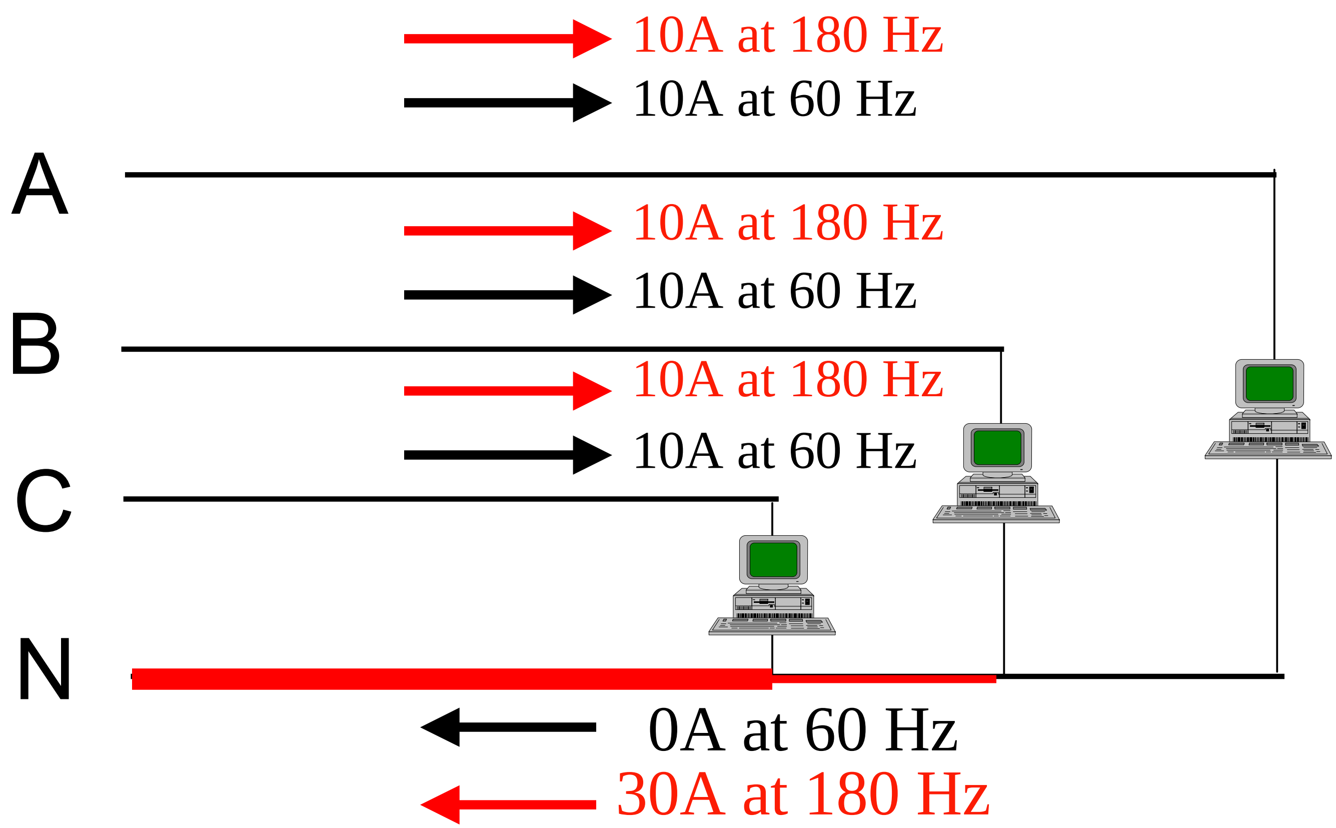
Individual Drives

Current %THD will decrease as you add more similar loads on a common bus – total load is a higher percentage of the source impedance (like a line reactor). Voltage %THD will increase as you add more similar loads on a common bus.

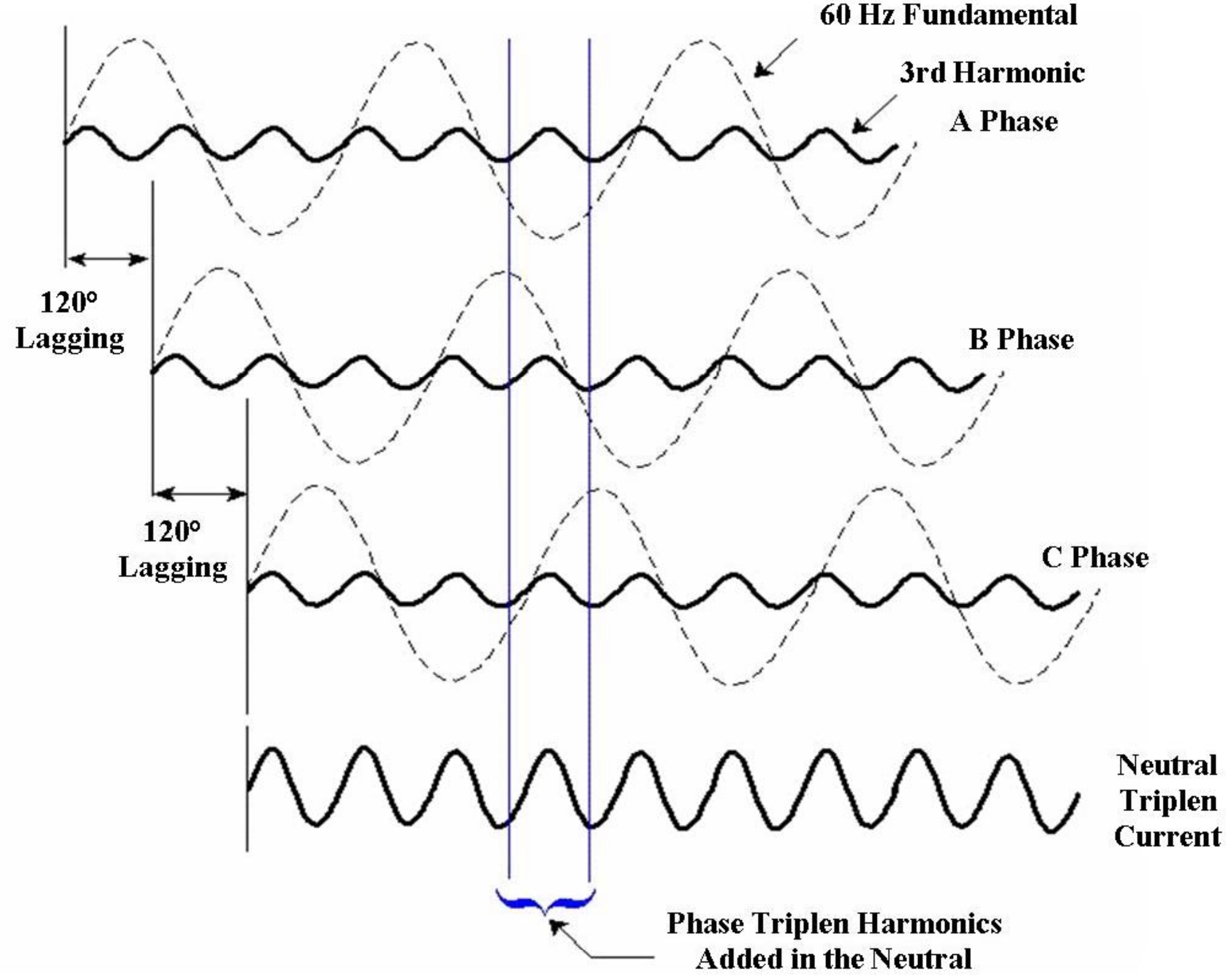
Transformers and Harmonic Currents

- Many people incorrectly assume that ALL harmonics are trapped by delta-wye transformers. The fact is:
  - only the balanced third harmonics (and multiples of the third) circulate in the delta winding and are therefore trapped.
  - other harmonic currents (5th and 7th, for example) and the unbalanced multiples of the third harmonics can pass through the transformer
  - harmonic currents are inductively coupled along with the 60 Hz current by the ratio of the primary turns to the secondary turns.
- Higher order harmonics (> 25th) may or may not be inductively coupled through the transformer.
- Sometimes, higher frequency harmonics are capacitively coupled from secondary to primary (not by the turns ratio).

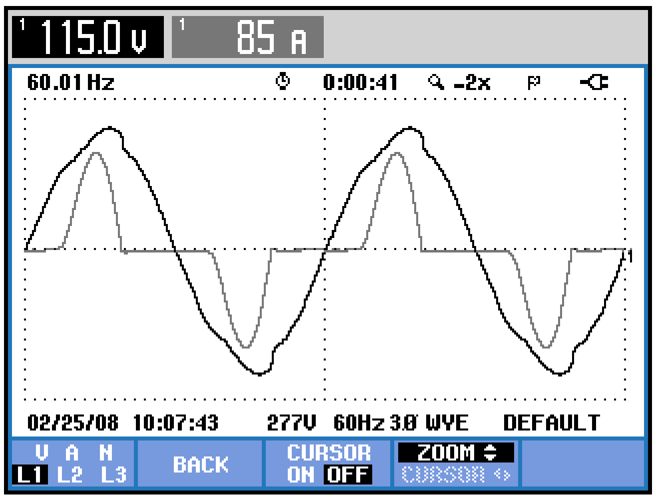
Neutral Heating – Oversize Equipment

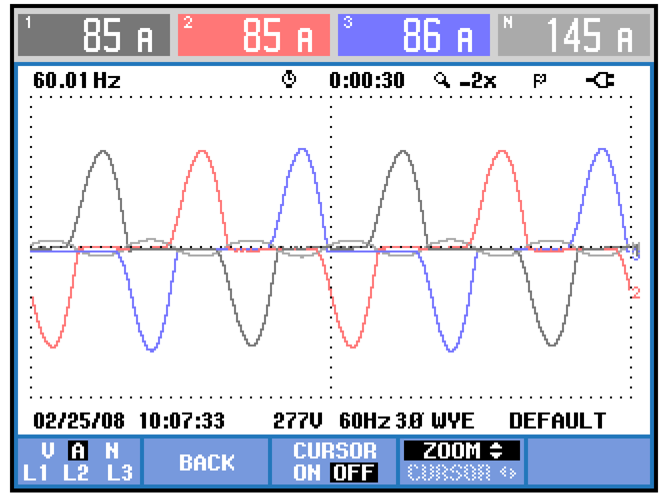


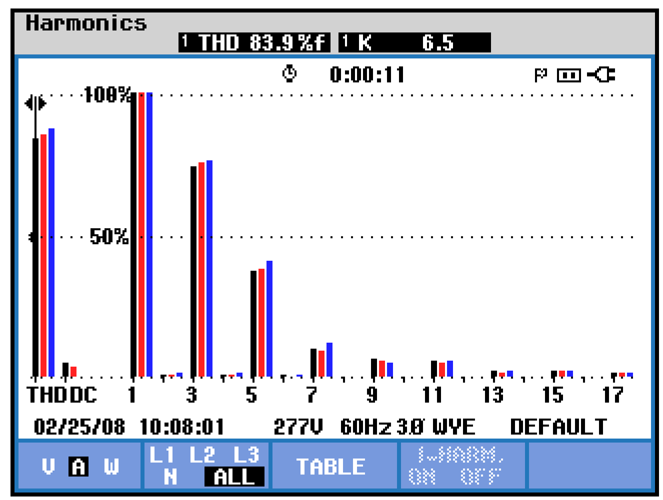
3rd Harmonic Summation in Neutral



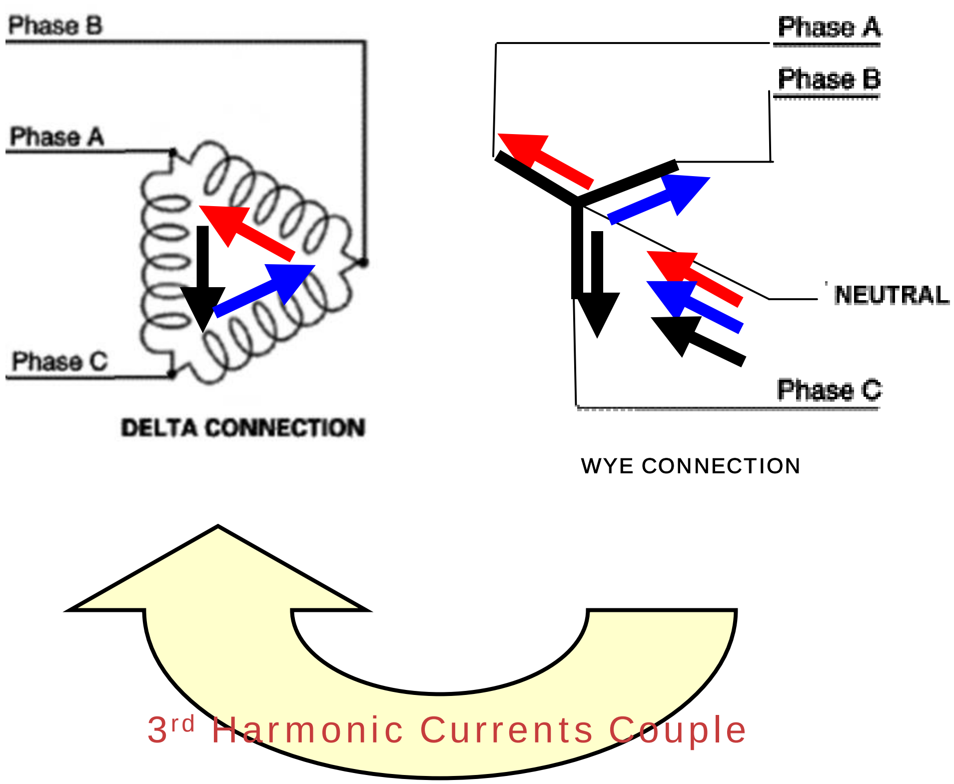
3rd Harmonic Summation in Neutral





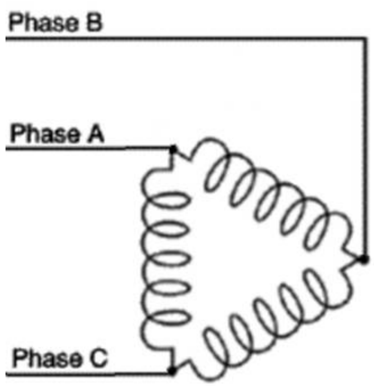


3rd Harmonics and Delta/Wye Transformers

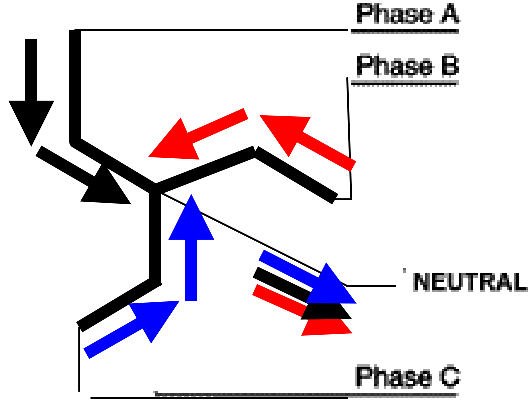


- Third harmonic current flowing in the phases adds up in the neutral.
- On the primary, the third harmonic current is trapped in the delta if it is balanced. Otherwise, the difference flows in the phases.
- Balanced third harmonic currents are called “triplen” harmonic currents (3rd, 9th, etc.).
- Delta-wye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

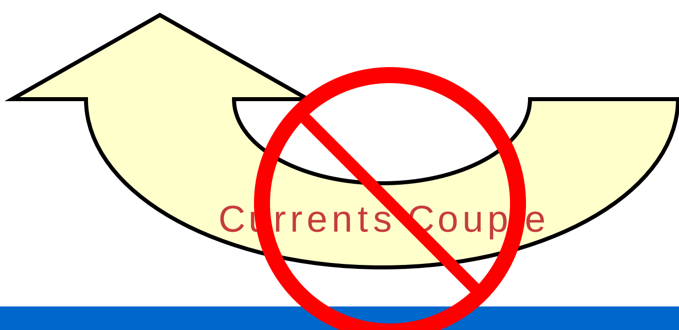
Secondary Treatment of Triplens (HMT's)



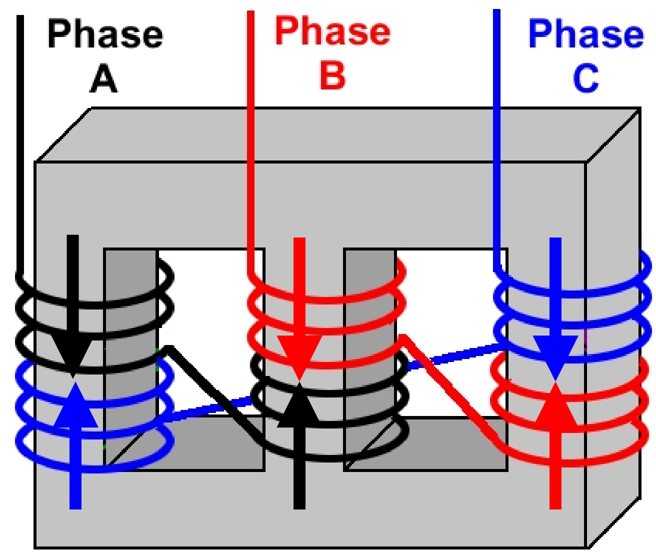
DELTA CONNECTION



ZIG-ZAG CONNECTION



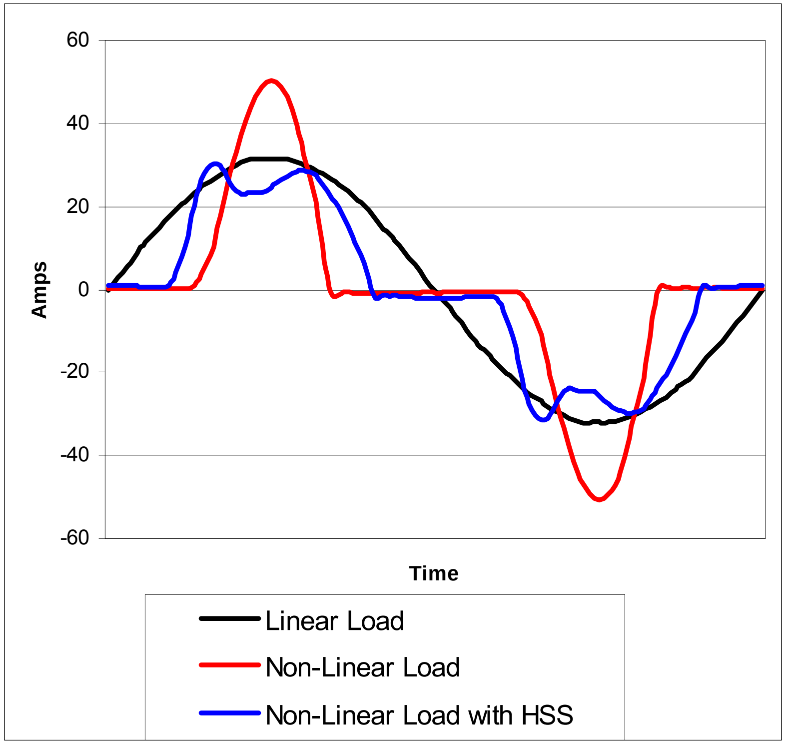
HMT Secondary



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

3rd Harmonic Blocking Filter

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



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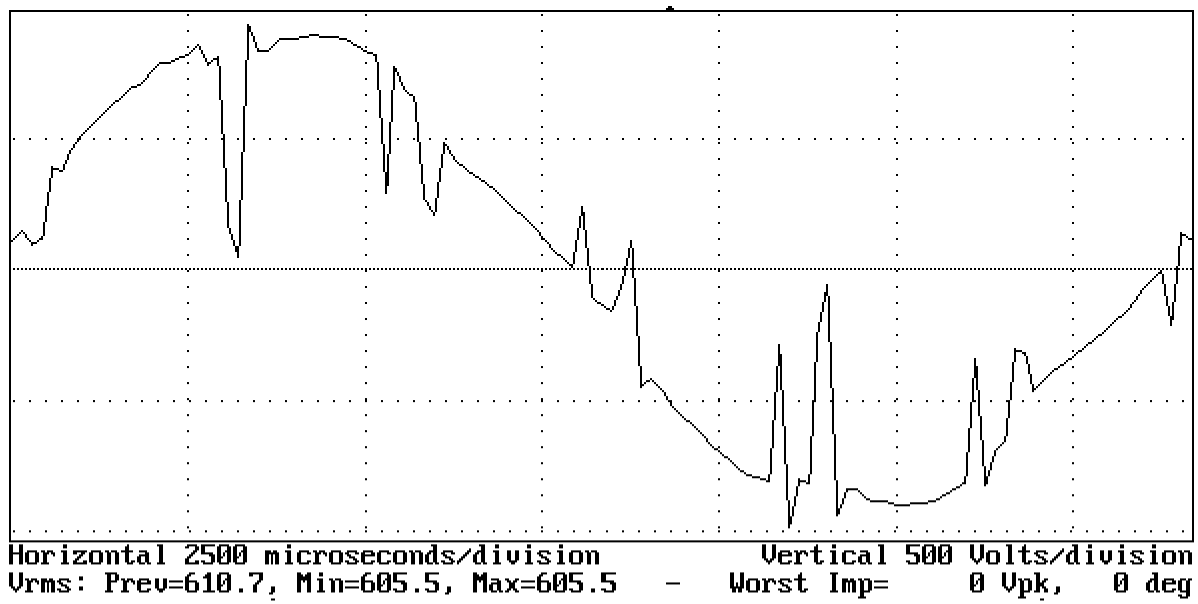
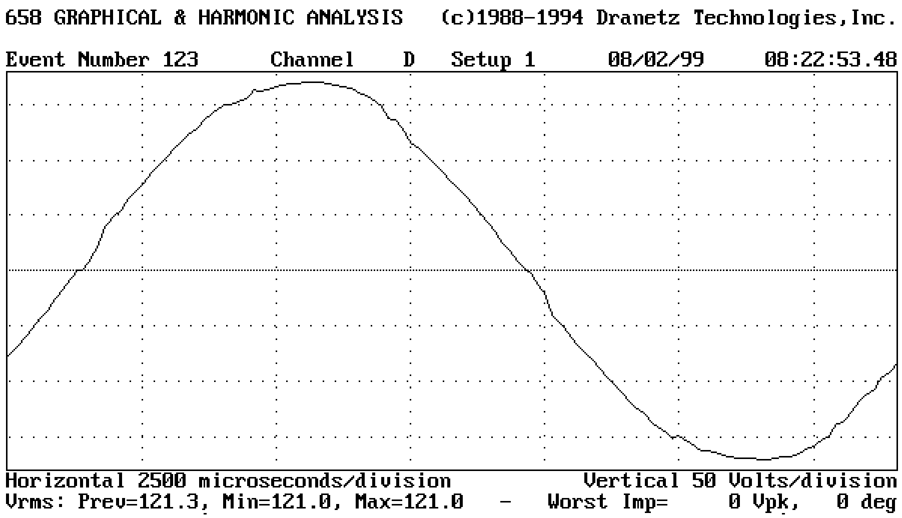
Notching and Generators

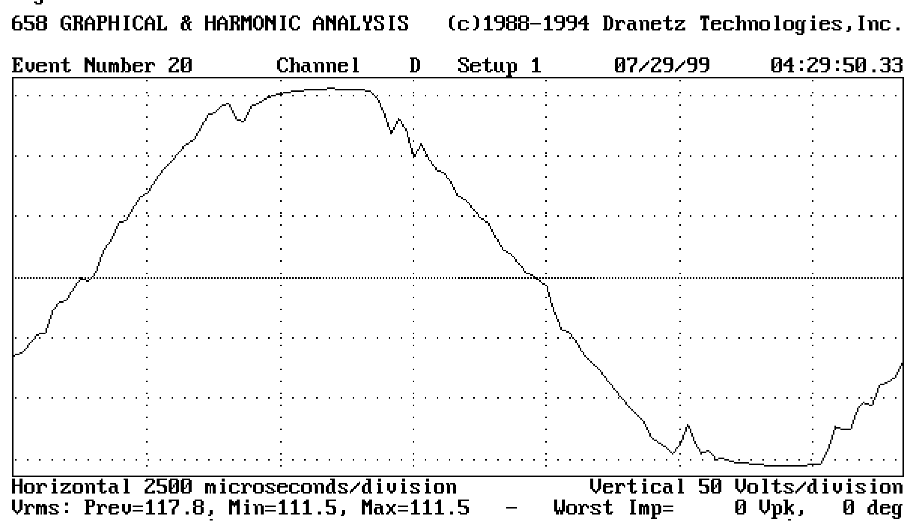
Generator Source may result in larger commutation notches and transients



Harmonics and Generators



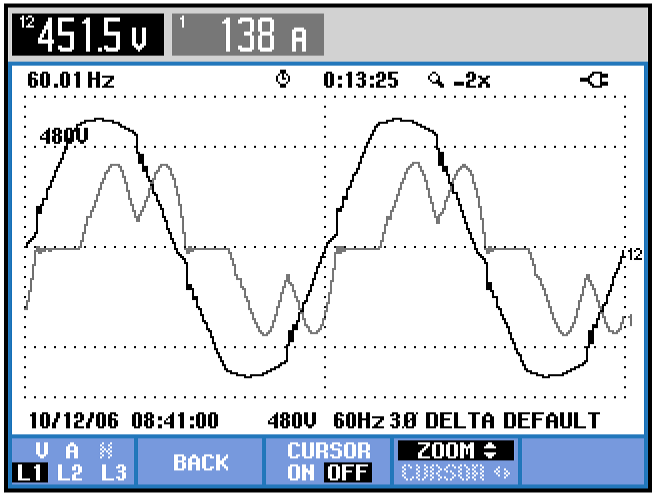
Utility Source
2.3% THD

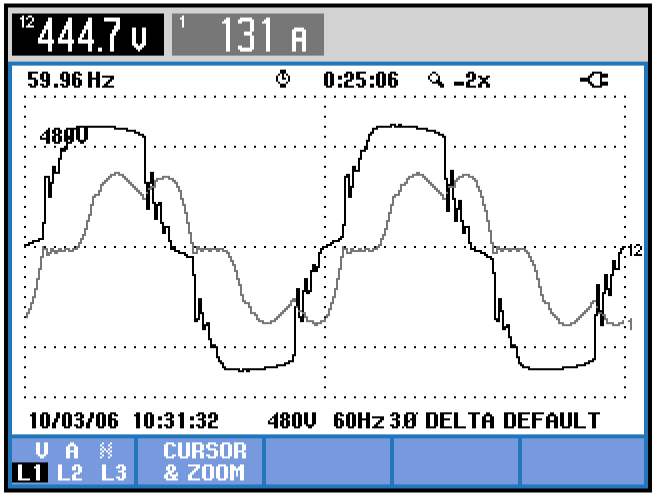


Generator Source
5.7% THD

Harmonics and Generators

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





Utility Souce

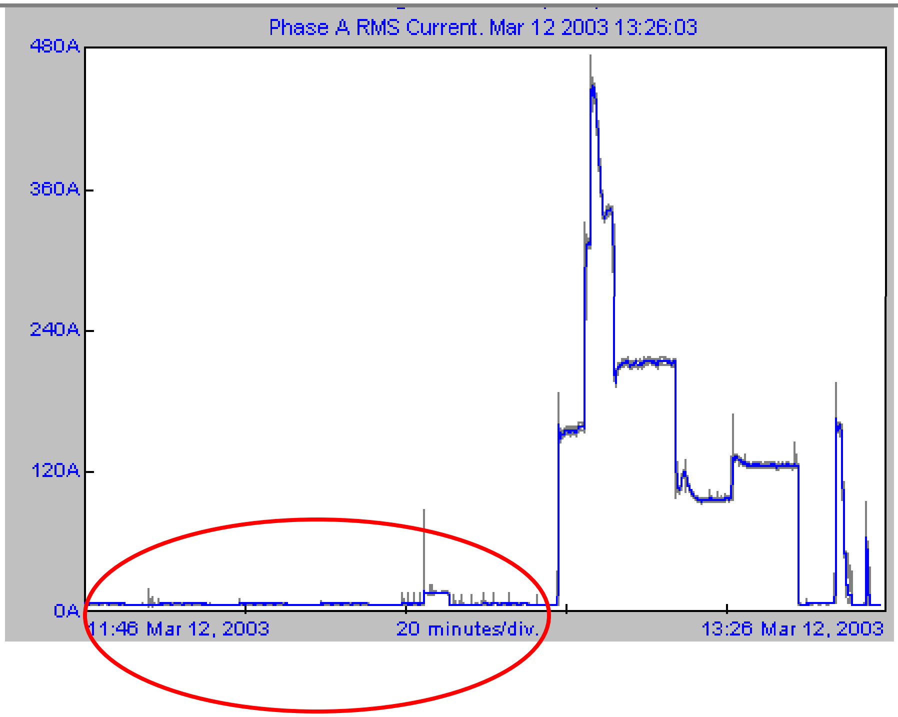
4.4% Vthd

Generator Source

13% Vthd

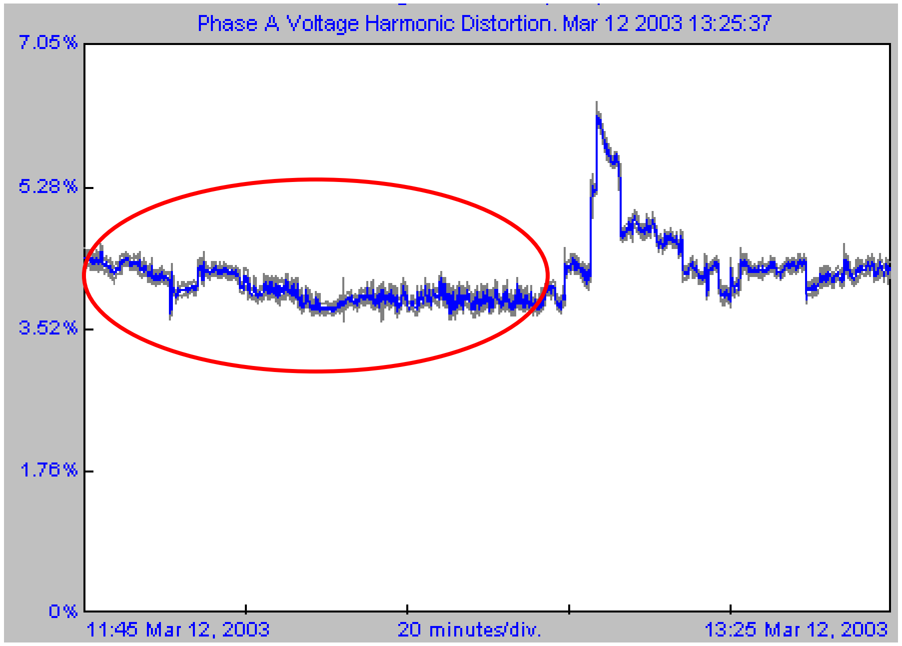
Same Load

Harmonic Limits - System Issues



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

Voltage distortion at no load is 4%!



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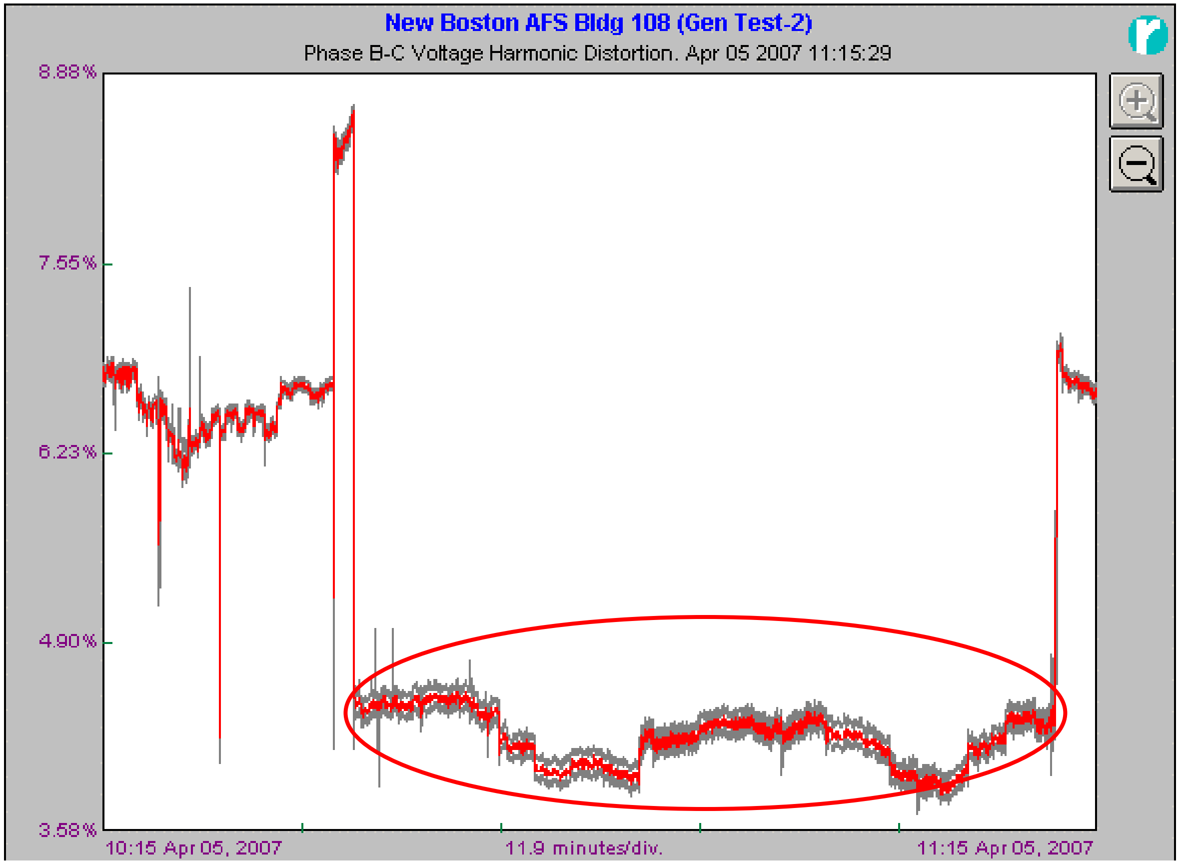
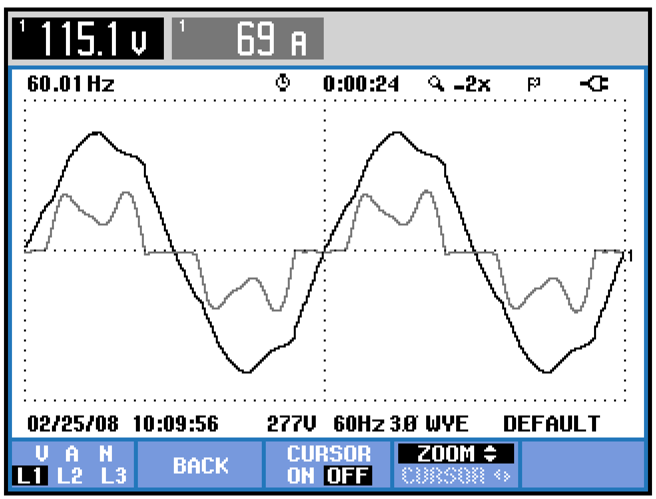
Harmonic Limits - System Issues

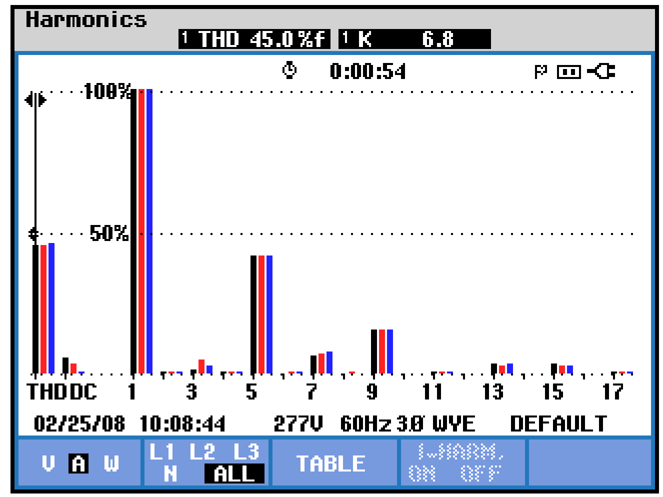


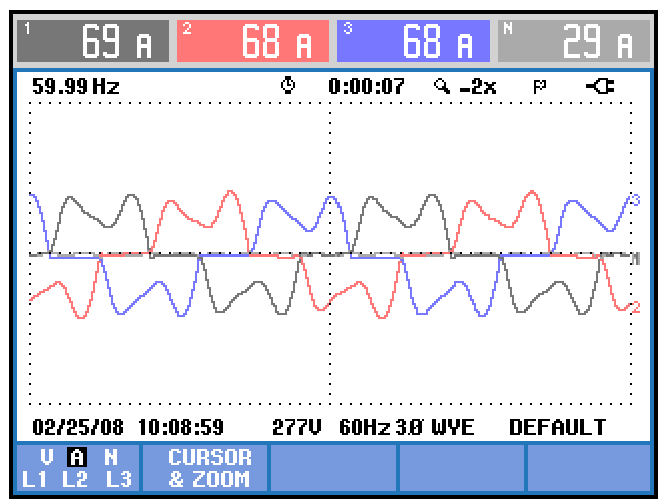
Large Generator vs. Weak Utility Source

Voltage distortion on generator is 4%!

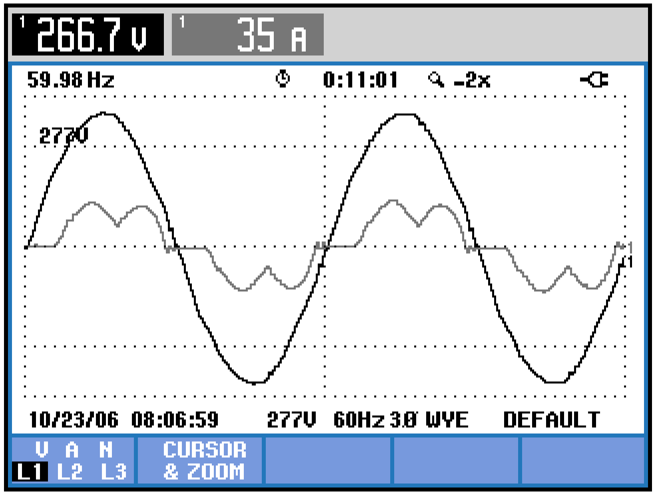
3^{rd} Harmonic Blocking Filter

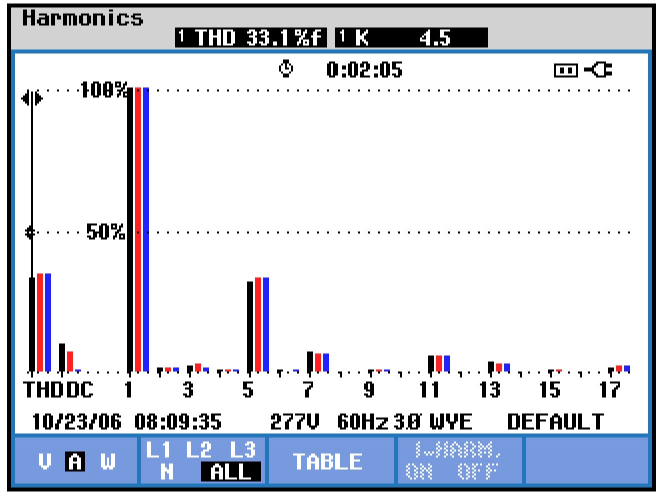






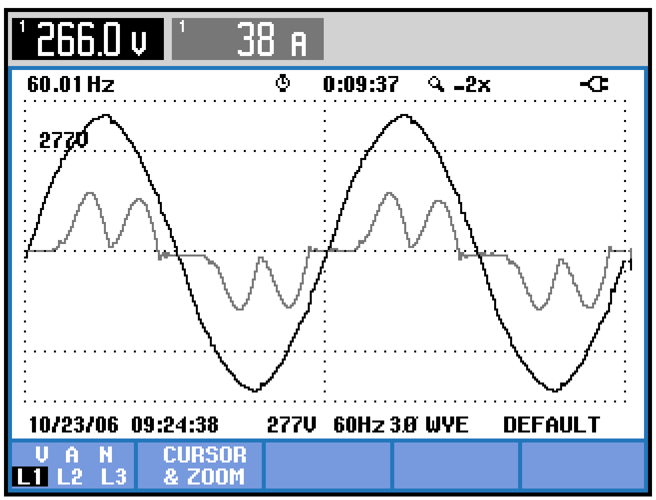
Reactor/Isolation Transformer

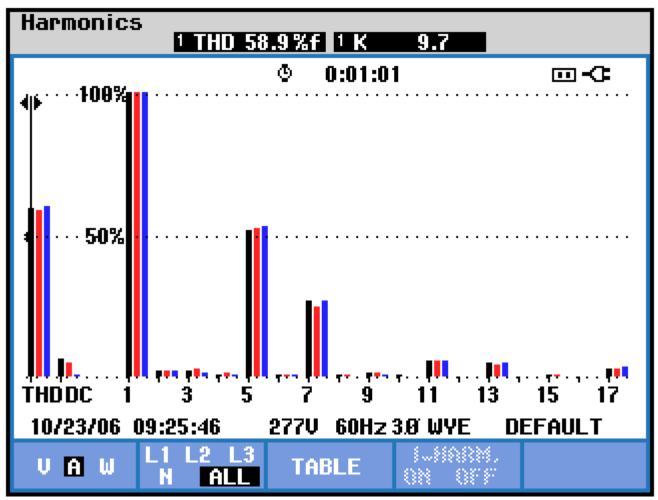




w/ isola trans

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



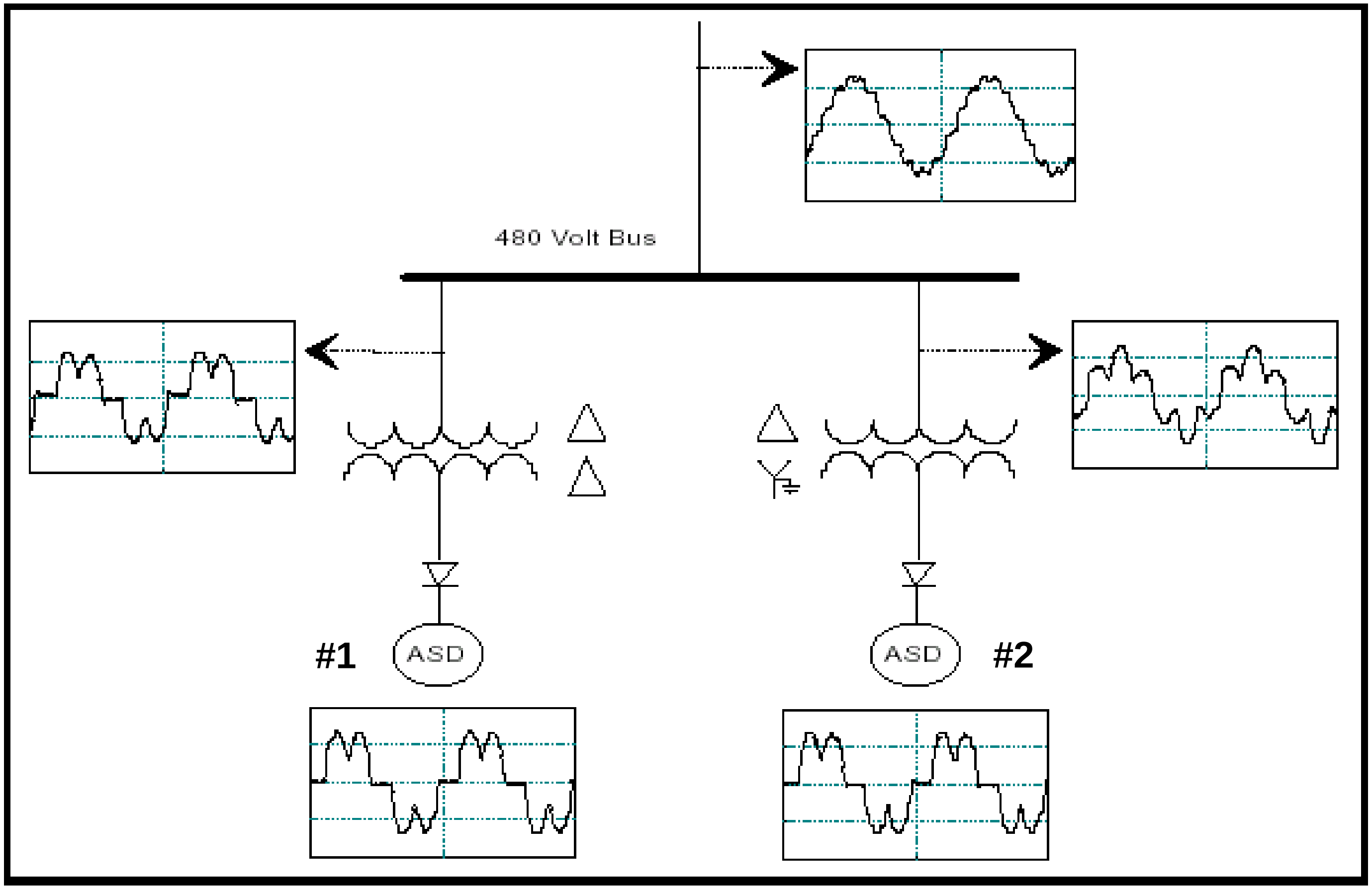


w/o isola trans

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

Phase Shifting/Cancellation

12 Pulse, 18 Pulse or 24 Pulse Cancellation by Design



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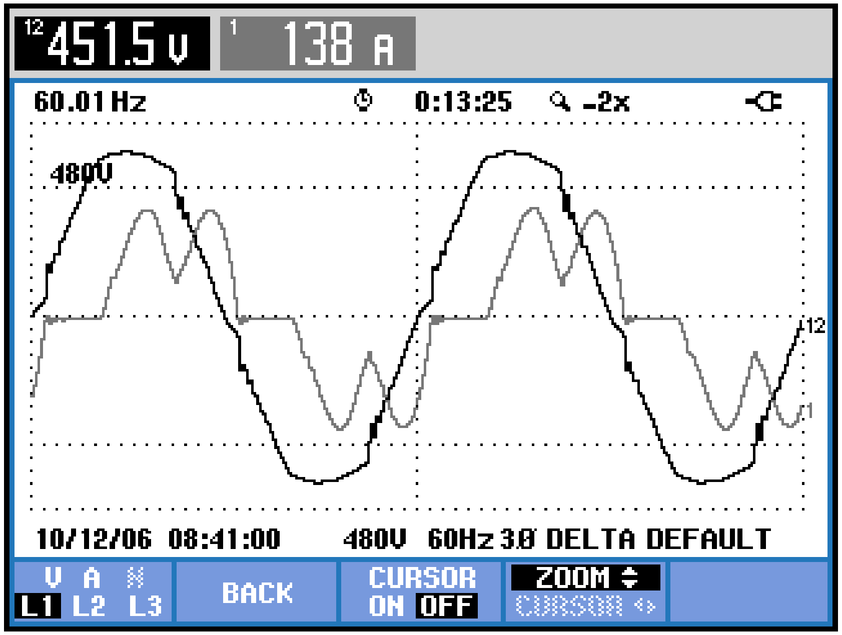
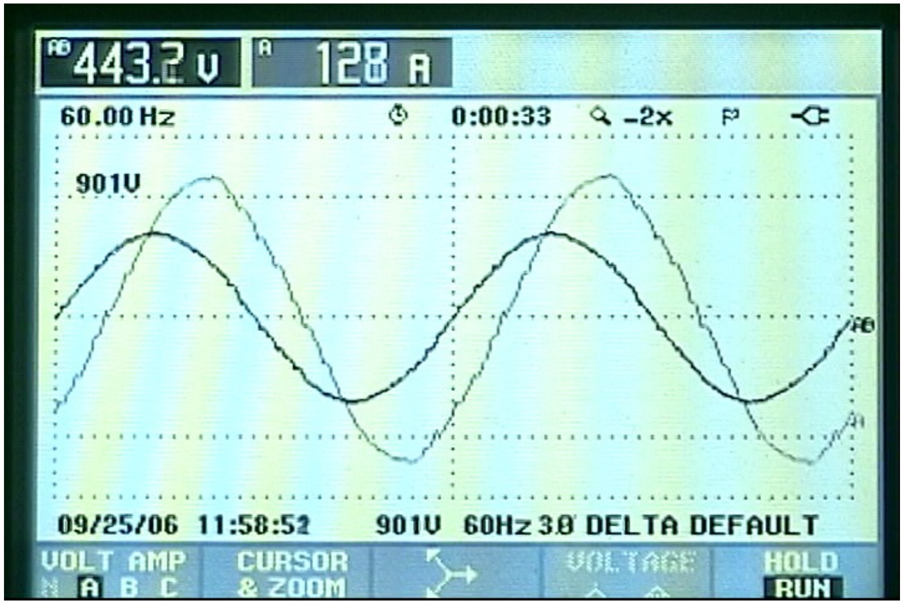
Phase Shifting/Cancellation

Without Cancellation



With Cancellation



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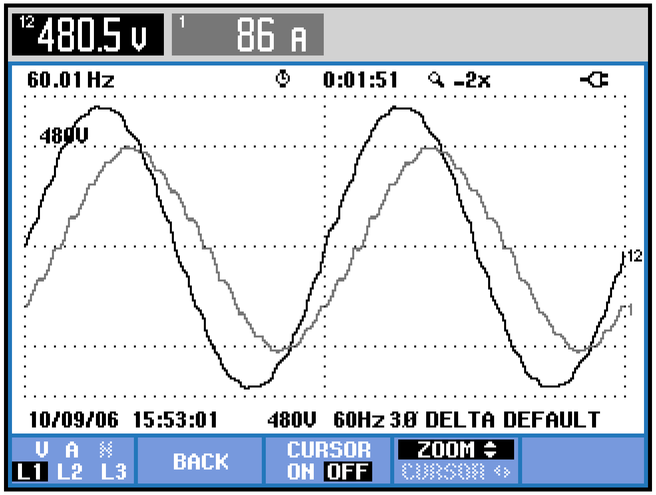
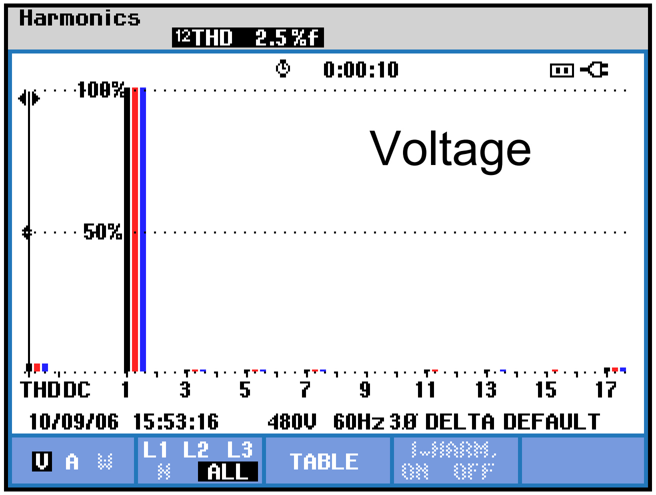
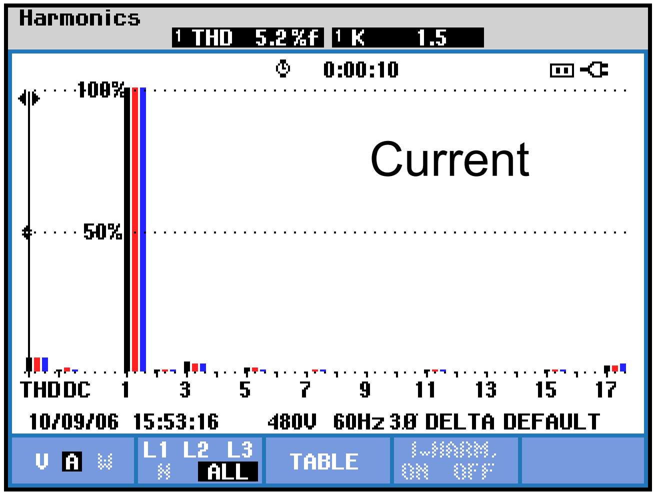
18 Pulse Rectifier

18 Pulse Design







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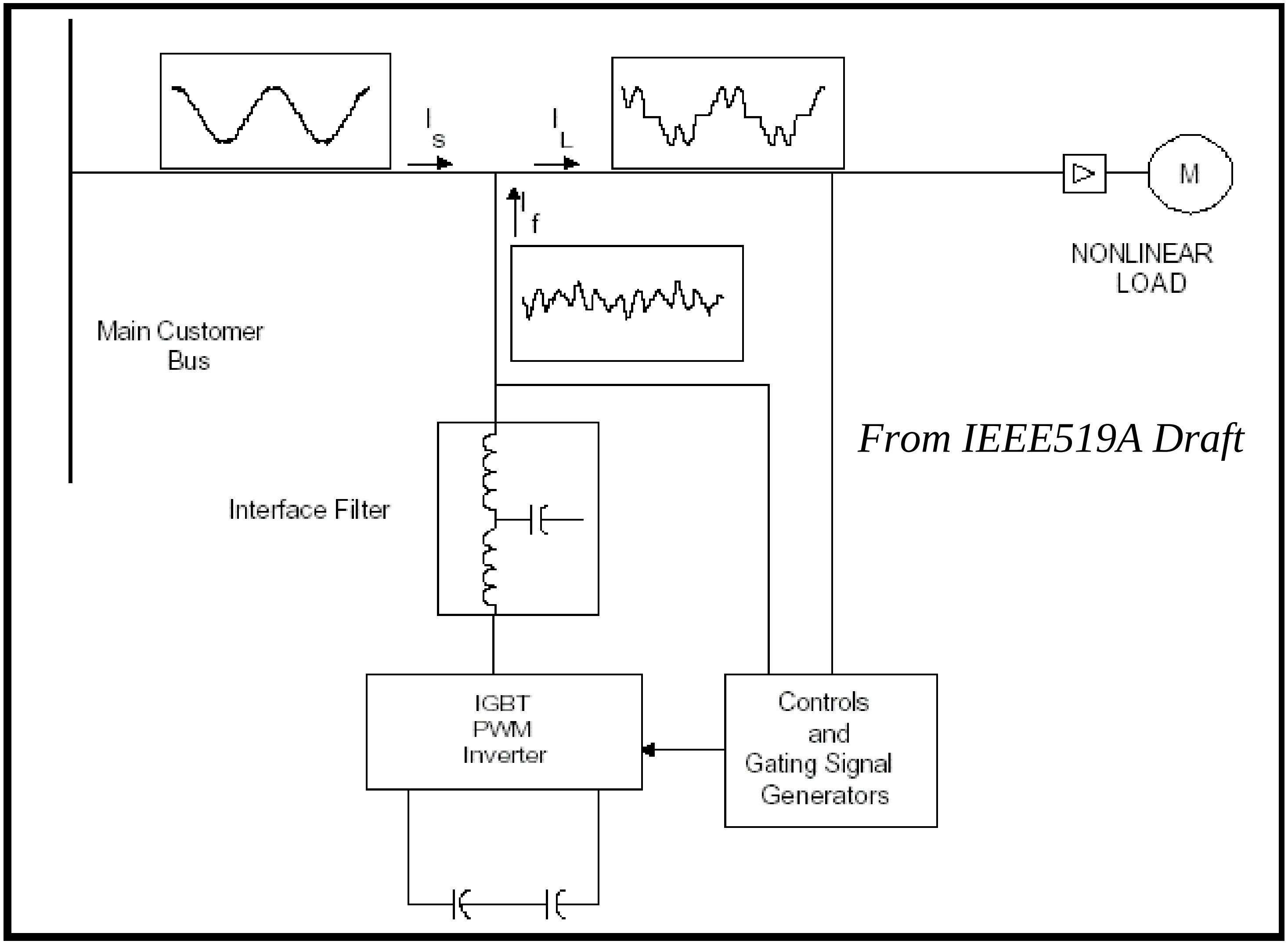
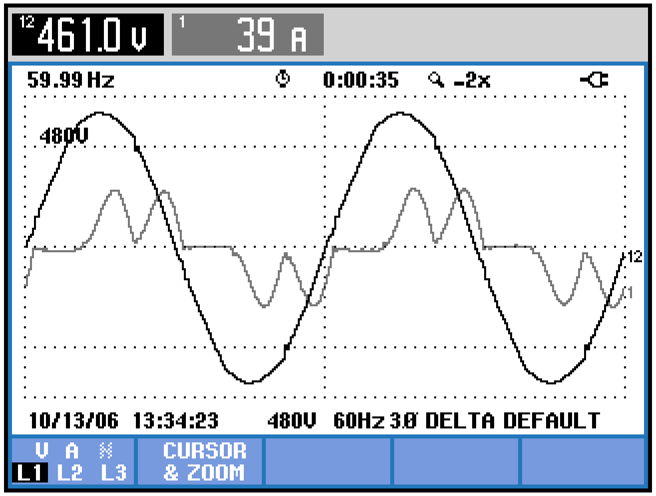
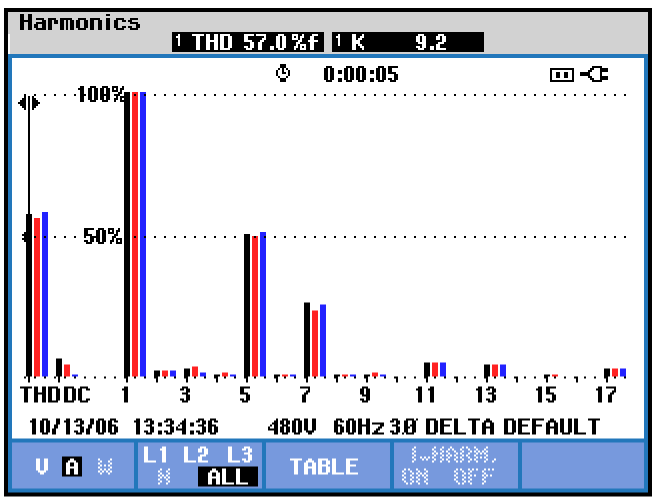
Active Filters



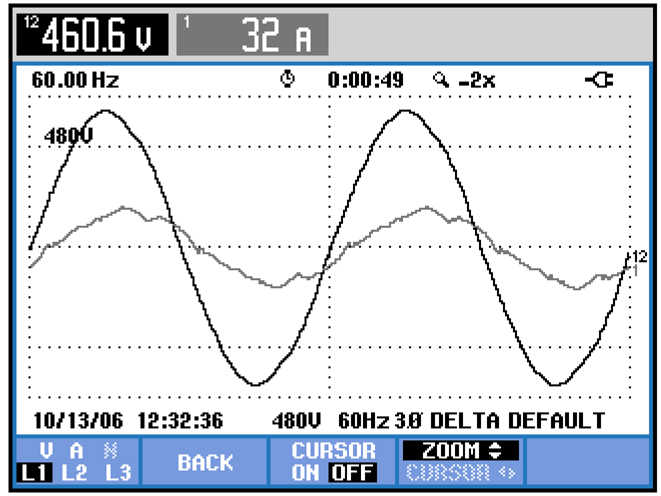
Drive/UPS Dedicated Filter

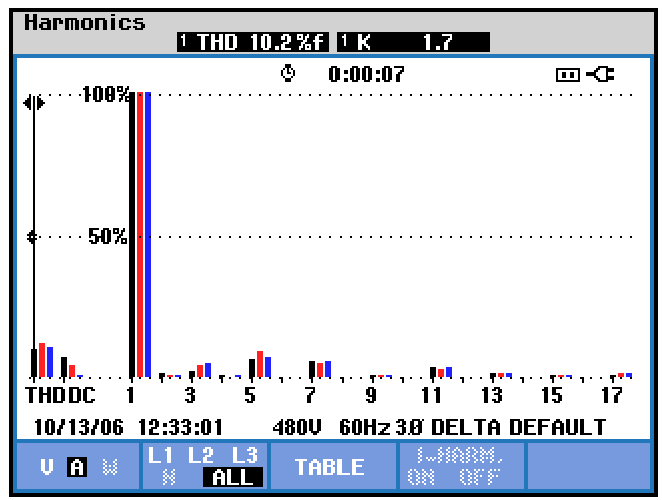
Standard Drive





Drive with Dedicated Filter





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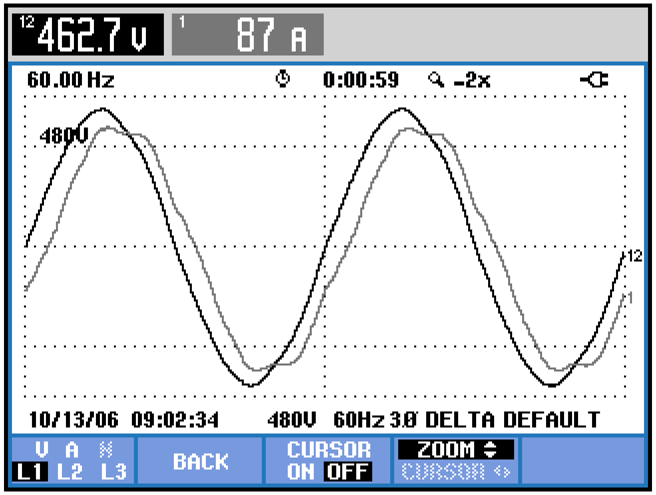
UPS Harmonics - Demonstrations

Active Rectifier UPS (with Either Output)

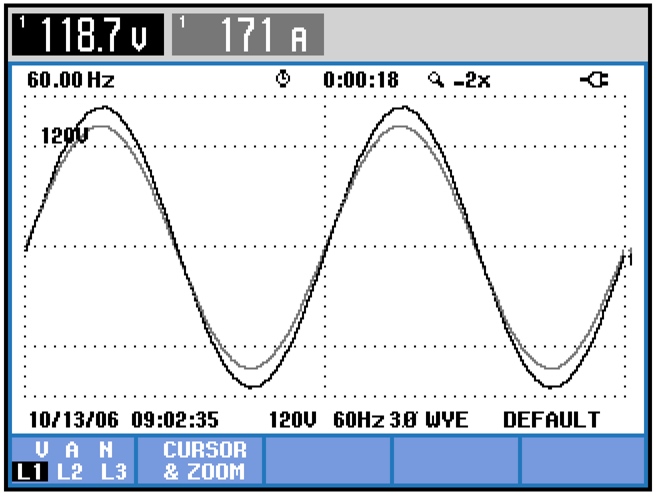
UPS Output

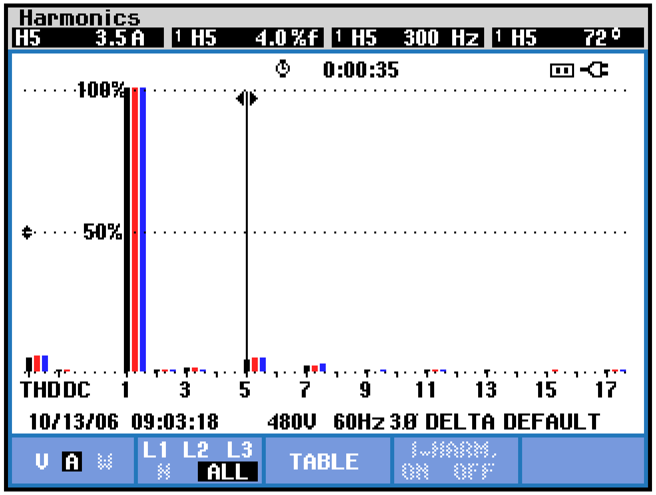


100%

Resistive

Load

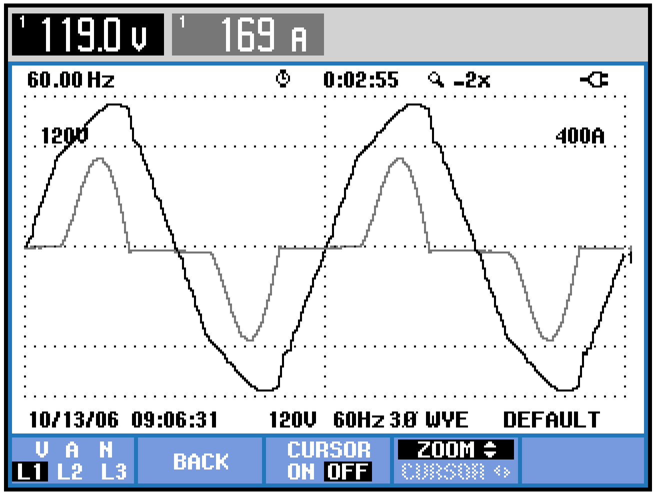




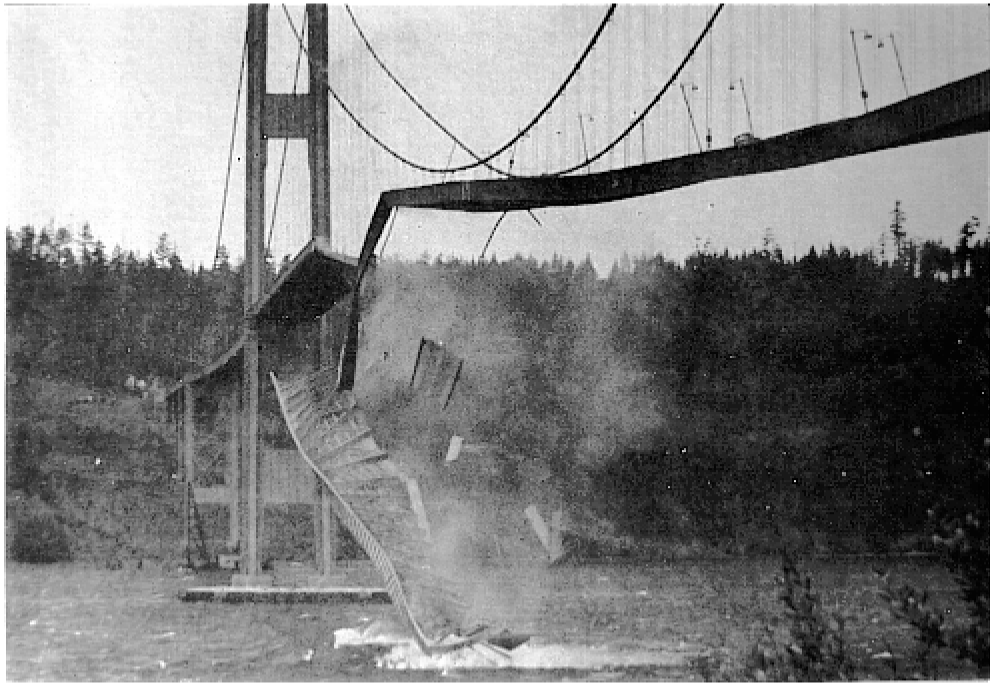
100%

Harmonic

Load



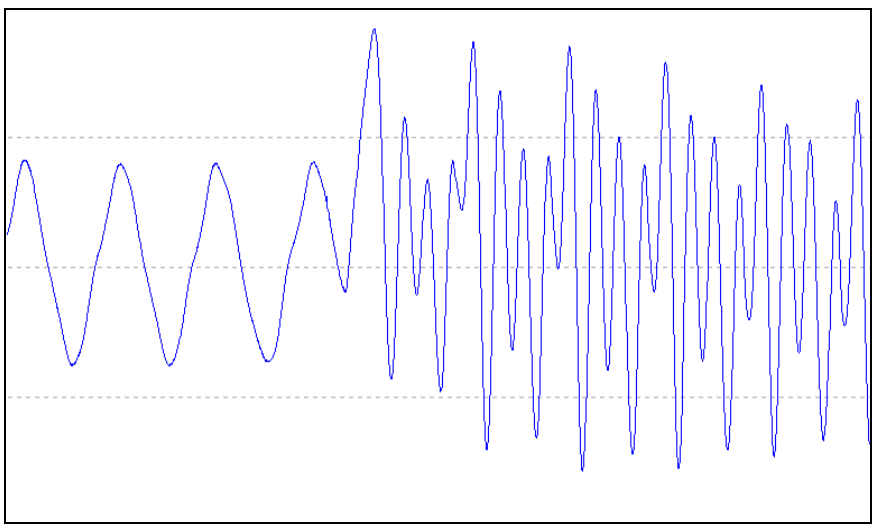
Harmonic Resonance



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

Harmonic Resonance

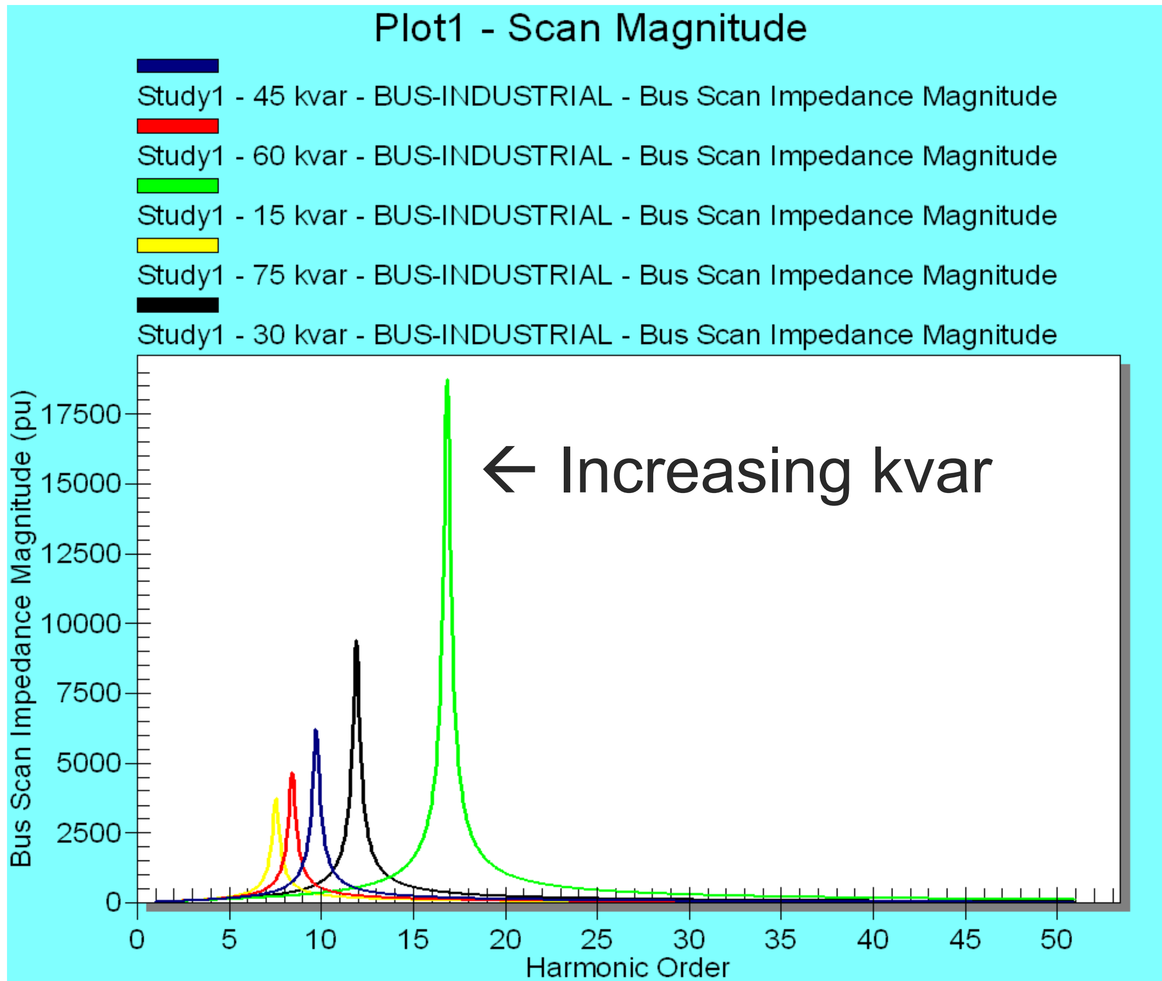
- The “Self Correcting” Problem
  - Blown Fuses
  - Failed Capacitors
  - Damaged Transformer



Harmonic Resonance

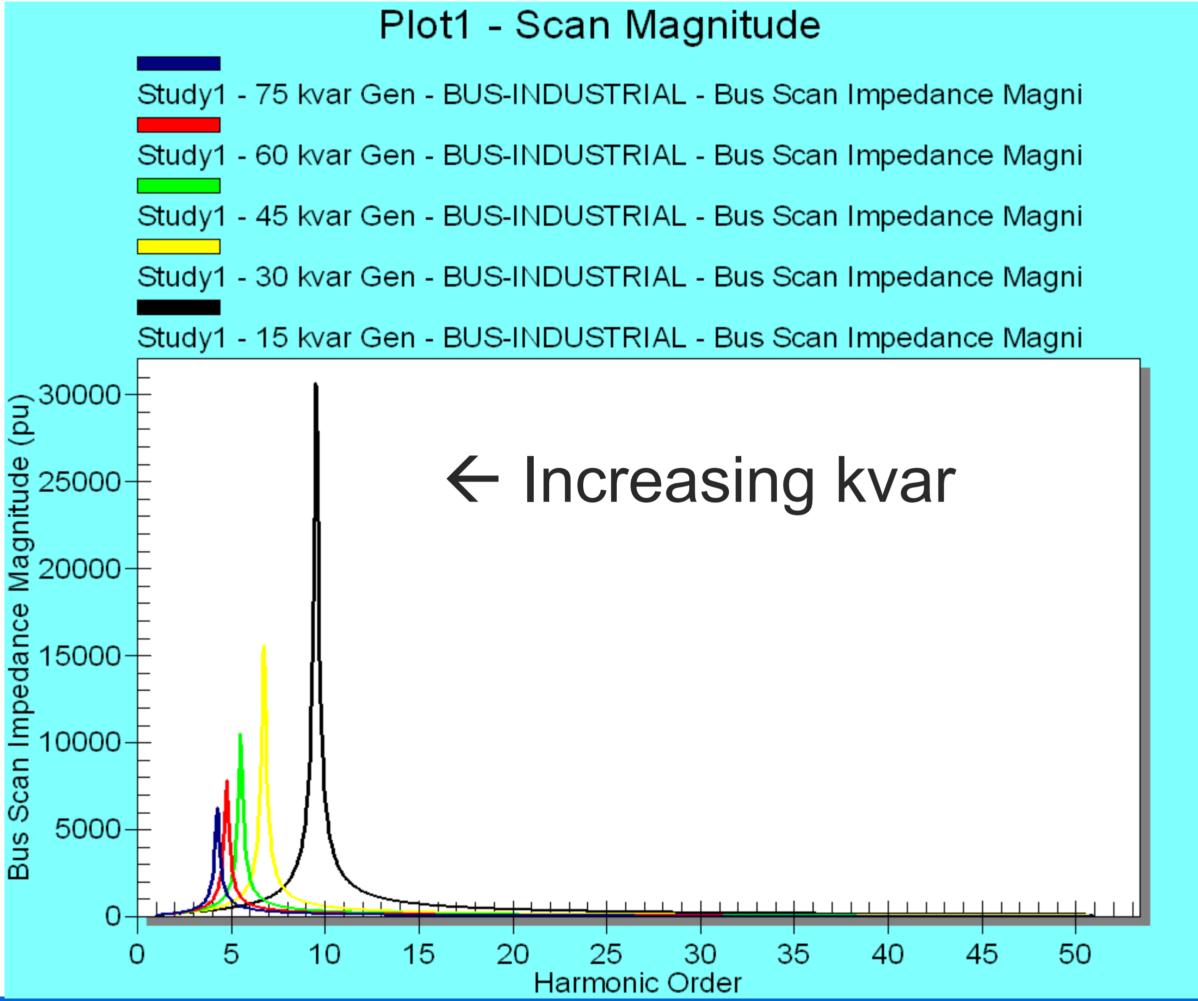
Modeling vs. Lab Results

Normal Source



Modeling vs. Lab Results

Generator Source



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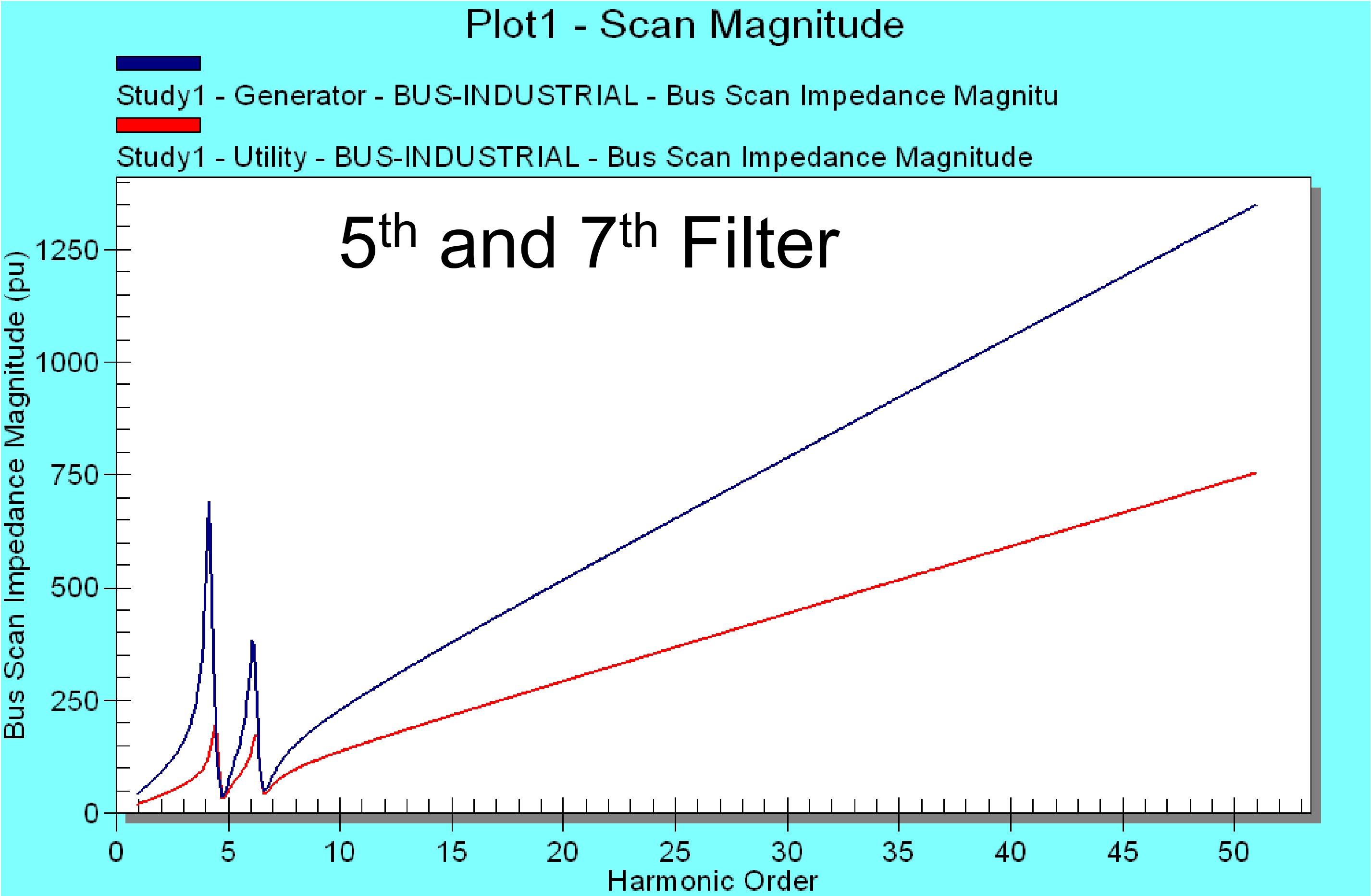
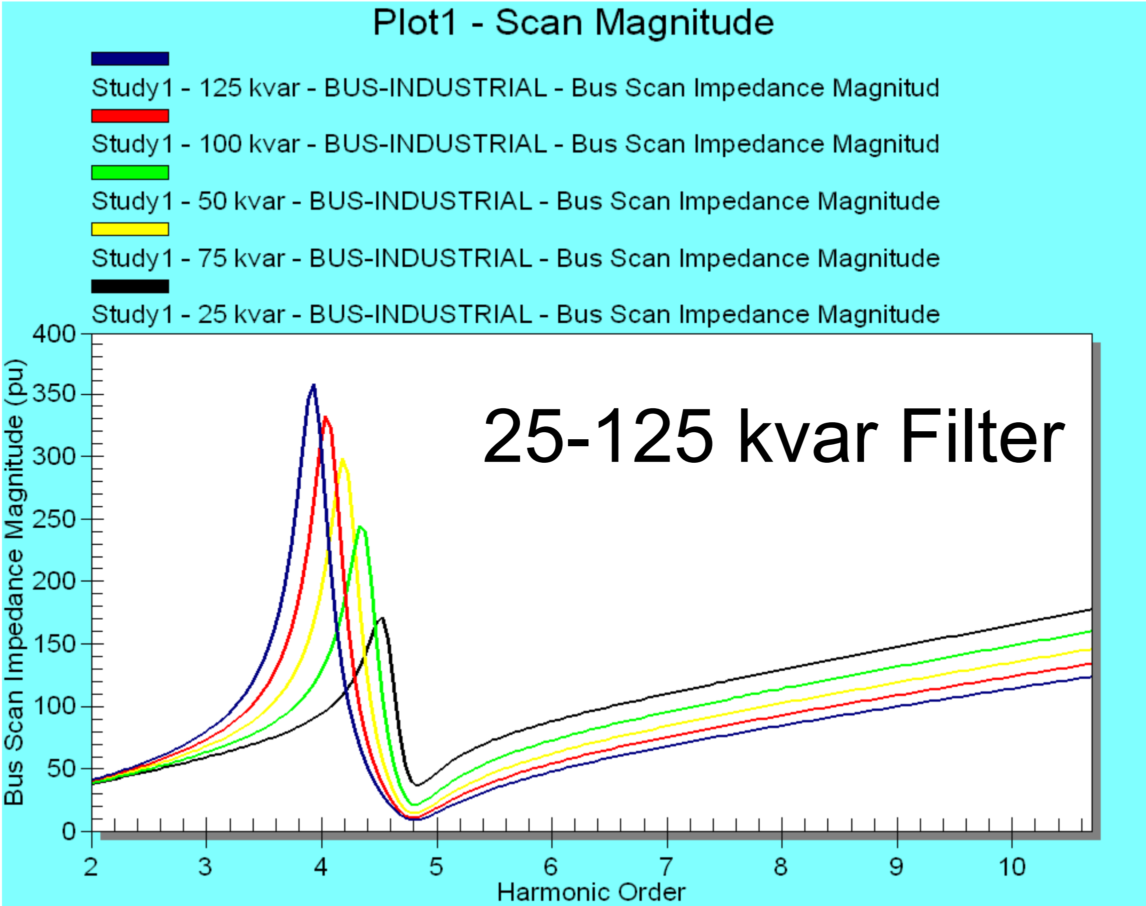
Filter Design Considerations

SKM Frequency Scan (Normal and Generator Source)



Filters Control Parallel Resonance Point

SKM Frequency Scan



Parallel resonant point is usually about 1 order below the “tuning” frequency

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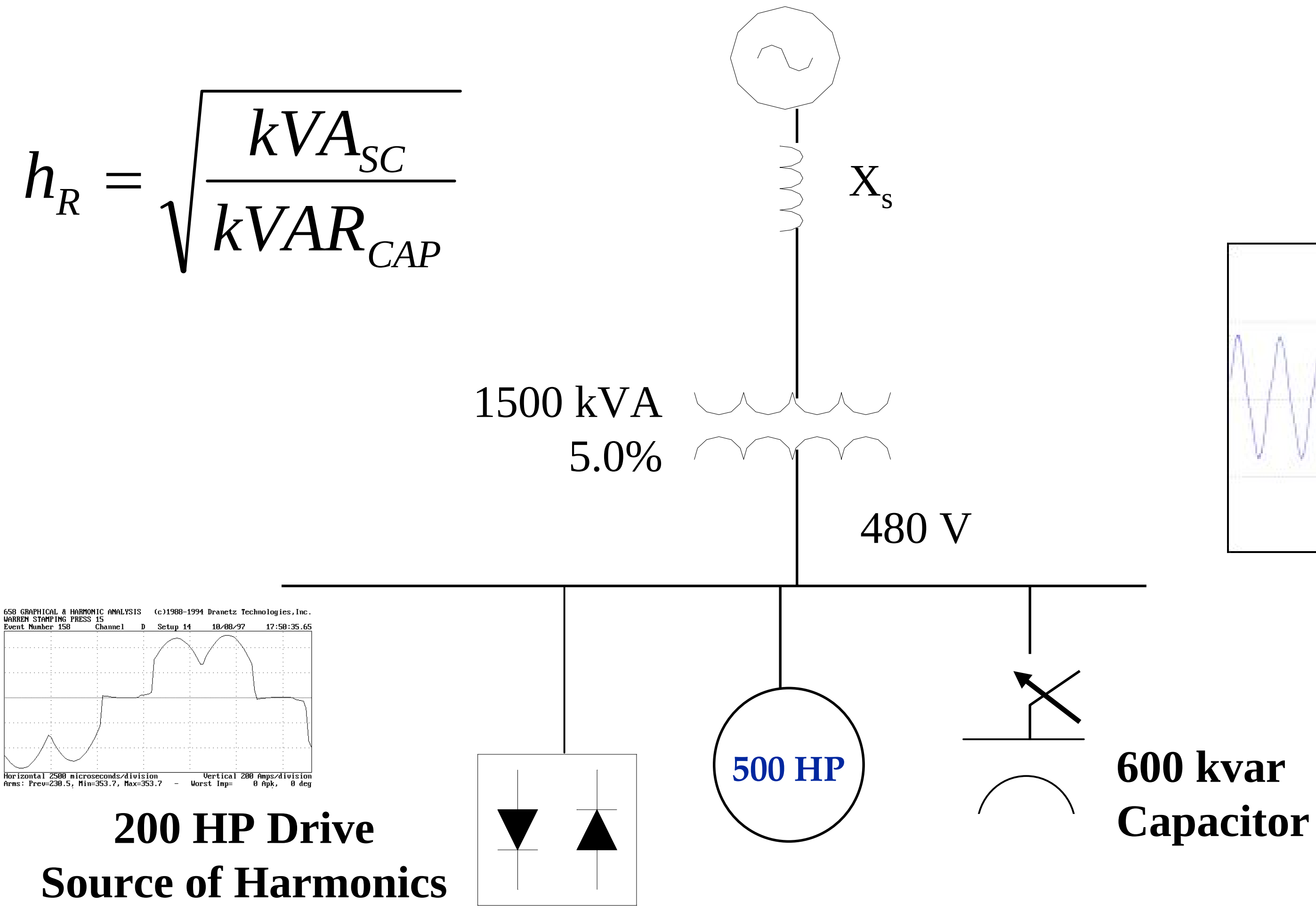
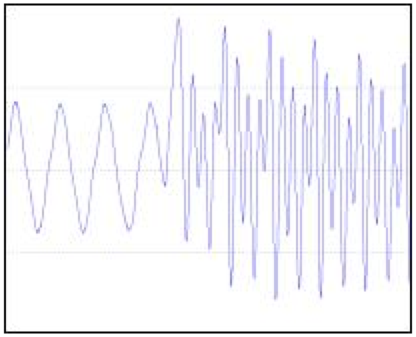
Harmonic Resonance

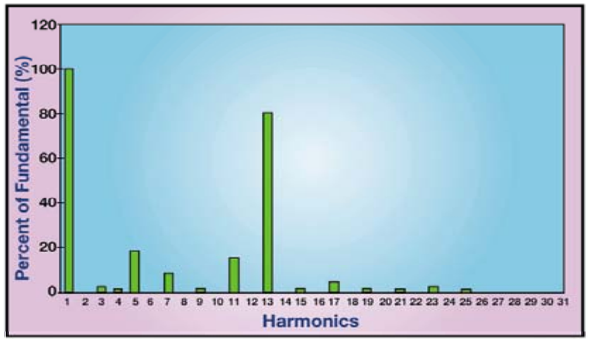
$$h_R = \sqrt{\frac{kVA_{SC}}{kVAR_{CAP}}}$$

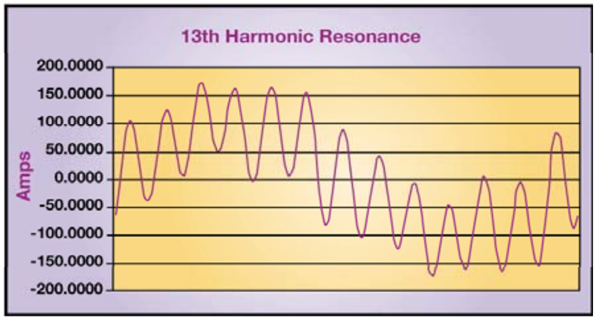


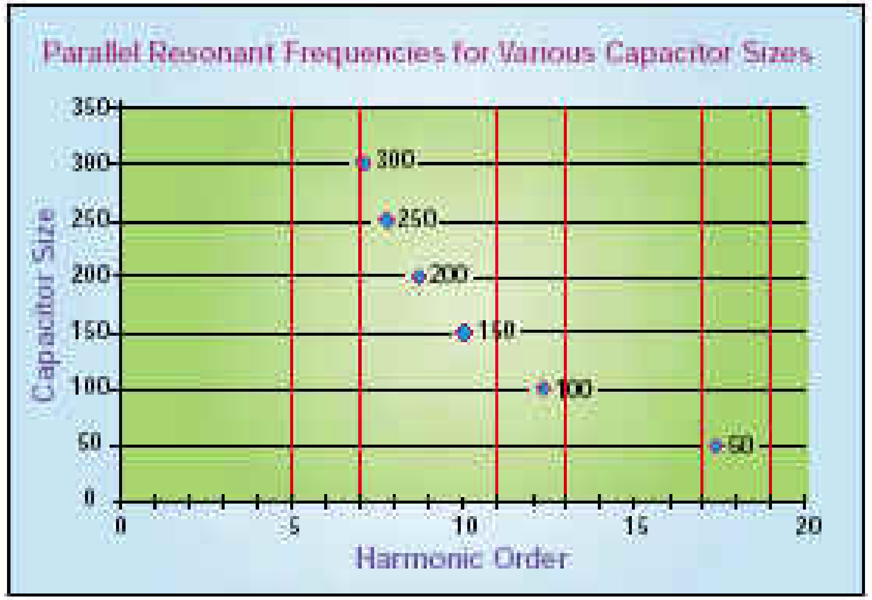


Harmonic Resonance - Solutions

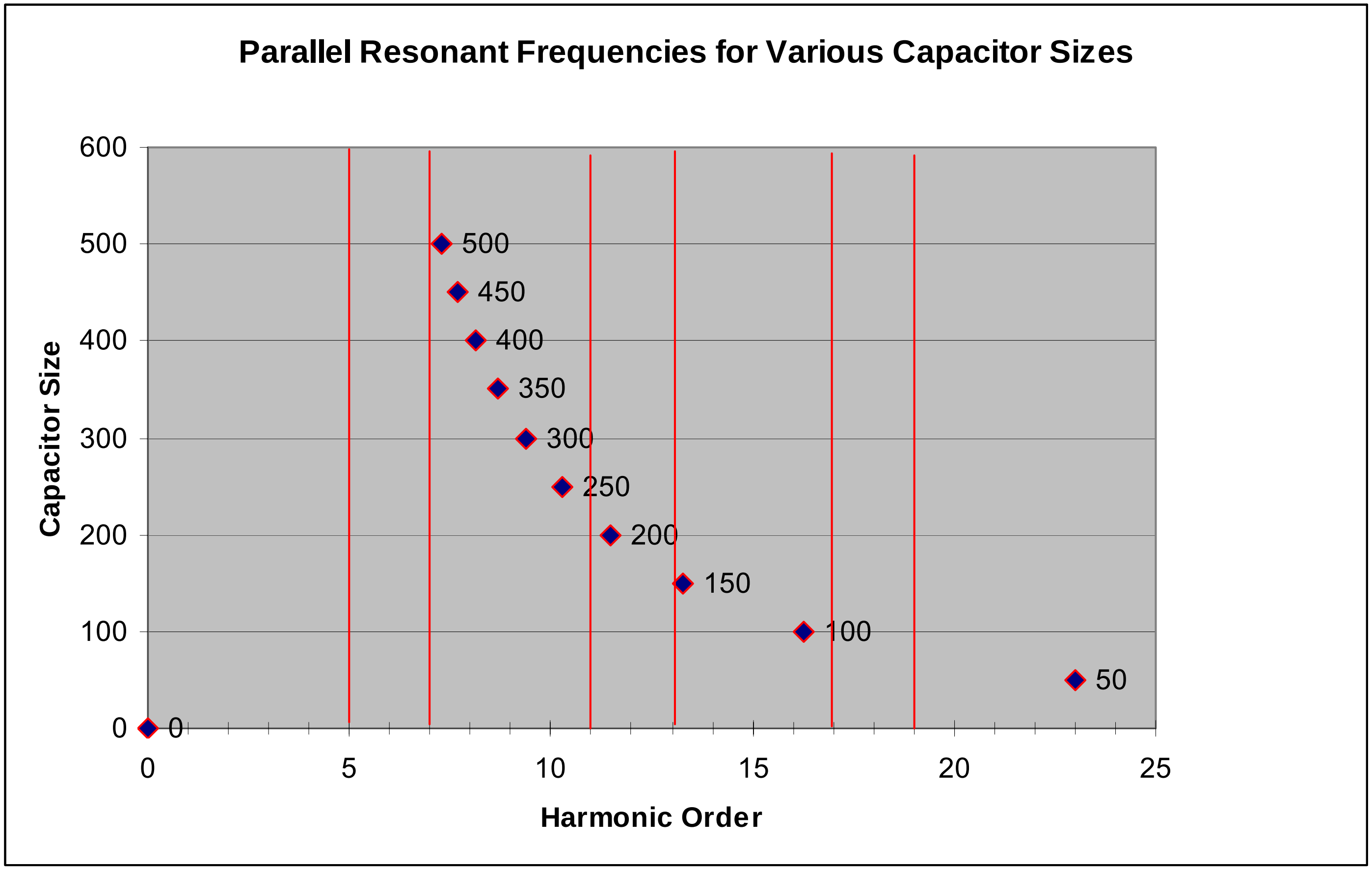
1. **Change the method** of kvar compensation (harmonic filter, active filter, etc.)
2. **Change the size** of the capacitor bank to over-compensate or under-compensate for the required kvar and live with the ramifications (i.e. overvoltage or PF penalty).



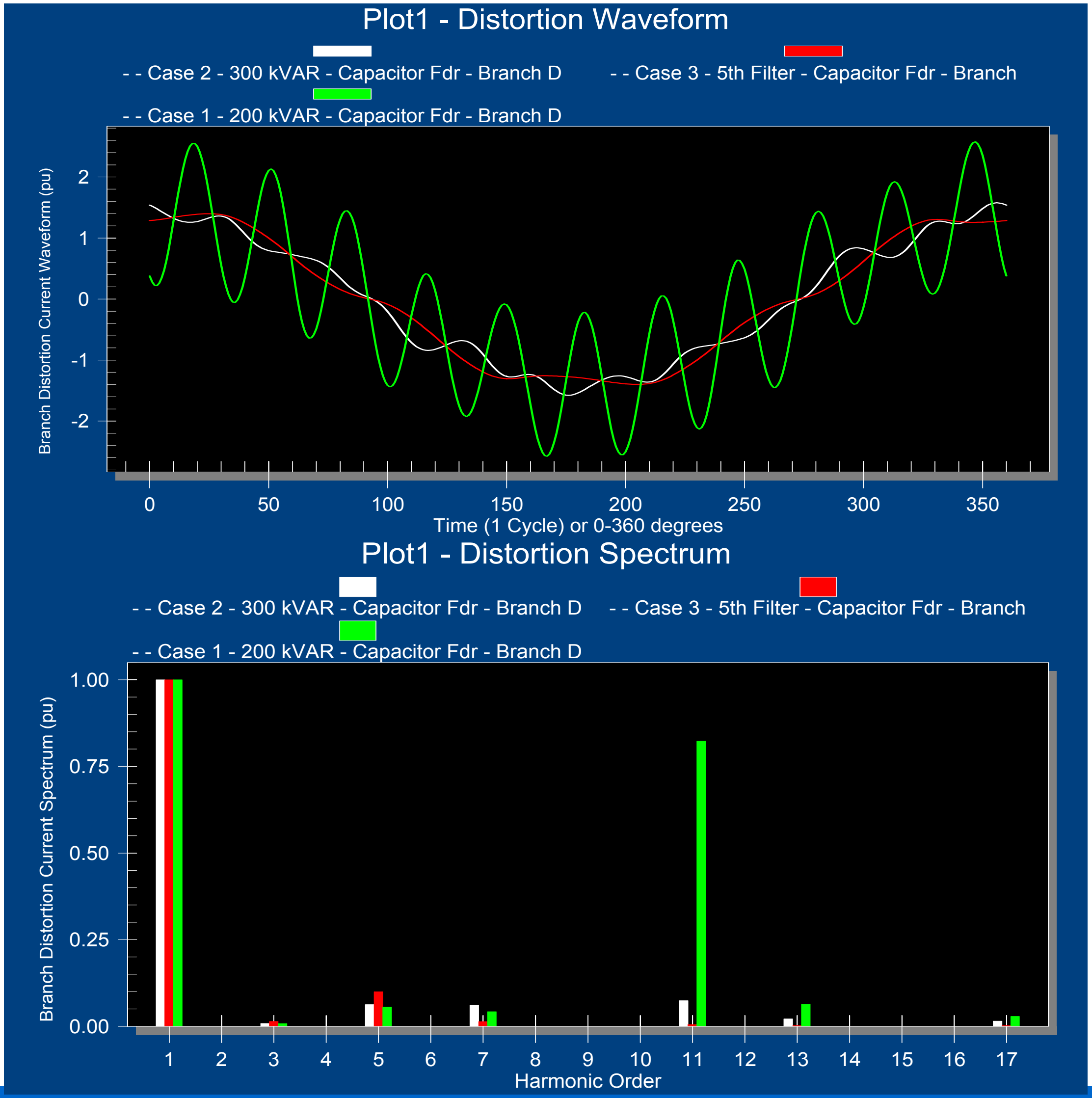




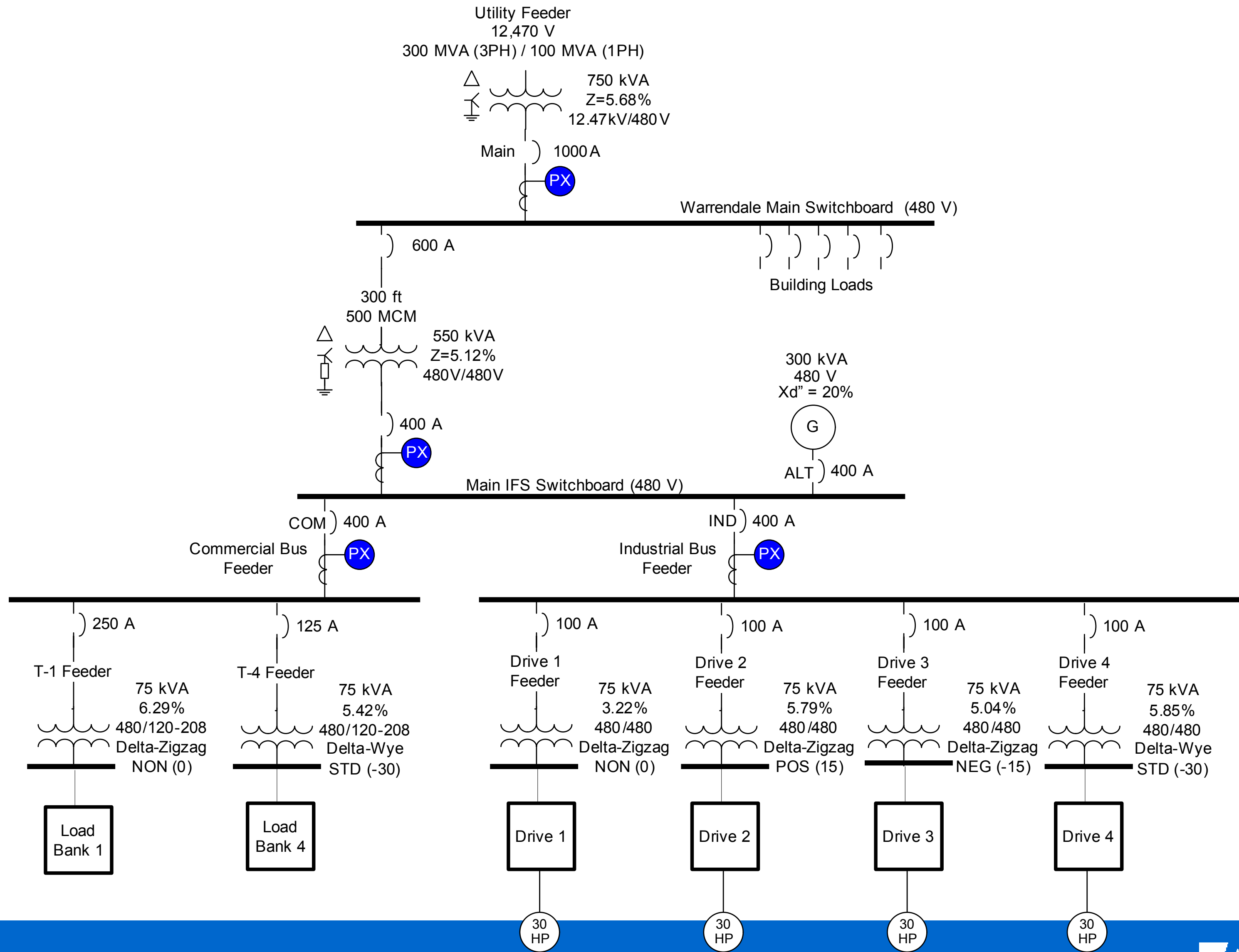
Harmonic Resonance – Switched Capacitor



Harmonic Resonance – SKM Output



Lab One-Line for Model

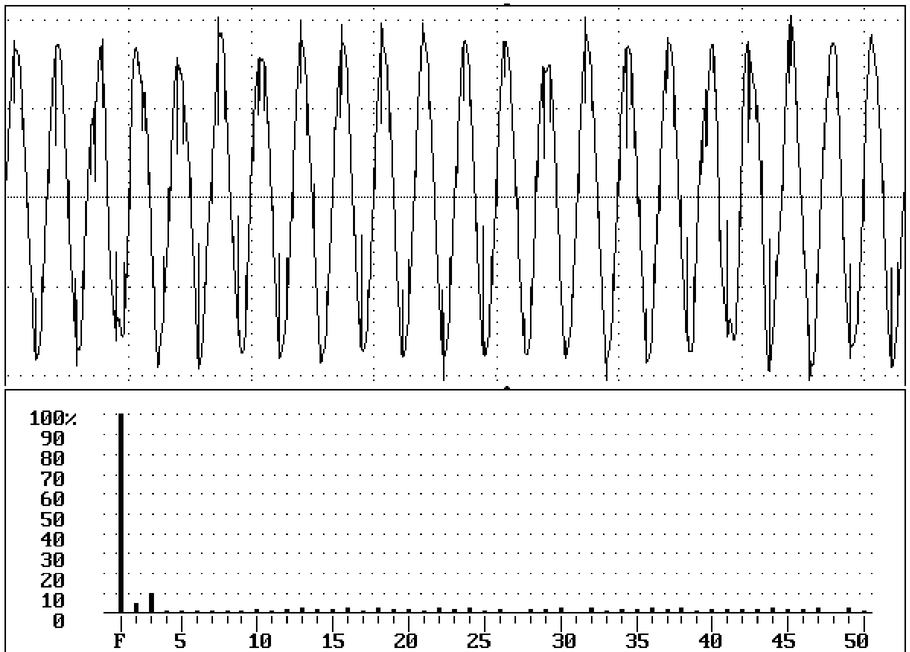


Resonance Calculation – Exercise

- Calculate the parallel resonance point (harmonic order) for the following system for each capacitor switching step
- Calculate using the Normal and Alternate Source impedance

		Source			
Capacitor		Normal		Generator	
Step	kvar	Calc	HW	Calc	HW
1	15				
2	30				
3	45				
4	60				
5	75				

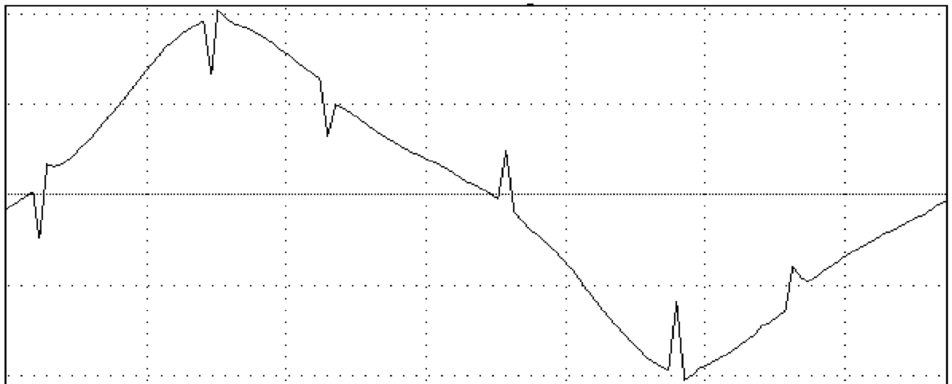
Parallel Resonant Example
3^{rd} Harmonic Voltage

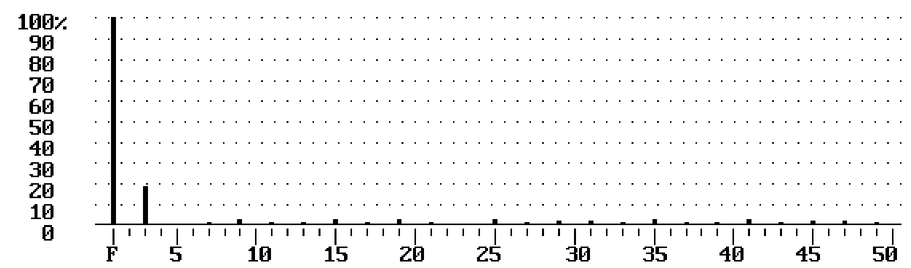


HARMONIC NUMBER:	50	3rd:	10.1% Phase: 275 degrees
TOTAL HARMONIC DISTORTION:	16.7%	2nd:	5.0% Phase: 111 degrees
ODD CONTRIBUTION:	12.6%	38th:	2.8% Phase: 195 degrees
EVEN CONTRIBUTION:	11.0%	32nd:	2.6% Phase: 129 degrees

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

Parallel Resonant Example
3rd Harmonic Voltage

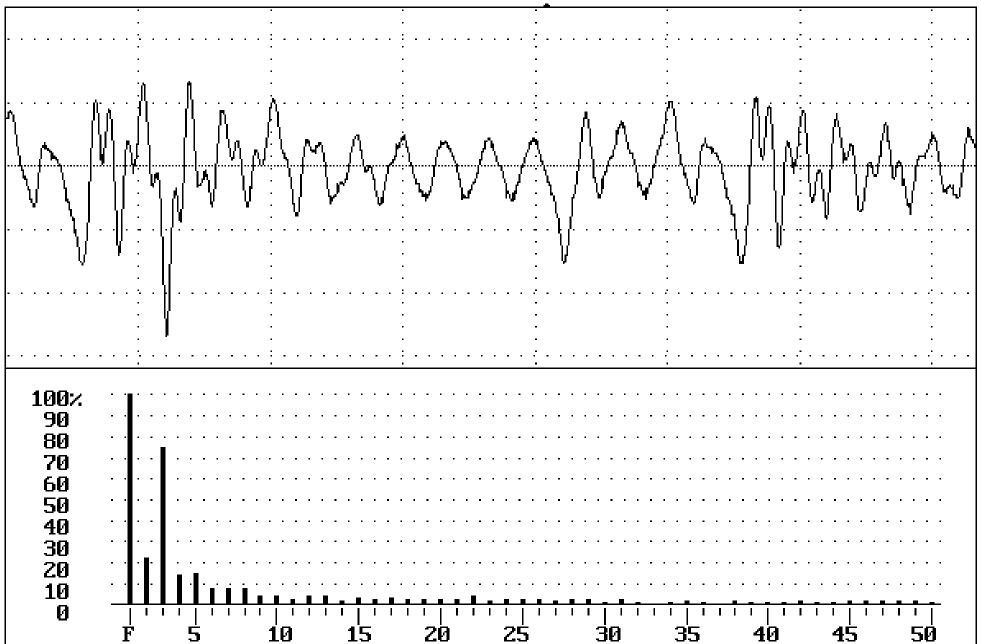




HARMONIC NUMBER:	50	3rd:	18.6% Phase: 171 degrees
TOTAL HARMONIC DISTORTION:	20.2%	9th:	2.8% Phase: 47 degrees
ODD CONTRIBUTION:	20.2%	25th:	2.8% Phase: 279 degrees
EVEN CONTRIBUTION:	1.7%	15th:	2.6% Phase: 3 degrees

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

Parallel Resonant Example
3rd Harmonic Current



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

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

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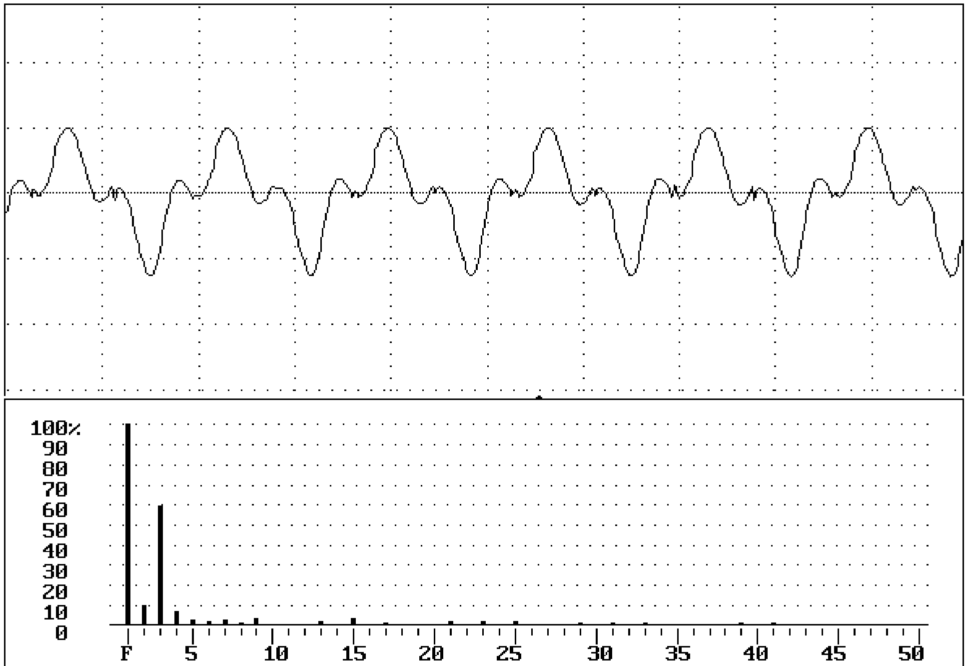
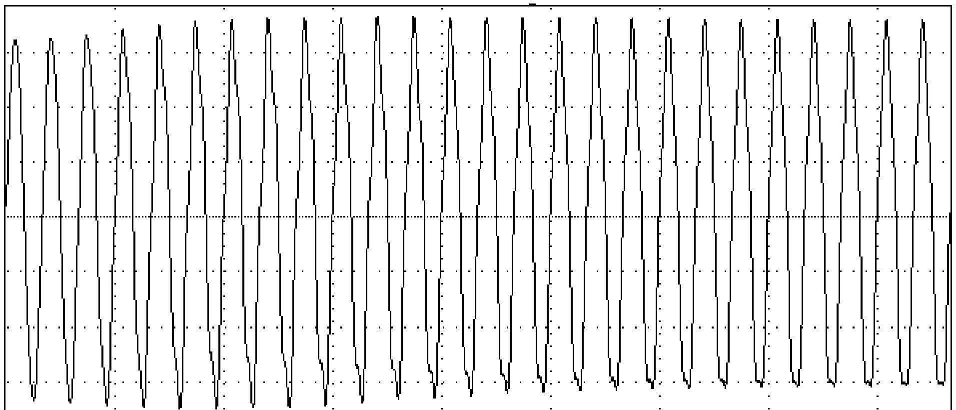
Parallel Resonant Example
3rd Harmonic Current

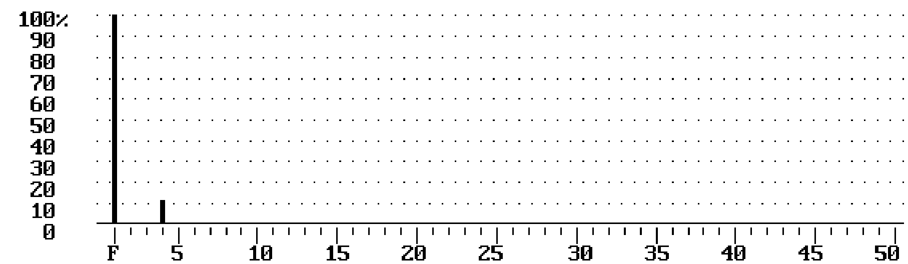


HARMONIC NUMBER:	50	3rd:	59.5%	Phase:	60	degrees
TOTAL HARMONIC DISTORTION:	61.1%	2nd:	9.5%	Phase:	114	degrees
ODD CONTRIBUTION:	59.9%	4th:	7.2%	Phase:	57	degrees
EVEN CONTRIBUTION:	12.3%	9th:	3.0%	Phase:	280	degrees

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

Parallel Resonant Example
4th Harmonic Voltage

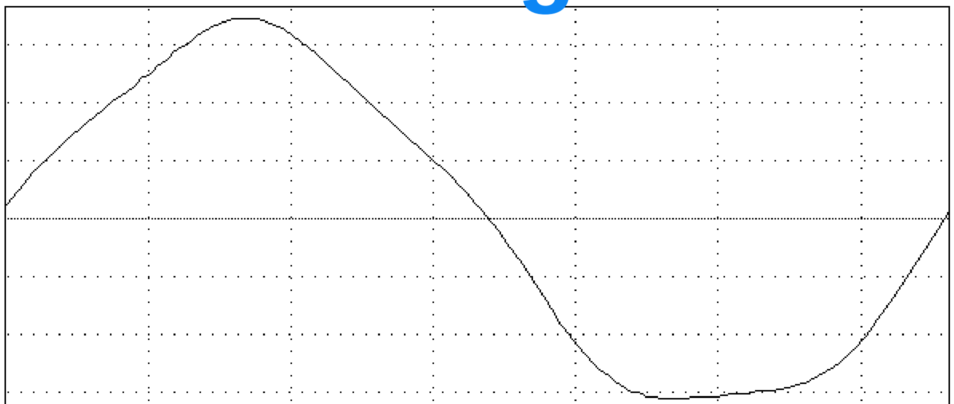


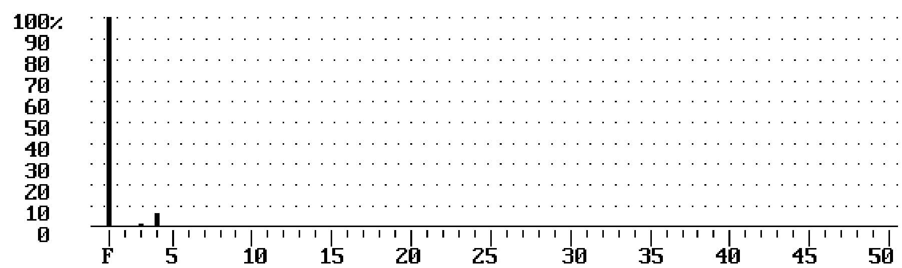


HARMONIC NUMBER:	50	4th:	11.0% Phase: 264 degrees
TOTAL HARMONIC DISTORTION:	11.0%	3rd:	0.3% Phase: 195 degrees
ODD CONTRIBUTION:	0.5%	2nd:	0.2% Phase: 316 degrees
EVEN CONTRIBUTION:	11.0%	7th:	0.2% Phase: 295 degrees

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

Parallel Resonant Example
4^{th} Harmonic Voltage

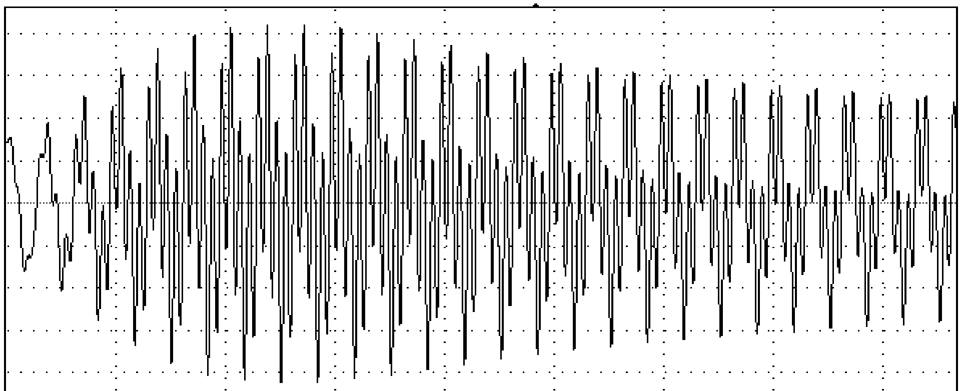


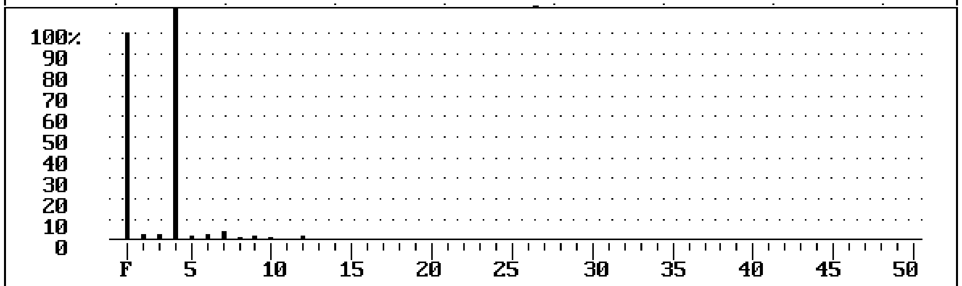


HARMONIC NUMBER:	50	4th:	6.4%	Phase:	11 degrees
TOTAL HARMONIC DISTORTION:	6.5%	3rd:	0.8%	Phase:	104 degrees
ODD CONTRIBUTION:	0.9%	7th:	0.2%	Phase:	293 degrees
EVEN CONTRIBUTION:	6.4%	2nd:	0.1%	Phase:	275 degrees

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

Parallel Resonant Example
4th Harmonic Current

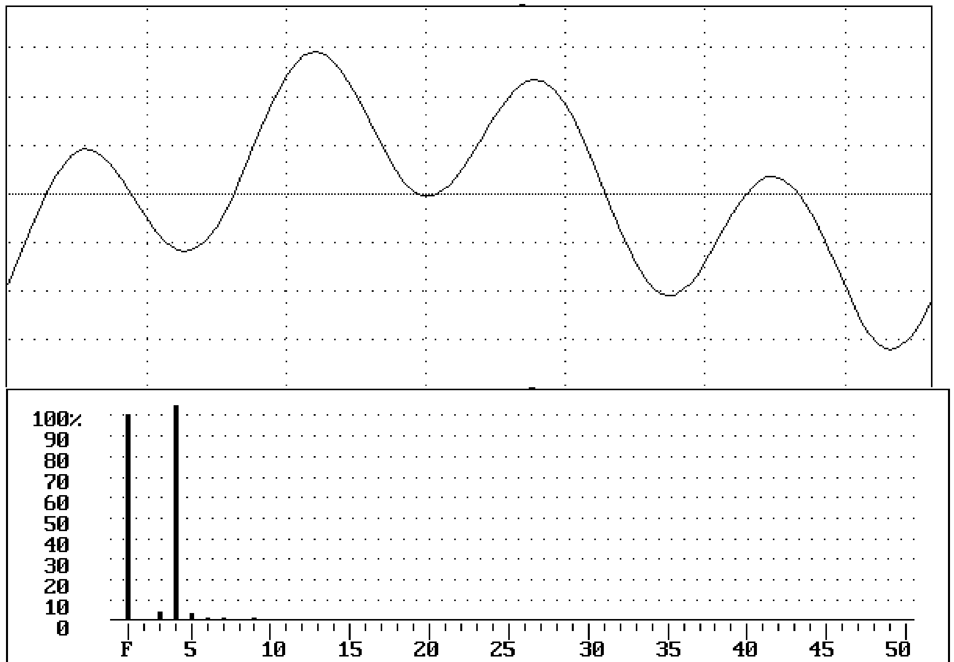




HARMONIC NUMBER:	50	4th:	171.1%	Phase:	323 degrees
TOTAL HARMONIC DISTORTION:	171.3%	7th:	4.1%	Phase:	149 degrees
ODD CONTRIBUTION:	5.6%	2nd:	2.8%	Phase:	162 degrees
EVEN CONTRIBUTION:	171.2%	3rd:	2.6%	Phase:	214 degrees

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

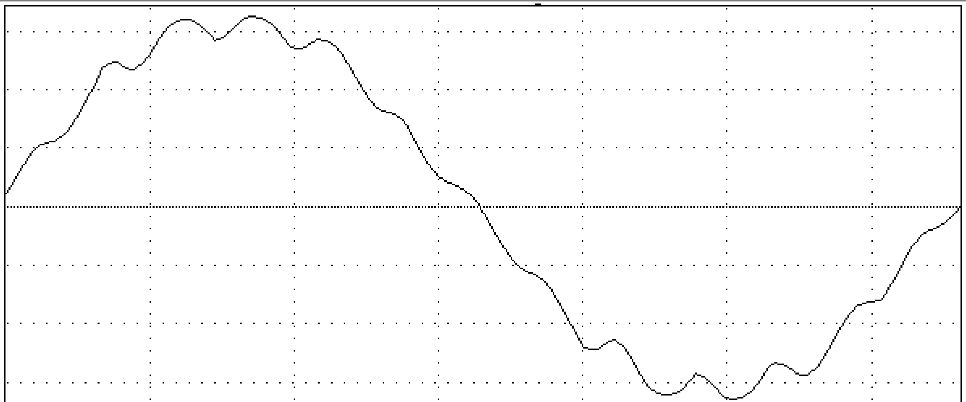
Parallel Resonant Example
4th Harmonic Current

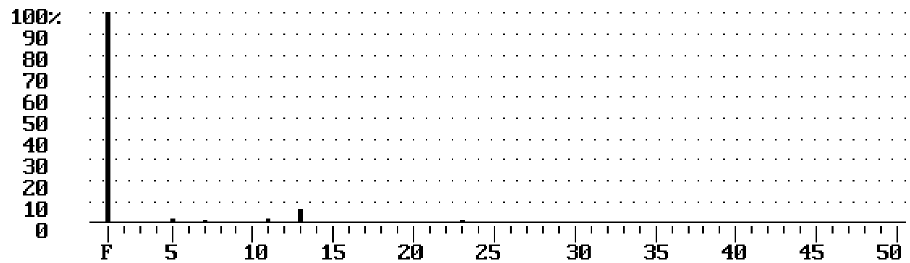


HARMONIC NUMBER:	50	4th:	104.7%	Phase:	109	degrees
TOTAL HARMONIC DISTORTION:	104.8%	3rd:	3.8%	Phase:	174	degrees
ODD CONTRIBUTION:	5.0%	5th:	2.9%	Phase:	107	degrees
EVEN CONTRIBUTION:	104.7%	7th:	1.2%	Phase:	128	degrees

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

Parallel Resonant Example
13th Harmonic Voltage





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

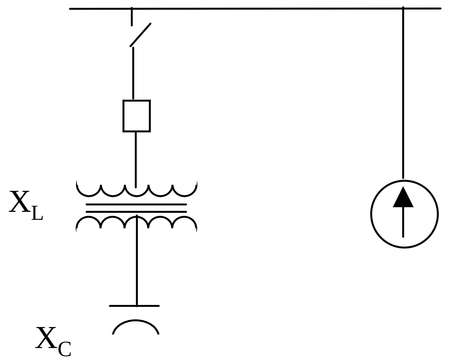
Fnd:	111.87V 85 deg	18th:	0.1% 160 deg	35th:	0.0% 126 deg
2nd:	0.0% 174 deg	19th:	0.4% 352 deg	36th:	0.0% 60 deg
3rd:	0.1% 33 deg	20th:	0.0% 150 deg	37th:	0.0% 141 deg
4th:	0.1% 178 deg	21st:	0.1% 95 deg	38th:	0.0% 11 deg
5th:	1.5% 238 deg	22nd:	0.0% 40 deg	39th:	0.1% 328 deg
6th:	0.5% 331 deg	23rd: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

Series Resonance

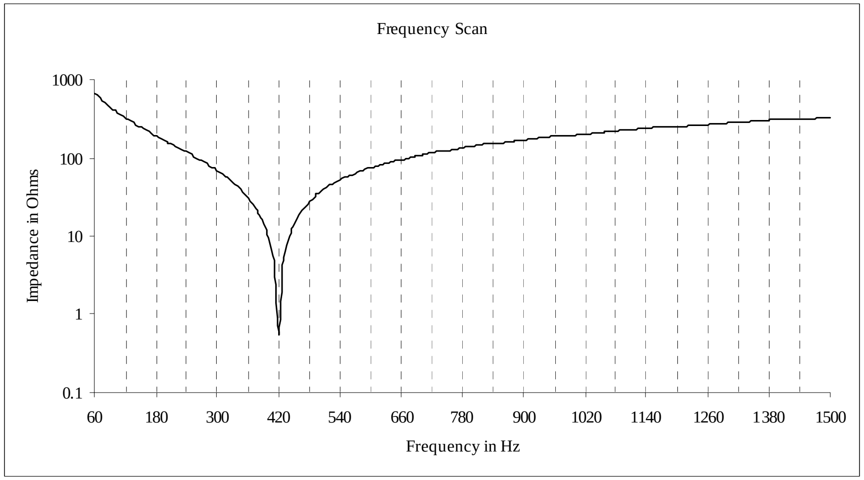
The series combination of impedance is:

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

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

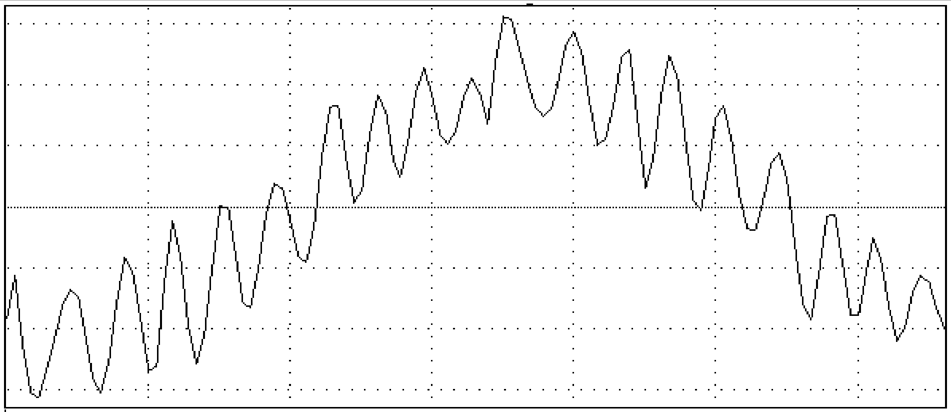


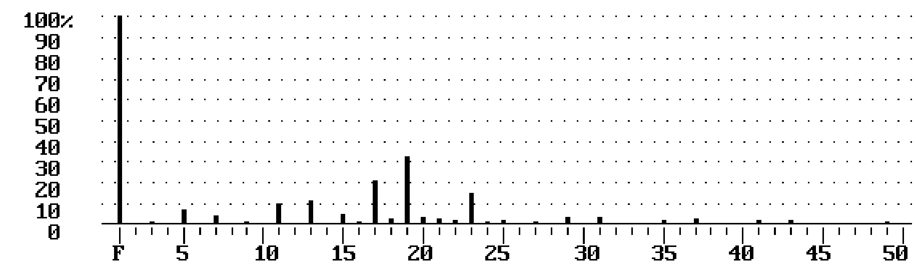
Equivalent Series Resonant Circuit



Frequency Scan for Series Resonant Circuit

Series Resonant Example
19th Harmonic Current





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

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

Ferroresonance

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

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

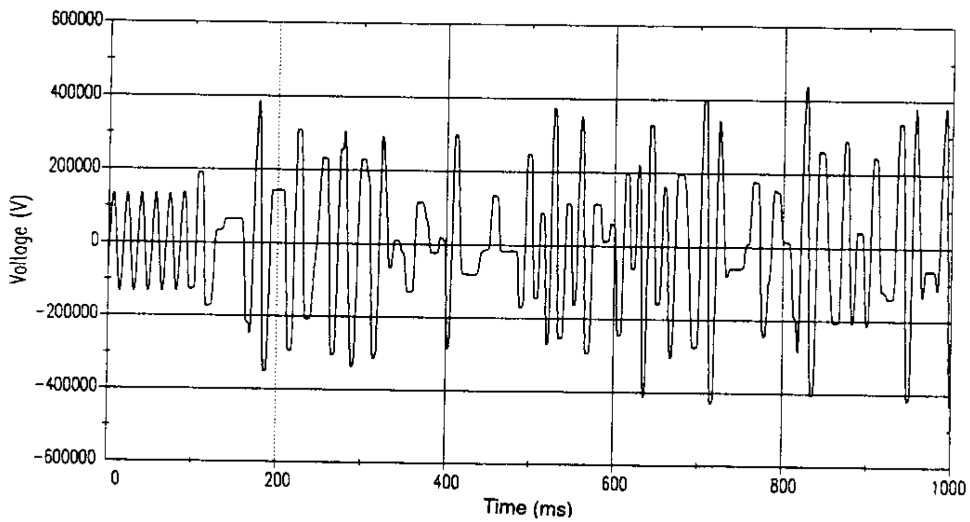
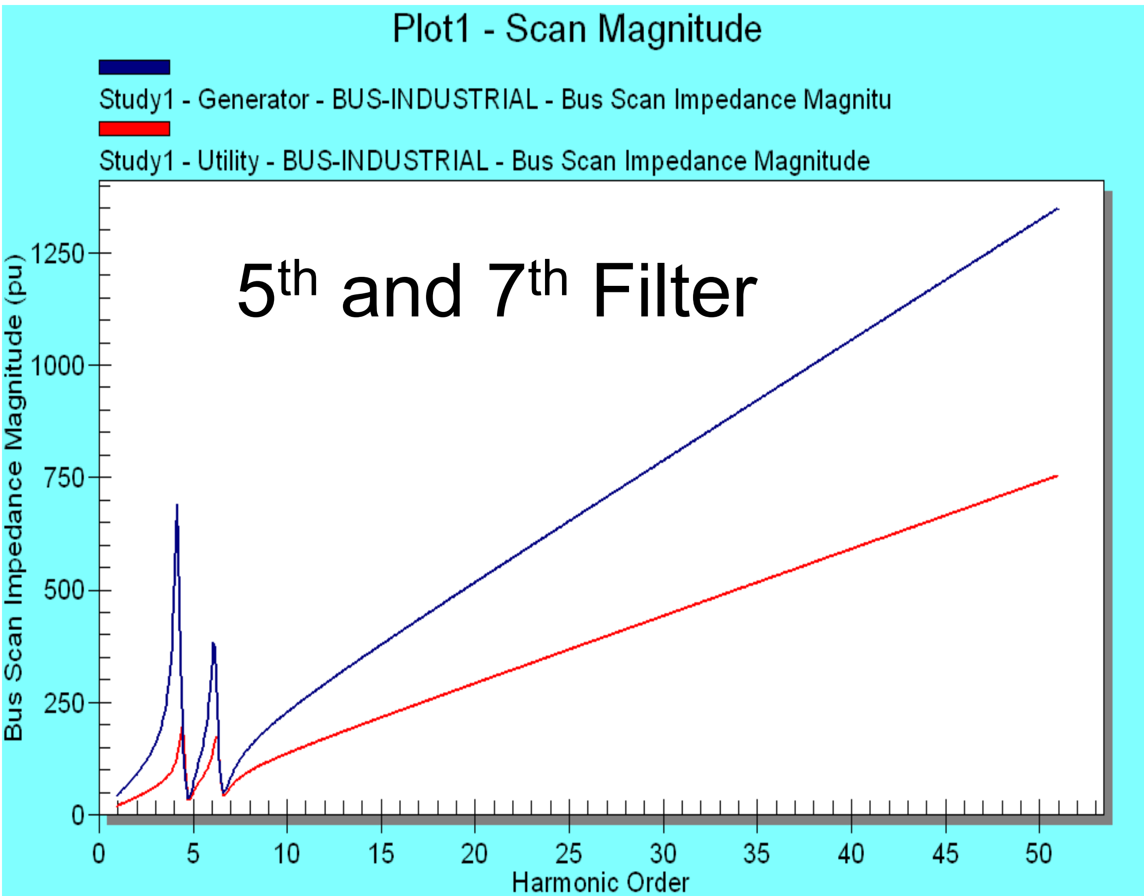


Figure 4—Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer

Multiple Stages of Filters – Exercise #8

SKM Frequency Scan (Normal and Generator Source)



- Multi-stage filters have multiple series and parallel resonant points

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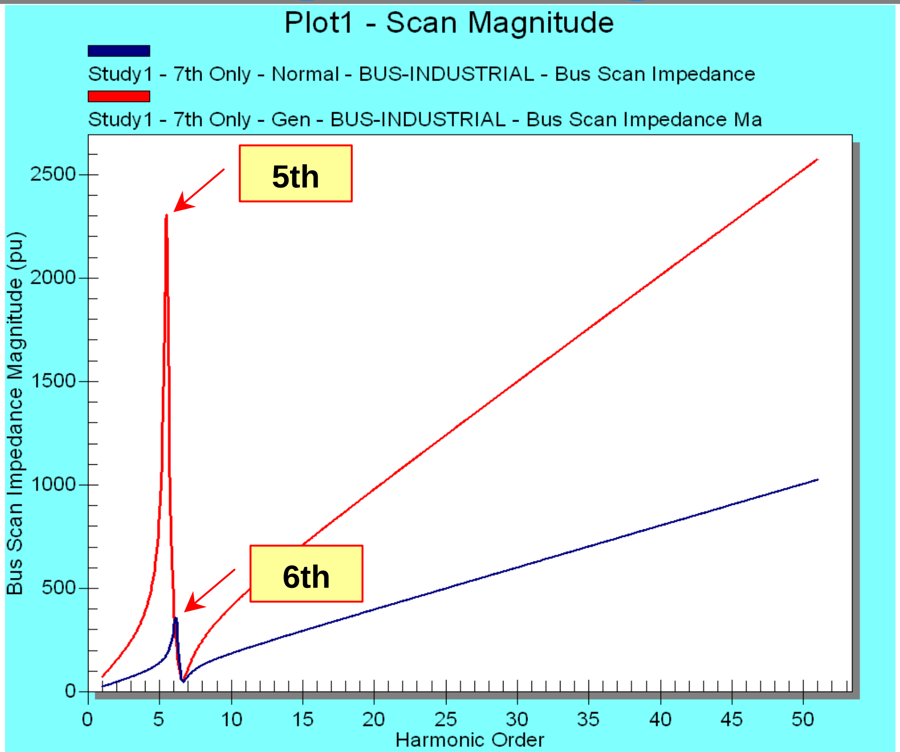
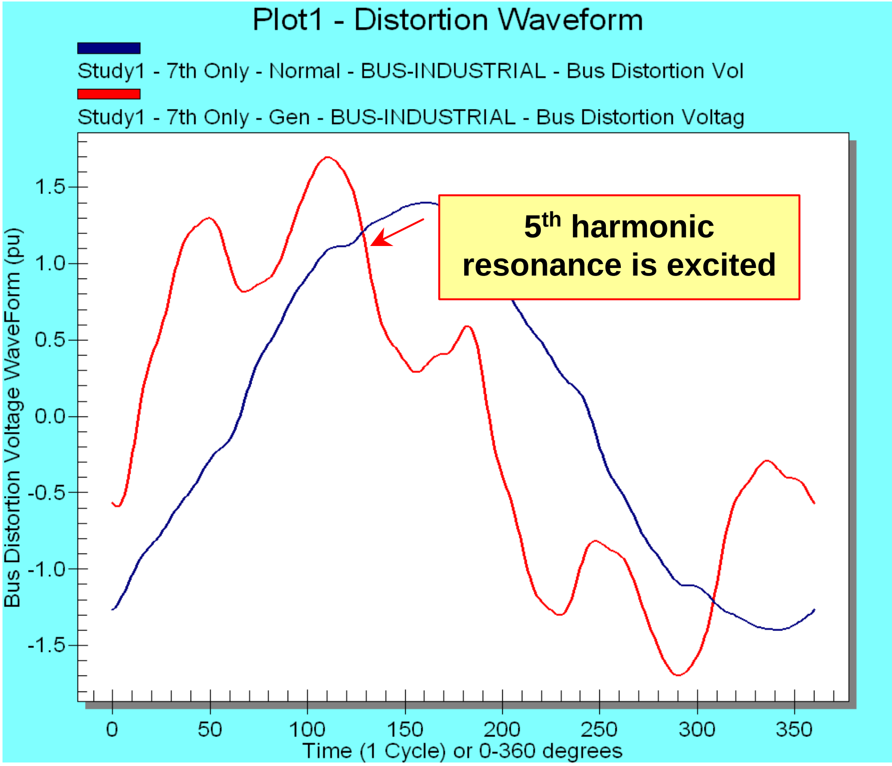
Multiple Stages of Filters



Tuning frequency and switching order are extremely important to control parallel resonance

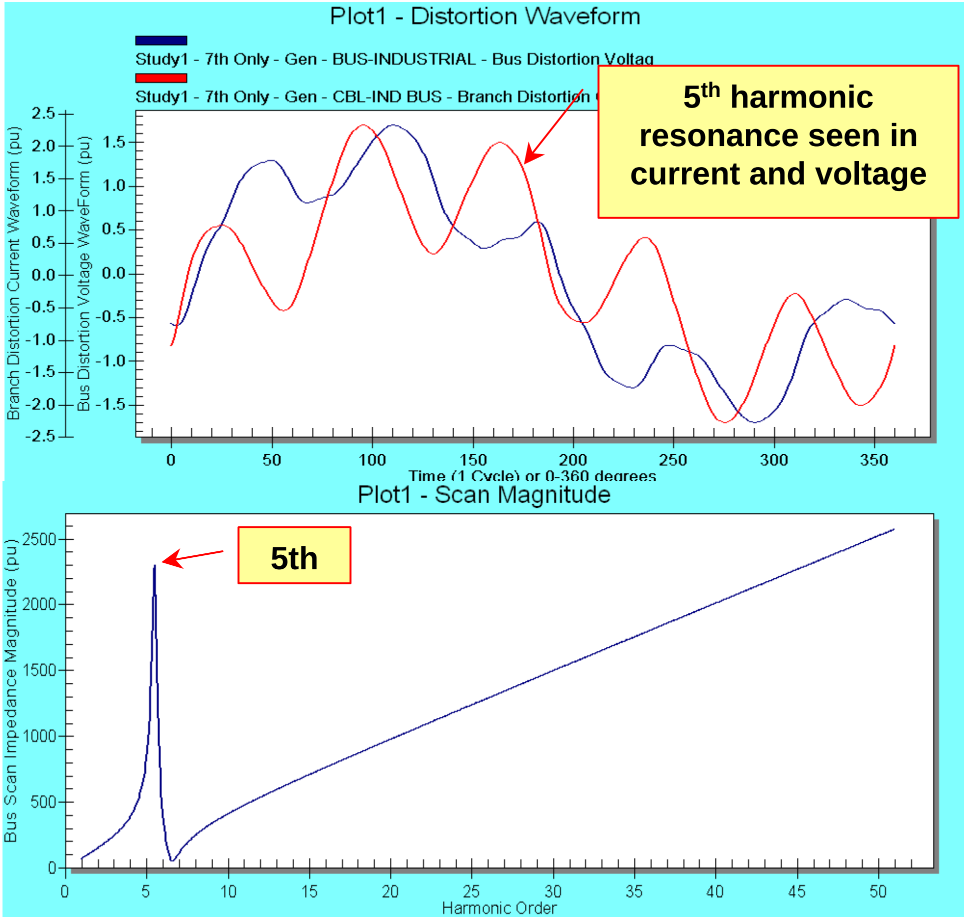


If 7th filter switched first, then the parallel resonance is of concern:

- Near 6th for utility source
- Near 5th for generator source!

Multiple Stages of Filters

- Switching 7th filter first with generator source results in:
- Parallel resonance at the 5th
- The 5th harmonic current from the VFD excites the resonance



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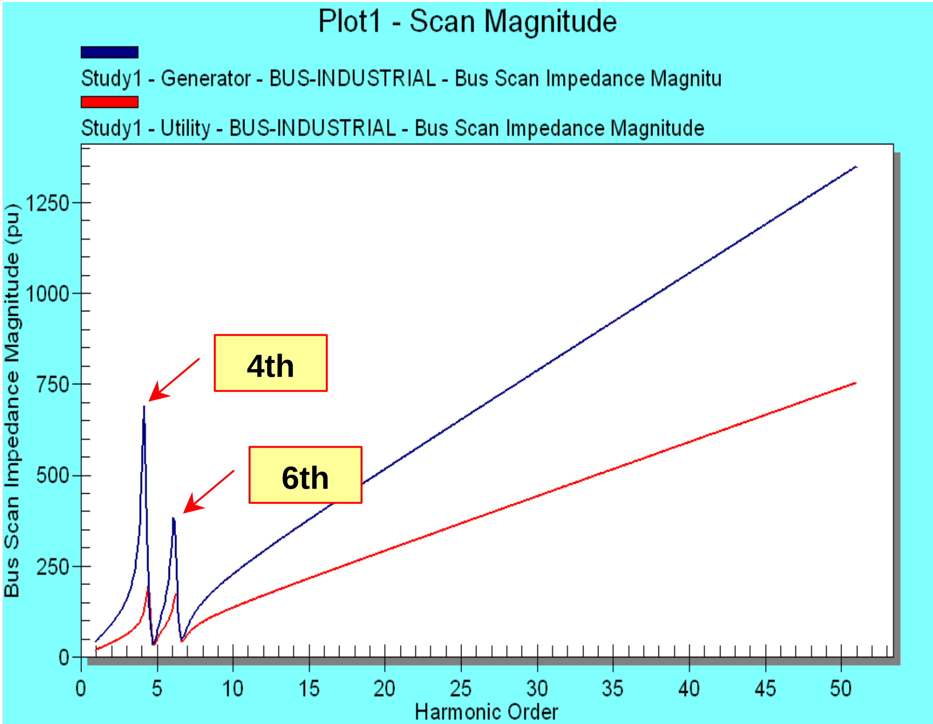
Multiple Stages of Filters

Correct Application

- Filter should be series tuned to lowest expected harmonic
- Typically 5th on 3 phase system with 6-pulse VFDs
- Proper switching order:

  lowest order "first on", "last off"

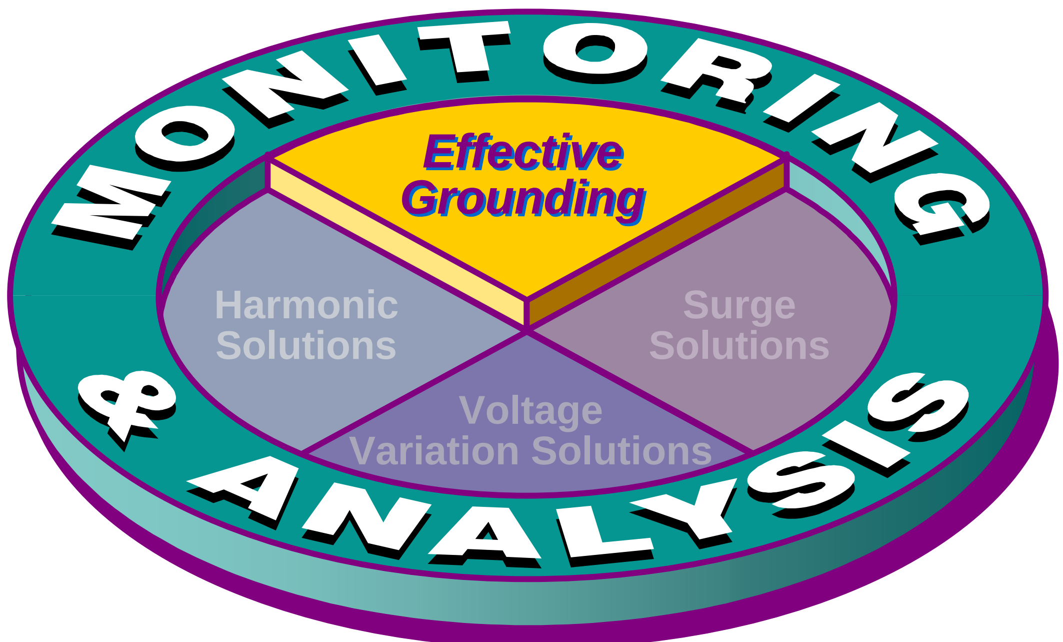
- Example: 5th and 7th Filter
  - **First on = 5th**
  - **Second on = 7th**
  - **First off = 7th**
  - **Second off = 5th**



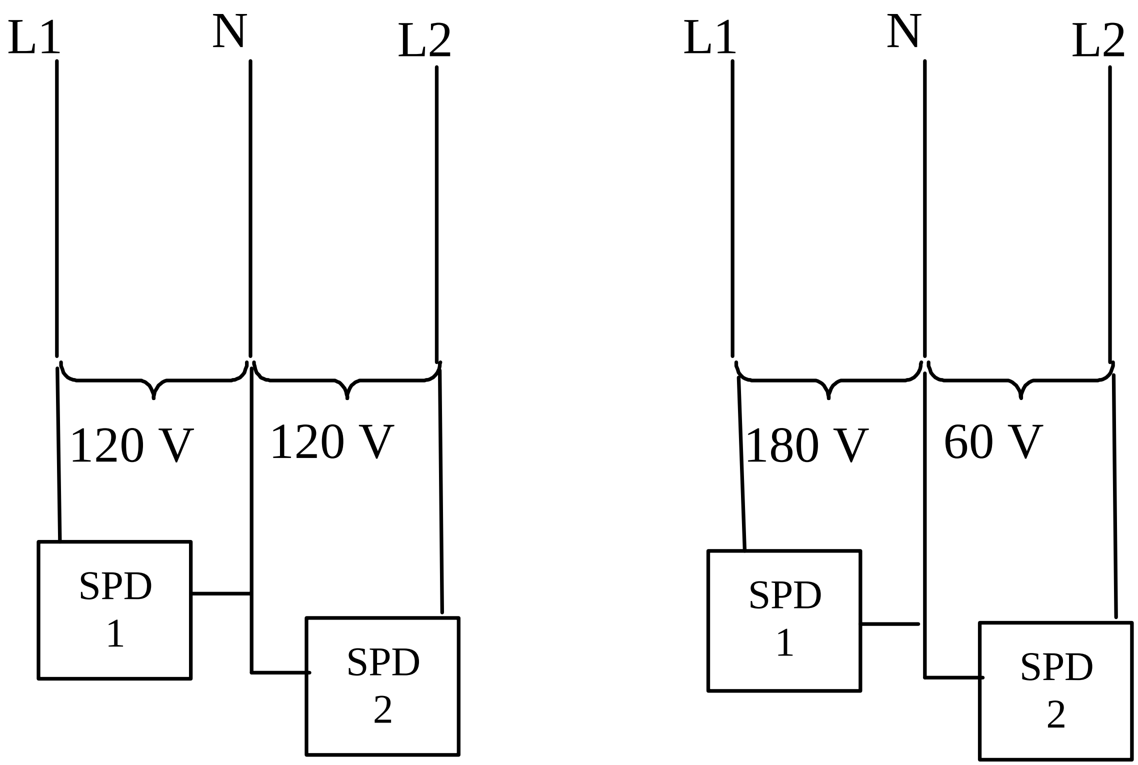
Equipment Grounding

- Foundation of a reliable electrical distribution system
- Critical to the operation of communication and computer network systems
- Critical to proper operation of surge protection

- Related to Over Half of All Power Quality Problems
- Typically least expensive to fix



Wiring/Grounding Issues – Open Neutral



Normal Conditions **Open Neutral**

Residential Power System

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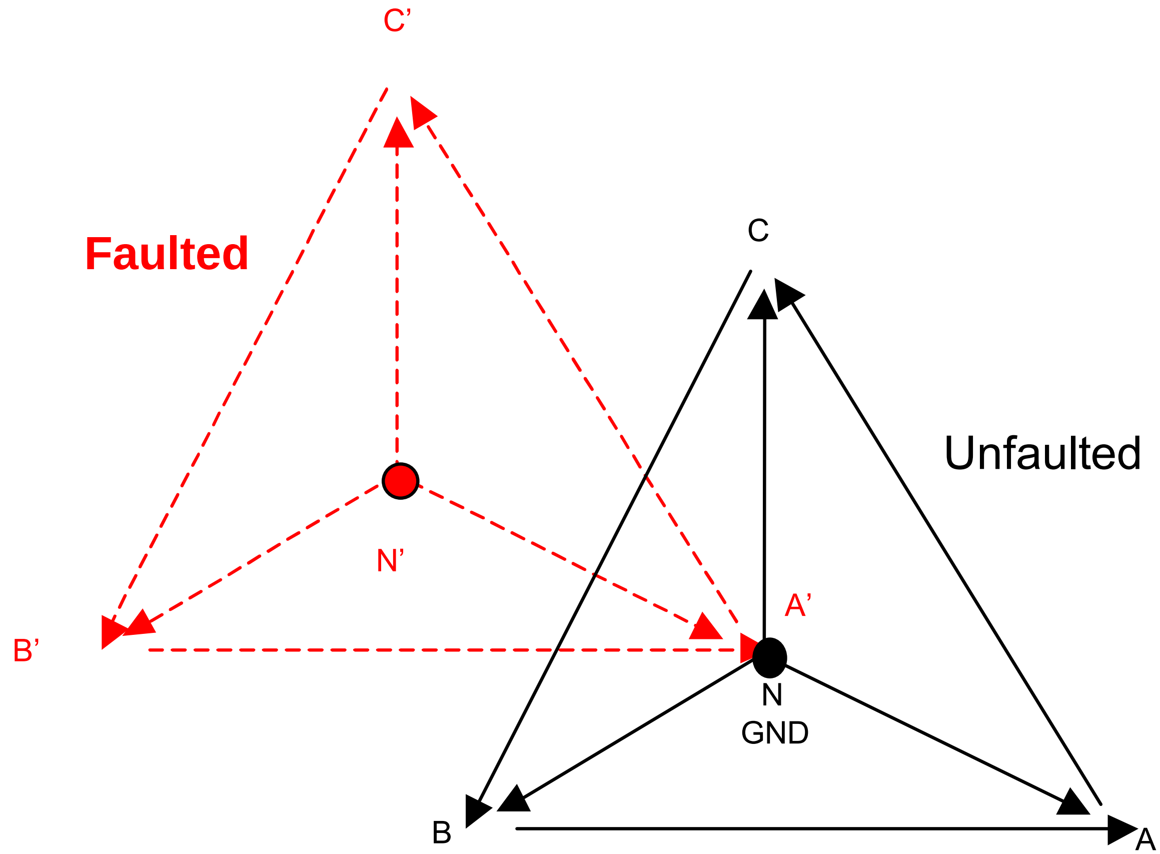
Faults on Ungrounded System

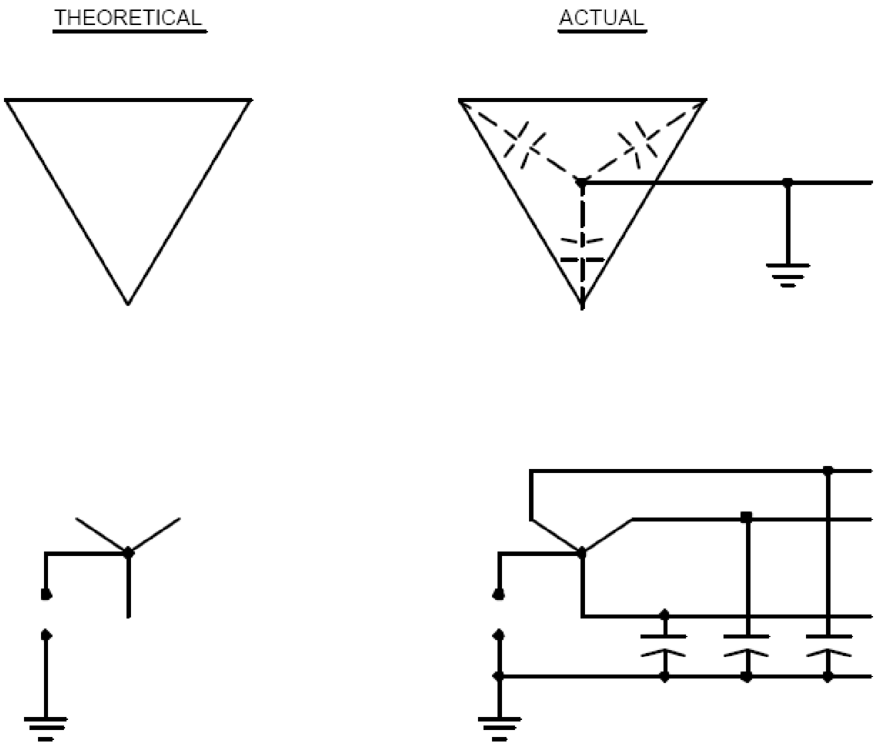
When a fault occurs on a distribution system, a sag (retained voltage is zero at the point of fault) will generally occur on all of the phases that are faulted unless a phase shifting transformer – delta/wye or wye/delta – is between the faulted section of the system and the common bus. A swell may occur on the unfaulted phases if the system is not solidly grounded.

If a line-to-ground fault occurs on an ungrounded or high resistance grounded system, the unfaulted phase(s) may experience line-to-line voltage to ground. The line-to-line voltages will maintain the proper relationship for a single-line-to-ground fault.

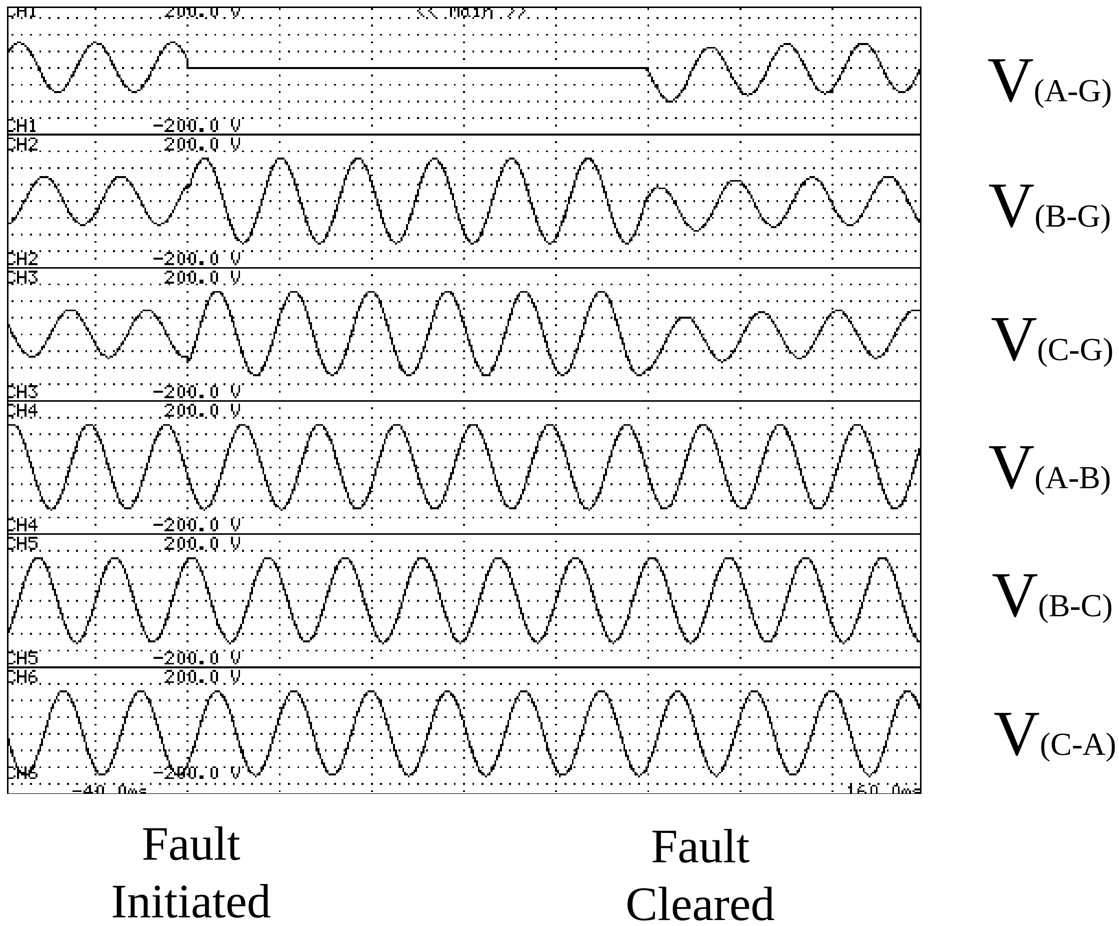


Grounding Example
Delta or Ungrounded Wye

- An ungrounded system has no intentional connection to ground, except through potential indicating or measuring devices or other very high impedance devices.
- Although called ungrounded, this type of system is in reality coupled to ground through the distributed capacitance of its phase windings and conductors.



SLGF on Ungrounded System



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Transformer Winding Connection

Relationship of Transformer Connection to Utilization Bus Voltage

When phase shifting transformers (delta/wye, wye/delta, etc.) are electrically located between the faulted part of the system and the monitoring location (the utilization bus), single-line-to-ground fault may be measured as a single-phase, two-phase, or three-phase voltage sag at the utilization bus. For example, a very severe single-line-to-ground fault on a 115 kV transmission system may appear as an insignificant two or three-phase sag on a 120 V outlet in an office building.

Consequently, although the most common faults (>80%) on a power system are single-line-to-ground faults, typical power quality monitoring shows that voltage sags are evenly split between single-phase, two-phase, and three-phase events. This is primarily the result of the effect of phase shifting transformers. Therefore, these transformers may be carefully applied to protect sensitive electronic equipment in some cases.

Transformer Winding Connection

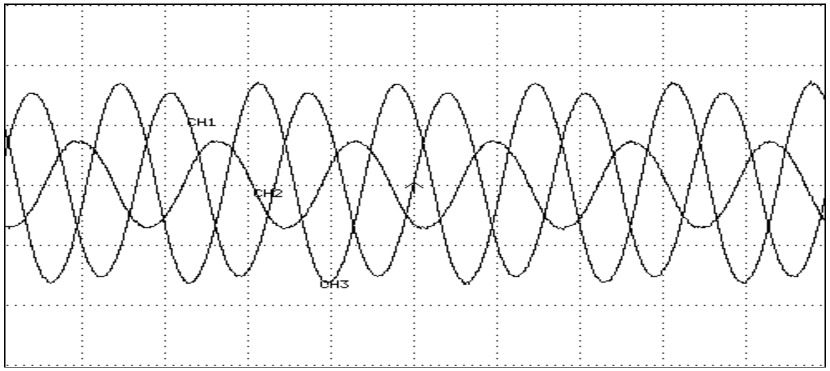


Figure (a) Delta-Wye Transformer – Primary Voltage Line-to-Ground

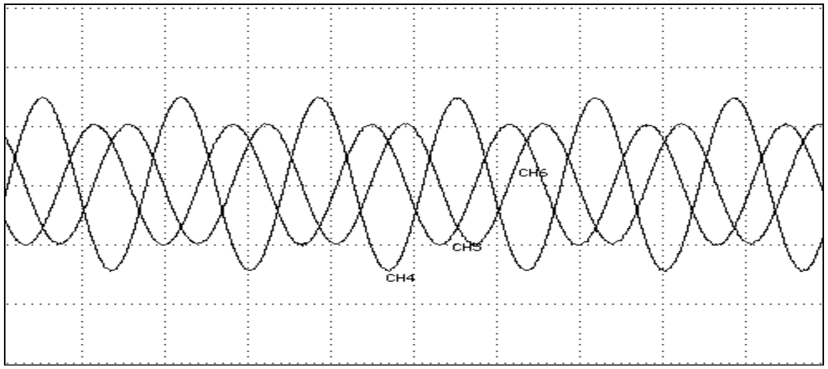
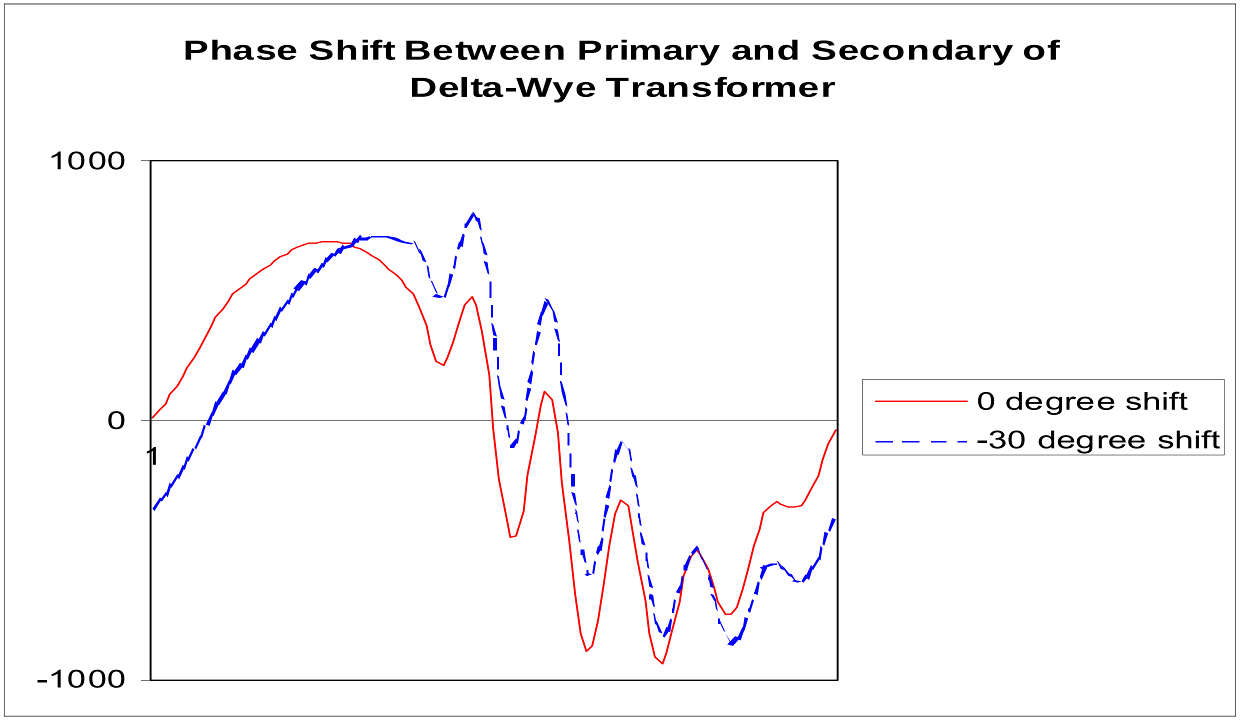


Figure (b) Delta-Wye Transformer – Secondary Voltage Line-to-Ground

Waveform Delta-Wye Transformer – Single-Phase Fault on Primary System

Phase Shifting Effect on Transients

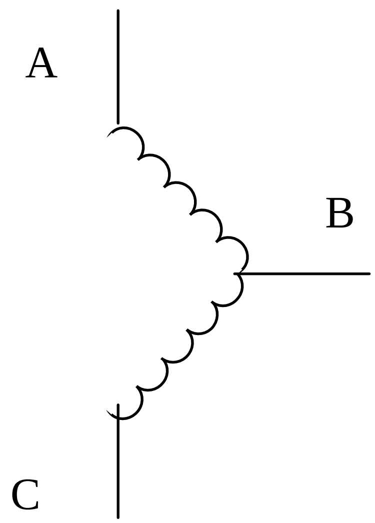
The transformer connection is also related to the effect of power system voltage transients on low voltage equipment. The following example shows the difference in voltage at two different 480 V buses for the same voltage transient initiated at a higher voltage level. Note the **multiple zero crossings**.

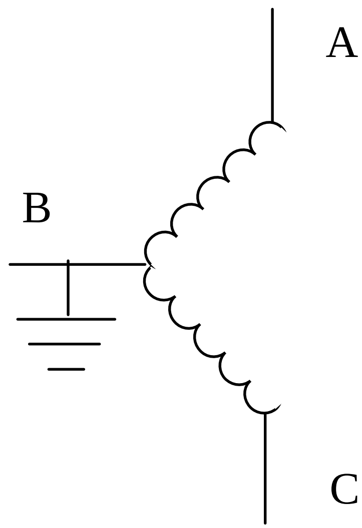


Monitoring on Open Delta PT's

- Normally, on medium voltage power systems, if a voltage measurement is required:
  - standard potential transformers are connected to the primary system (i.e. at 13.2 kV, for example) and they are either connected in a Wye configuration or in an Open-Delta configuration.
  - The arrangement of the PT's is typically a result of cost analysis and need for equivalent line-to-line or line-to-ground measurements.
  - Usually, only line-to-line measurements are required (or important) on a medium voltage system.
  - Therefore, the less expensive solution for monitoring the line-to-line voltage is to connect two PT's in an open delta arrangement.
- Physically, the arrangement is usually as shown below:
  - The two windings accurately represent the three-phase line-to-line primary voltage.
  - The midpoint of the transformers on the secondary (Phase B) is normally grounded. Therefore, if line-to-ground measurements are required (for power measurements, for example) care must be taken to ensure that the meter recognizes that the output voltages are the line-to-line values – a magnitude and phase angle adjustment must be made to determine the actual line-to-ground equivalent.
  - Line-to-ground measurements on the secondary will typically yield measurements of 120 V, 0 V, and 120 V, respectively for phases A, B, and C. Line-to-line measurements will yield 120 V, 120 V and 120 V, for VA-B, VB-C, and VC-A, respectively.

Monitoring Using Open-Delta PTs





$V_{primary}$ = 13.2 kV line-to-line

$V_{primary}$ = 7.62 kV line-to-ground

$V_{secondary}$ = 120 V line-to-line

$V_{secondary}$ = 120 V line-to-ground (phases A and C)

$V_{secondary}$ = 0 V line-to-ground (phase B)

Outline

- Introduction
  - Describing a Power Quality Waveform
  - Sample PQ Monitoring Videos
  - Sample PQ Waveforms
- Monitoring Equipment
- PQ Definitions
- Power Quality Issues and Expected Waveforms
  - Voltage Variations
  - Transients
  - Harmonics
  - Wiring and Grounding Considerations
- Power Quality Lab Overview
- Final Exam

"Seeing is Believing"

Power Quality Experience Center and Lab

Power Quality Lab

- Overview of Lab and Capabilities
  - Purpose
    - To demonstrate and Test PQ Problems and Solutions
    - Power Quality solutions, especially harmonic solutions, are difficult to understand
    - Demystify solutions – mis-information and confusion regarding PQ and energy savings

  - Equipment (Harmonic Related)
    - 18 Pulse Drives
    - HMT's
    - Active Filters
    - Broadband Filters
    - Passive (Fixed) Filters
    - Passive (Switched) Filters
    - Active Rectifier (UPS)
    - Reactors
    - 3rd Harmonic Filter
    - Drive Transformers
    - K-Rated Transformers
    - Load Banks/Drives

Power Quality Experience Center and Lab

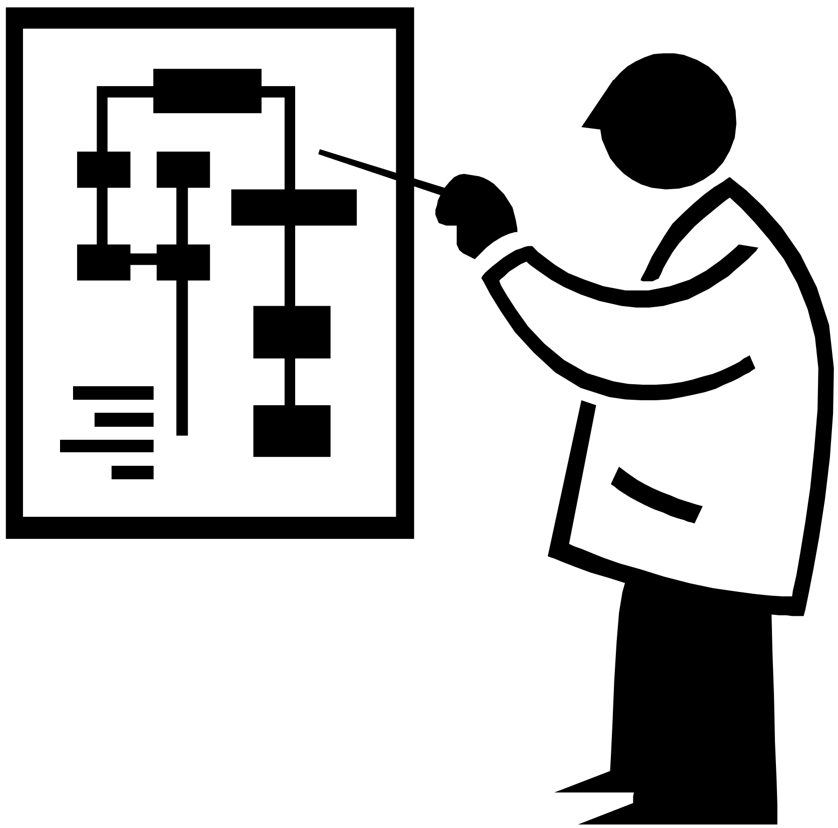
Full Scale Power System for Demonstrating and Testing PQ Problems and Solutions

Purpose

- **Teach –** Power Quality solutions, especially harmonic solutions, are difficult to understand
- **Demonstrate –** monitoring solutions including PQ meters and system software
- **Demystify –** there is a considerable amount of mis-information and confusion in the marketplace regarding PQ and energy savings
- **Help –** end users in selecting the most appropriate (economic and technical) solution
- **Prove –** It's not a "mock up", it's a full scale demonstration with actual equipment – seeing is believing!

Usage

- Demonstrations
- R&D/Testing
- Training



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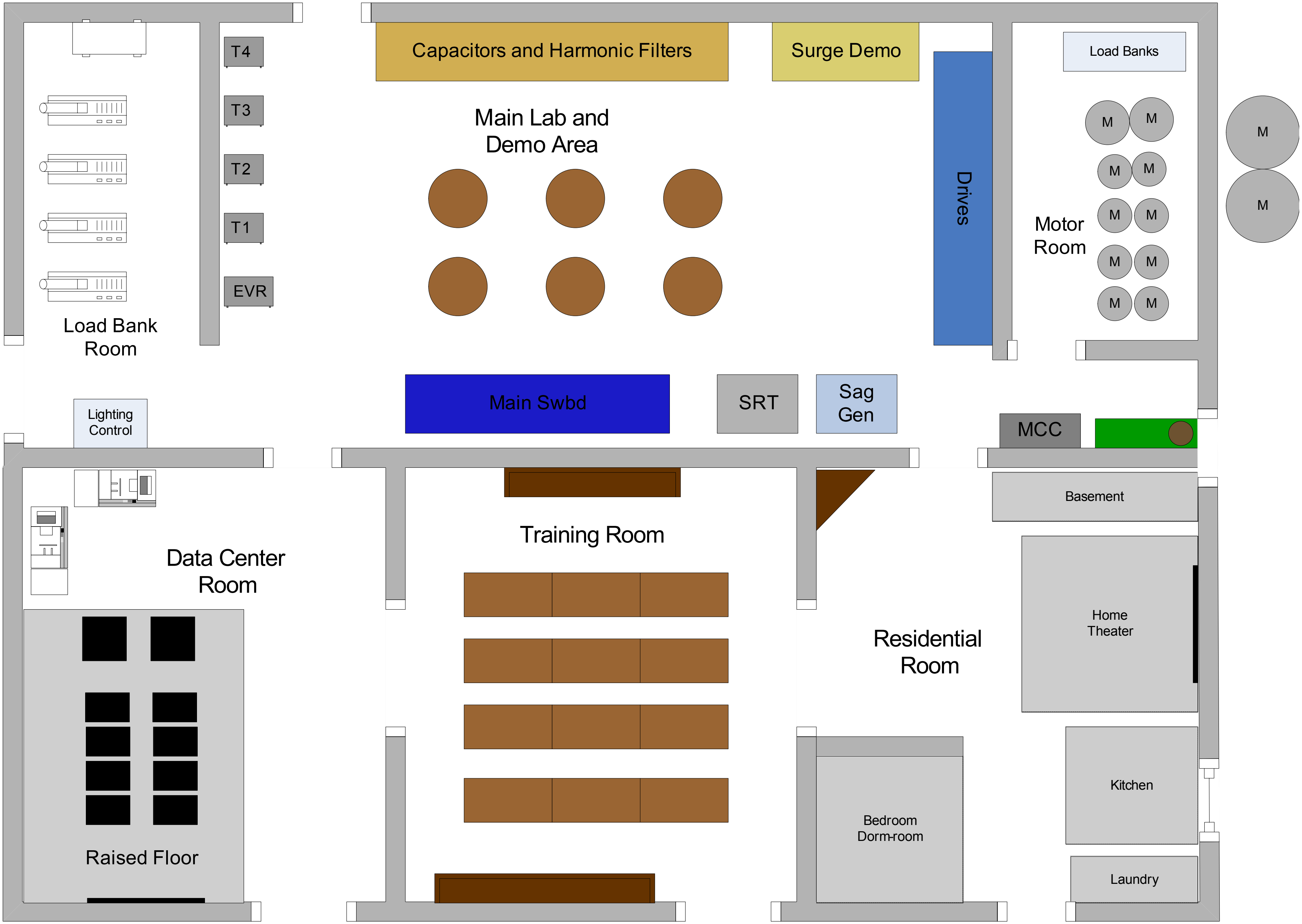
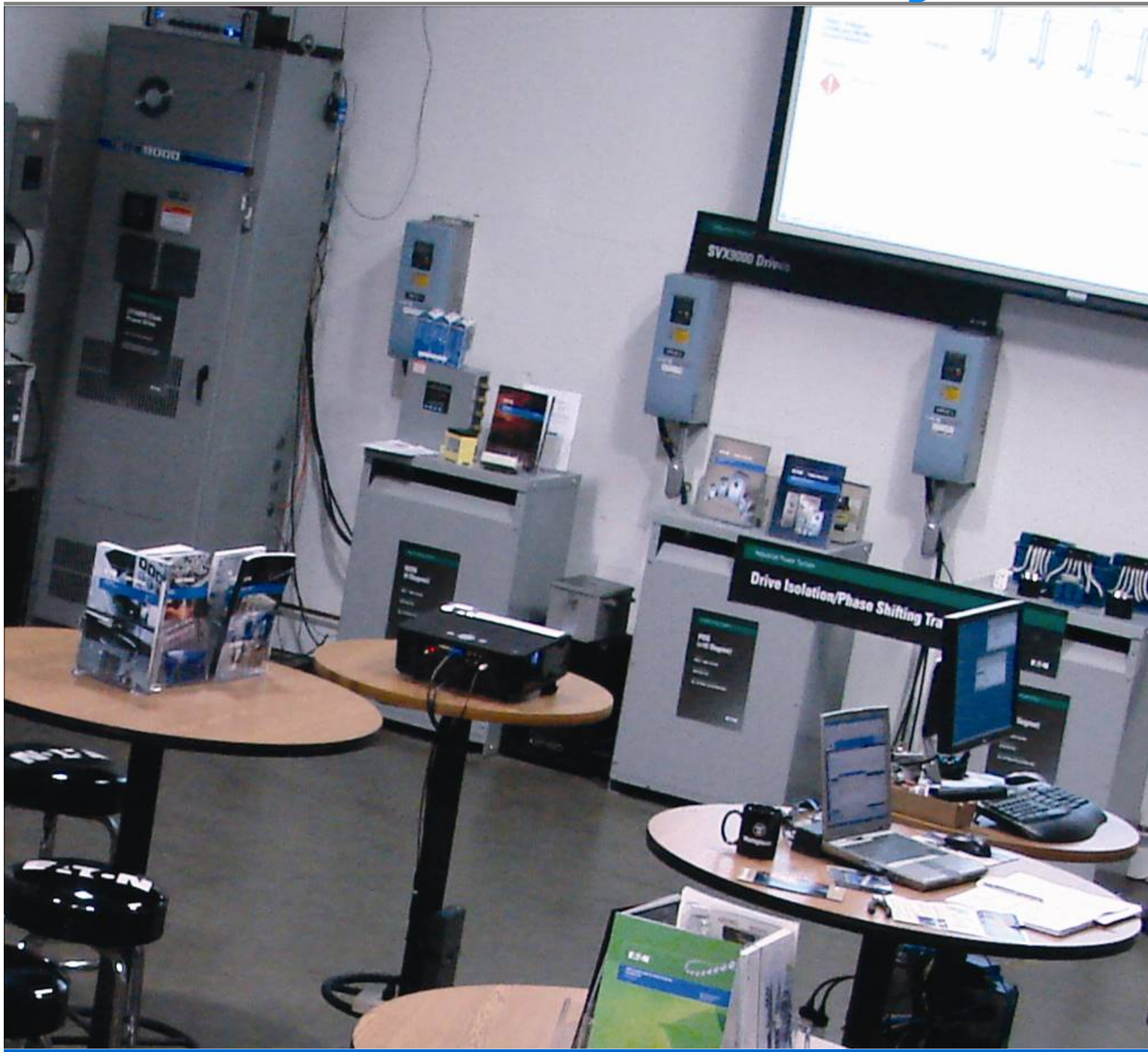
General Layout

- Main Power System
- Commercial Power System
- Industrial Power System
- Residential Room
- Data Center Room
- Medium Voltage Room


Capacitors and Harmonic Filters
Surge Demo
Load Banks
T4
T3
T2
T1
EVR
Main Lab and
Demo Area
Drives
Motor
Room
M
Load Bank
Room
Lighting
Control
Main Swbd
SRT
Sag
Gen
MCC
Basement
Training Room
Data Center
Room
Residential
Room
Home
Theater
Kitchen
Bedroom
Dorm-room
Laundry
Raised Floor

Loads – Commercial System

Loads – Industrial System



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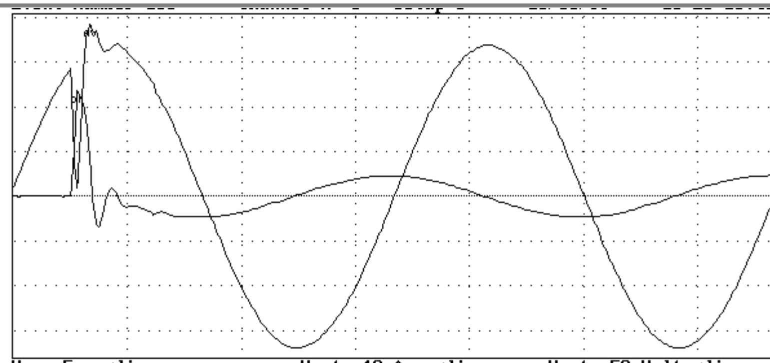
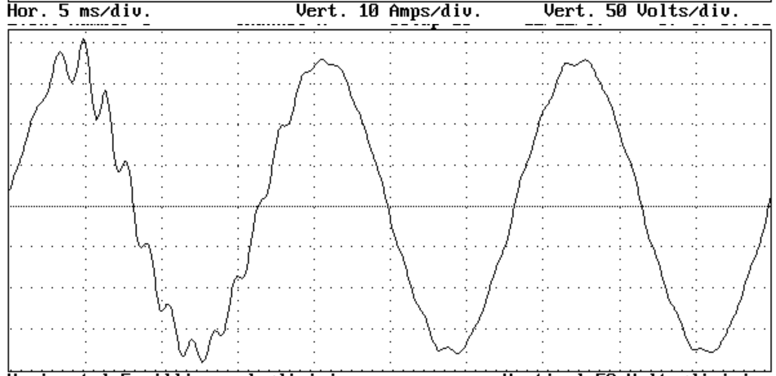
Final Exam

- Evaluate the following waveforms to determine what PQ issue might be to blame….

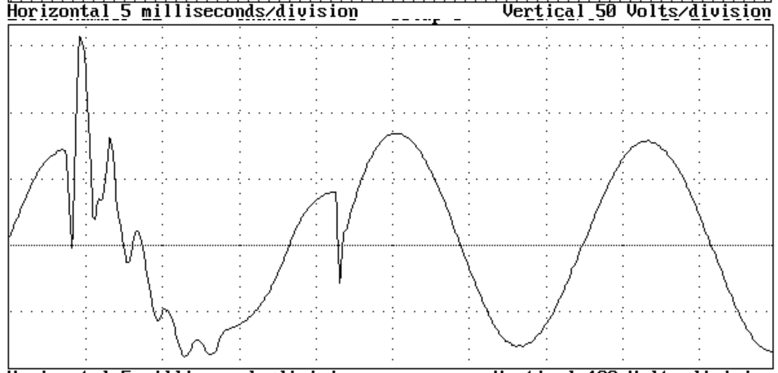
Waveforms



Hor. 5 ms/div. Vert. 10 Amps/div. Vert. 50 Volts/div.

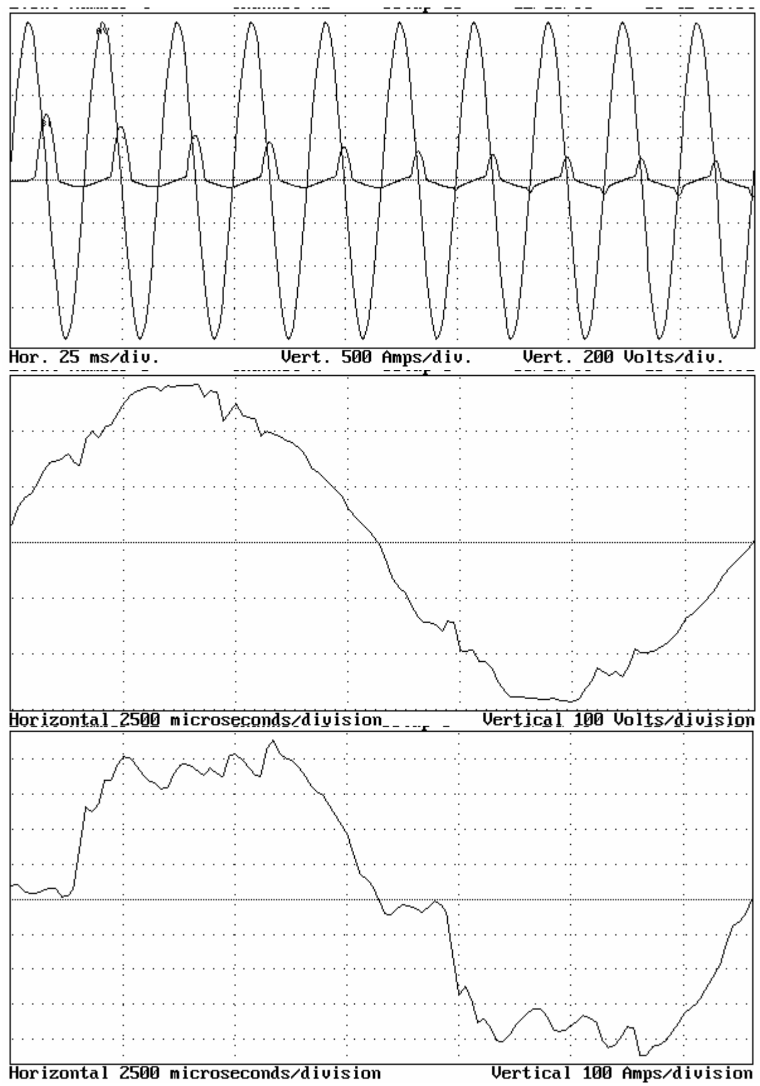


Horizontal 5 milliseconds/division Vertical 50 Volts/division

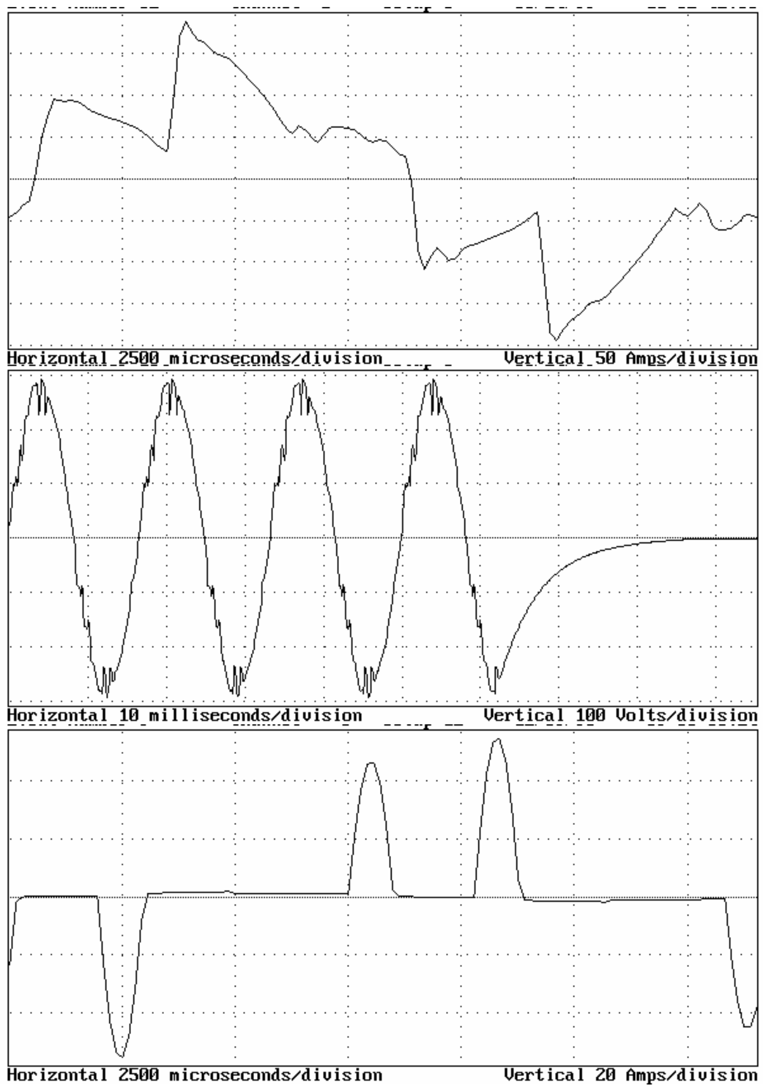


Horizontal 5 milliseconds/division Vertical 100 Volts/division

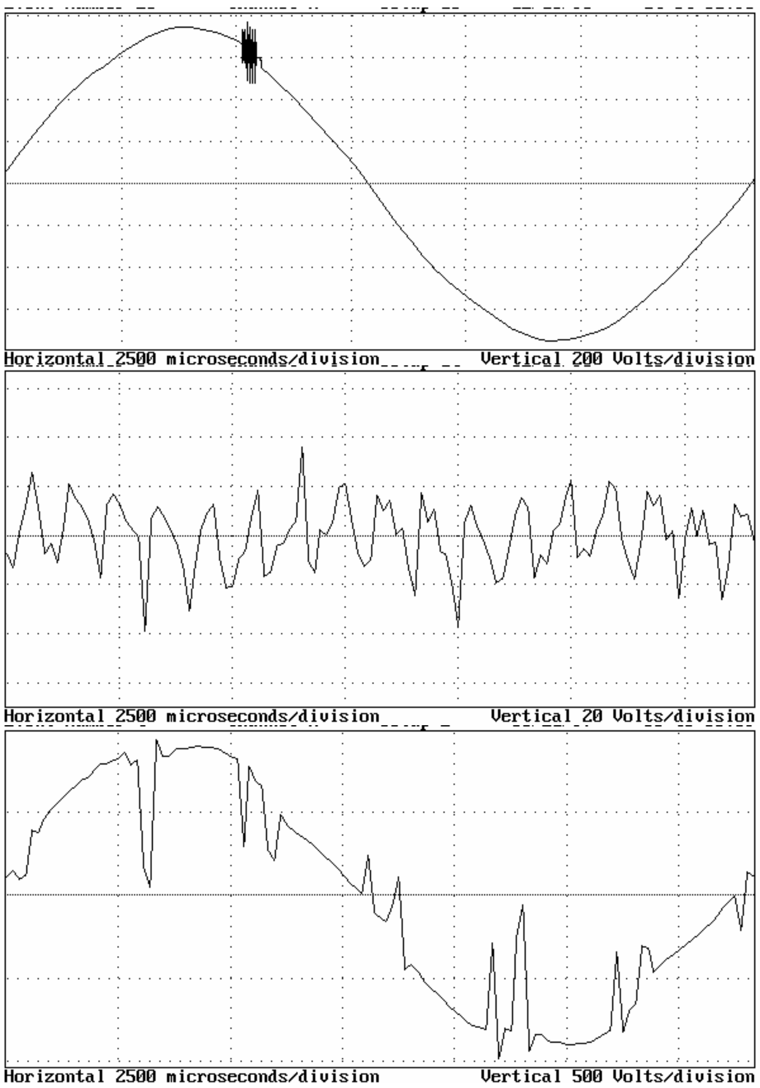
Waveforms


Hor. 25 ms/div.
Vert. 500 Amps/div.
Vert. 200 Volts/div.
Horizontal 2500 microseconds/division
Vertical 100 Volts/division
Horizontal 2500 microseconds/division
Vertical 100 Amps/division

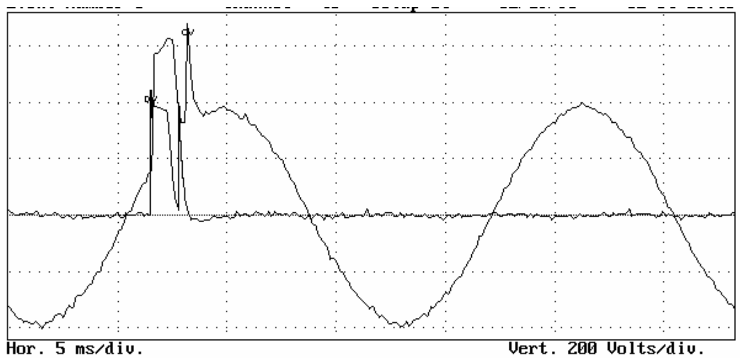
Waveforms

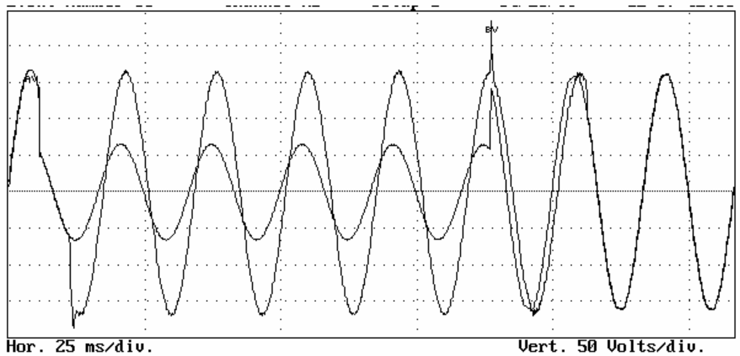

Horizontal 2500 microseconds/division
Vertical 50 Amps/division
Horizontal 10 milliseconds/division
Vertical 100 Volts/division
Horizontal 2500 microseconds/division
Vertical 20 Amps/division

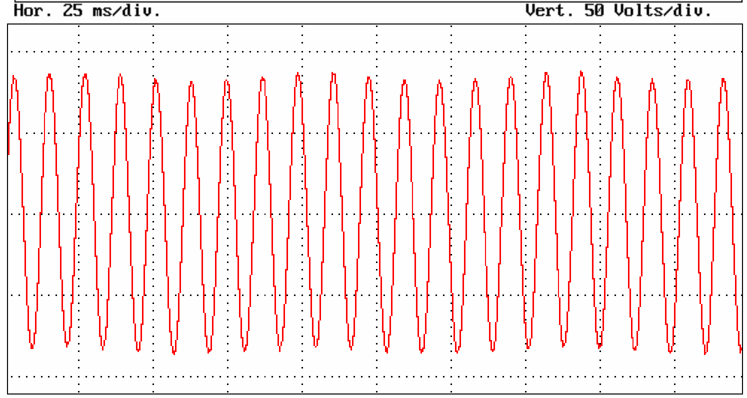
Waveforms


Horizontal 2500 microseconds/division
Vertical 200 Volts/division
Horizontal 2500 microseconds/division
Vertical 20 Volts/division
Horizontal 2500 microseconds/division
Vertical 500 Volts/division

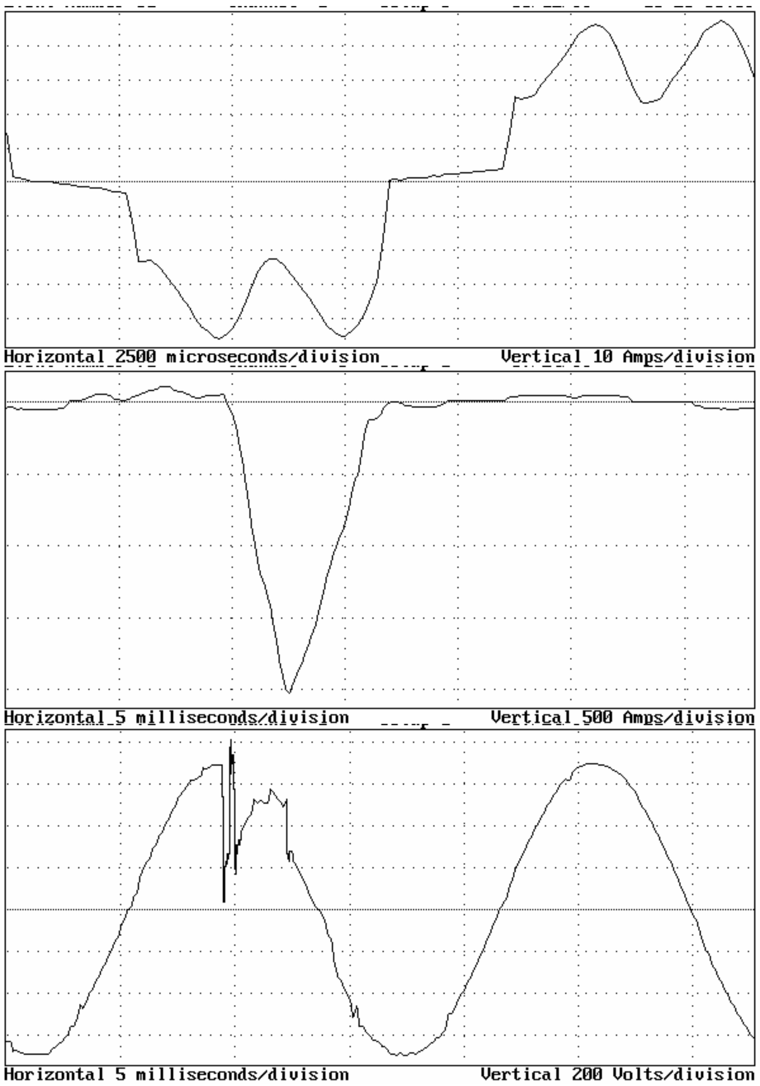
Waveforms





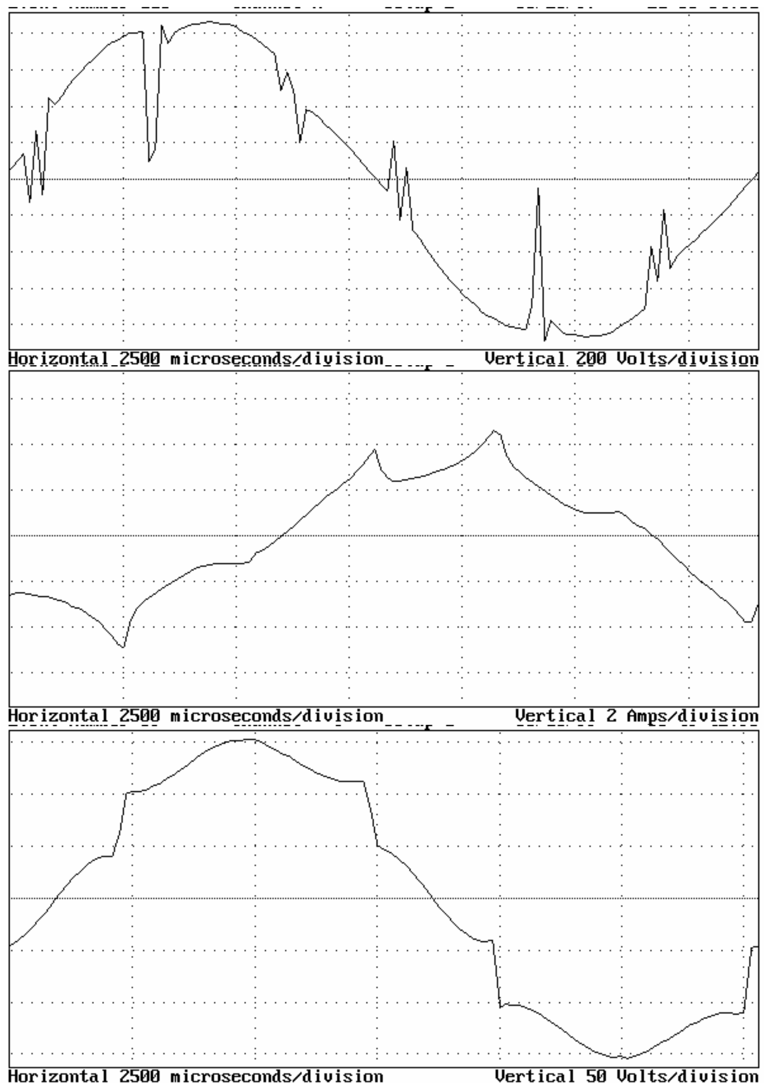


Waveforms

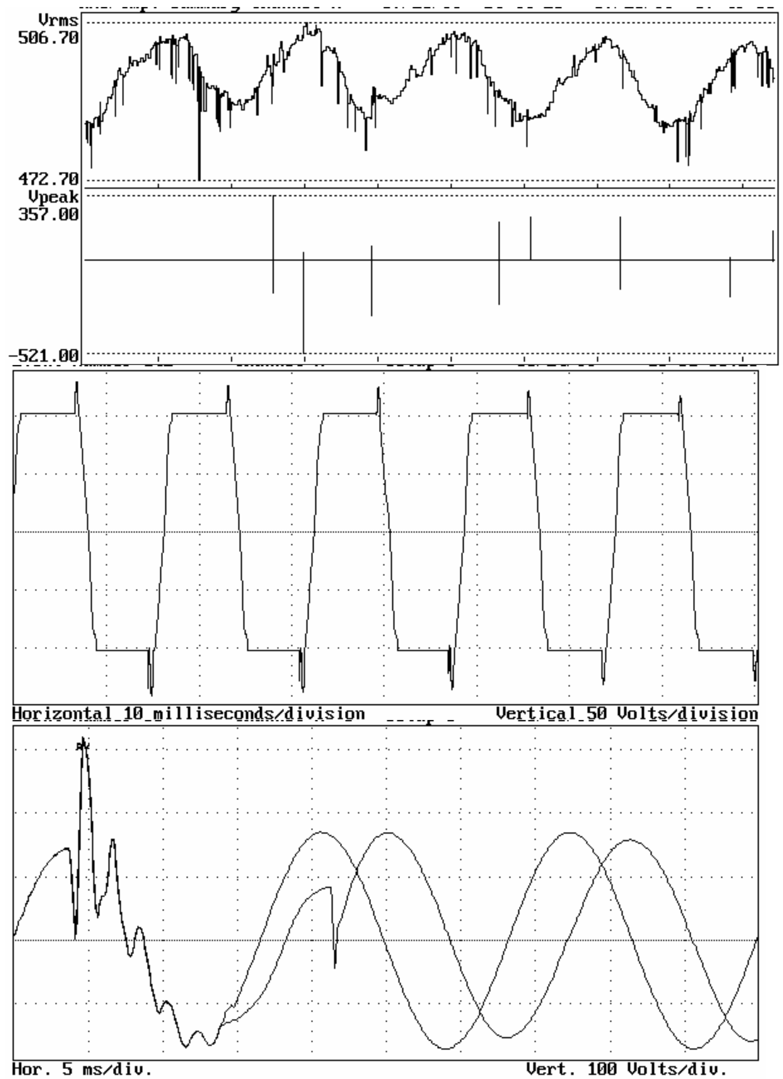


Horizontal 2500 microseconds/division
Vertical 10 Amps/division
Horizontal 5 milliseconds/division
Vertical 500 Amps/division
Horizontal 5 milliseconds/division
Vertical 200 Volts/division

Waveforms

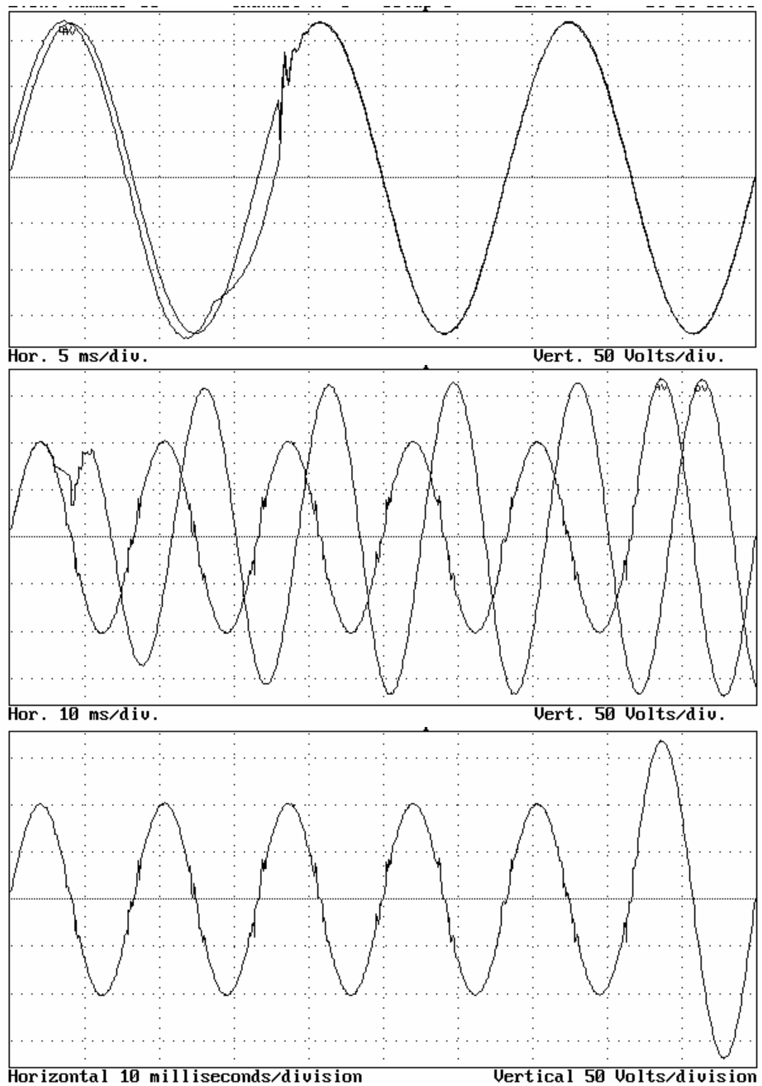

Horizontal 2500 microseconds/division
Vertical 200 Volts/division
Horizontal 2500 microseconds/division
Vertical 2 Amps/division
Horizontal 2500 microseconds/division
Vertical 50 Volts/division

Waveforms

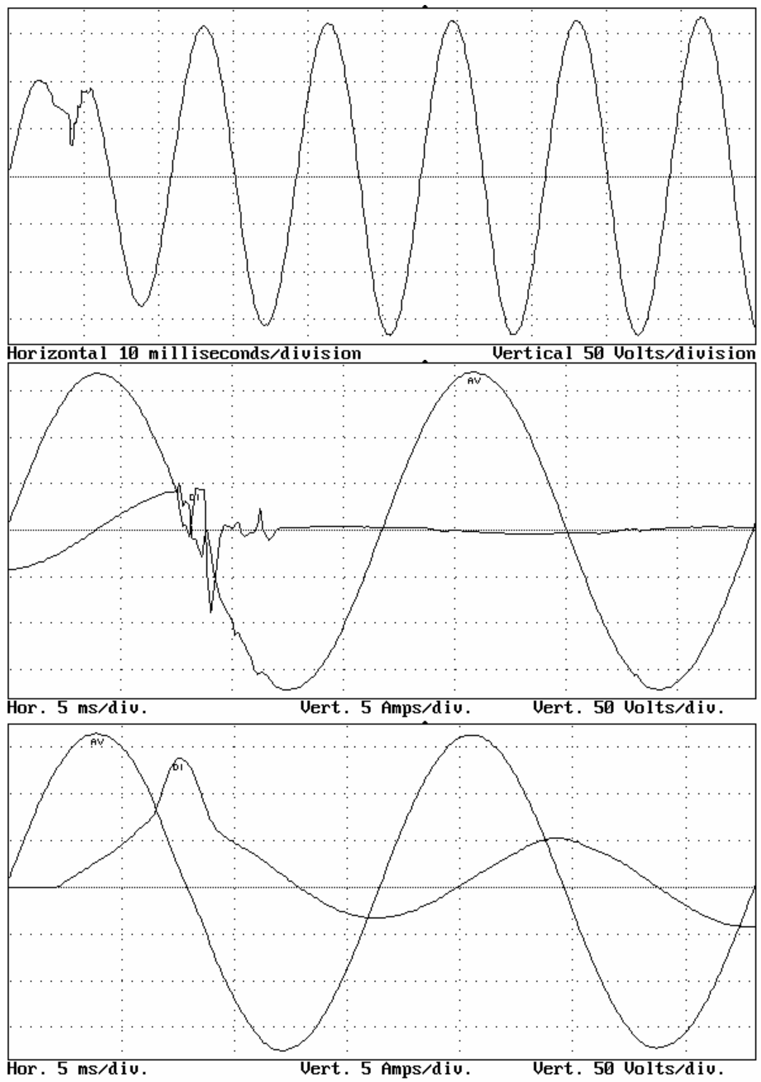


Vrms
506.70
472.70
Vpeak
357.00
-521.00
Horizontal 10 milliseconds/division
Vertical 50 Volts/division
Hor. 5 ms/div.
Vert. 100 Volts/div.

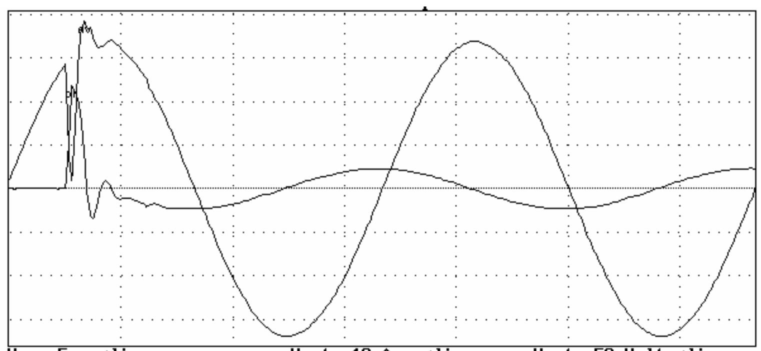
Waveforms


Hor. 5 ms/div.
Vert. 50 Volts/div.
Hor. 10 ms/div.
Vert. 50 Volts/div.
Horizontal 10 milliseconds/division
Vertical 50 Volts/division

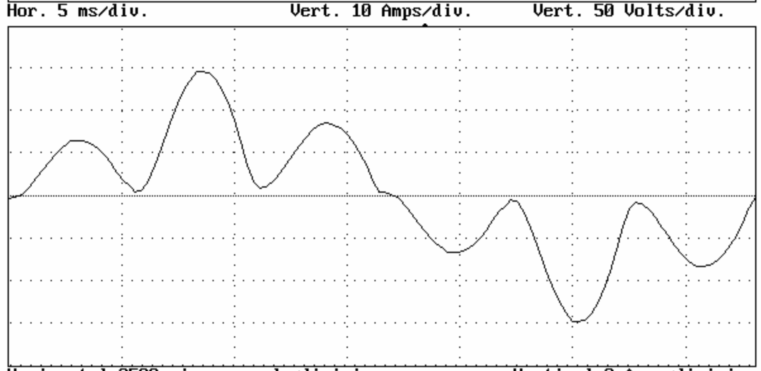
Waveforms


Horizontal 10 milliseconds/division
Vertical 50 Volts/division
AV
DI
Hor. 5 ms/div.
Vert. 5 Amps/div.
Vert. 50 Volts/div.
AV
DI
Hor. 5 ms/div.
Vert. 5 Amps/div.
Vert. 50 Volts/div.

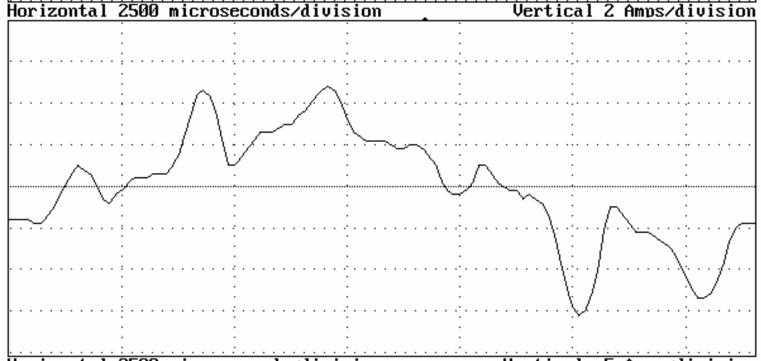
Waveforms



Hor. 5 ms/div. Vert. 10 Amps/div. Vert. 50 Volts/div.

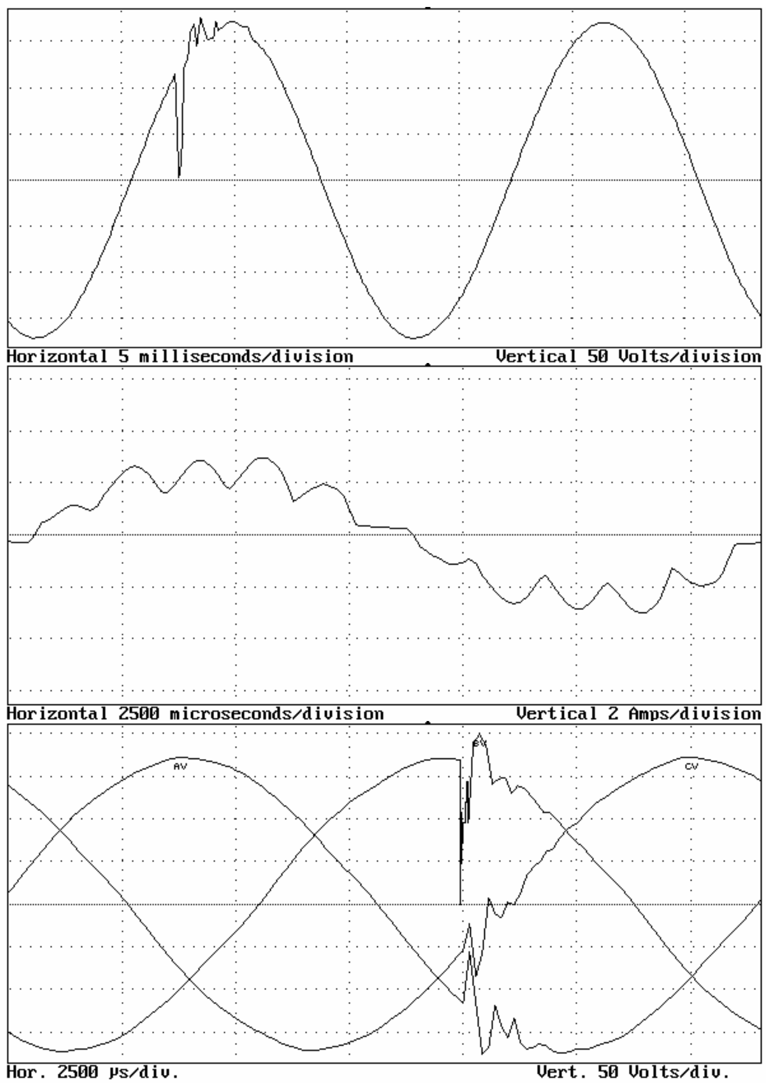


Horizontal 2500 microseconds/division Vertical 2 Amps/division



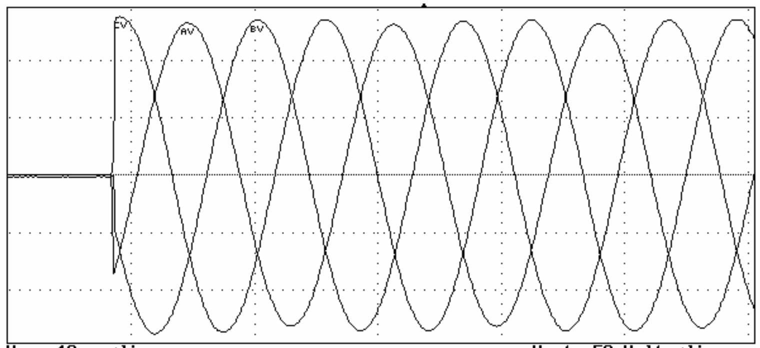
Horizontal 2500 microseconds/division Vertical .5 Amps/division

Waveforms

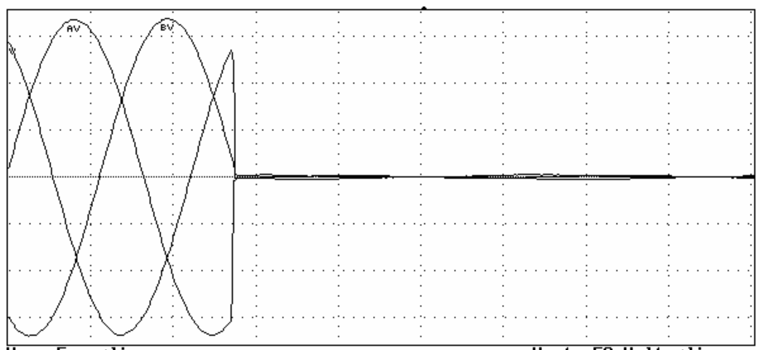


Horizontal 5 milliseconds/division
Vertical 50 Volts/division
Horizontal 2500 microseconds/division
Vertical 2 Amps/division
AV
CV
Hor. 2500 µs/div.
Vert. 50 Volts/div.

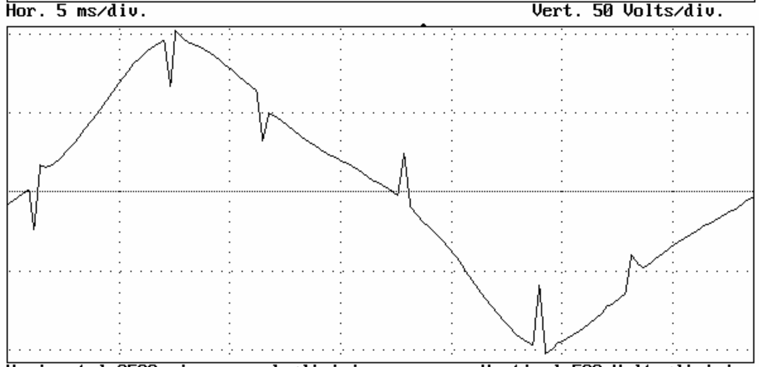
Waveforms



Hor. 10 ms/div. Vert. 50 Volts/div.

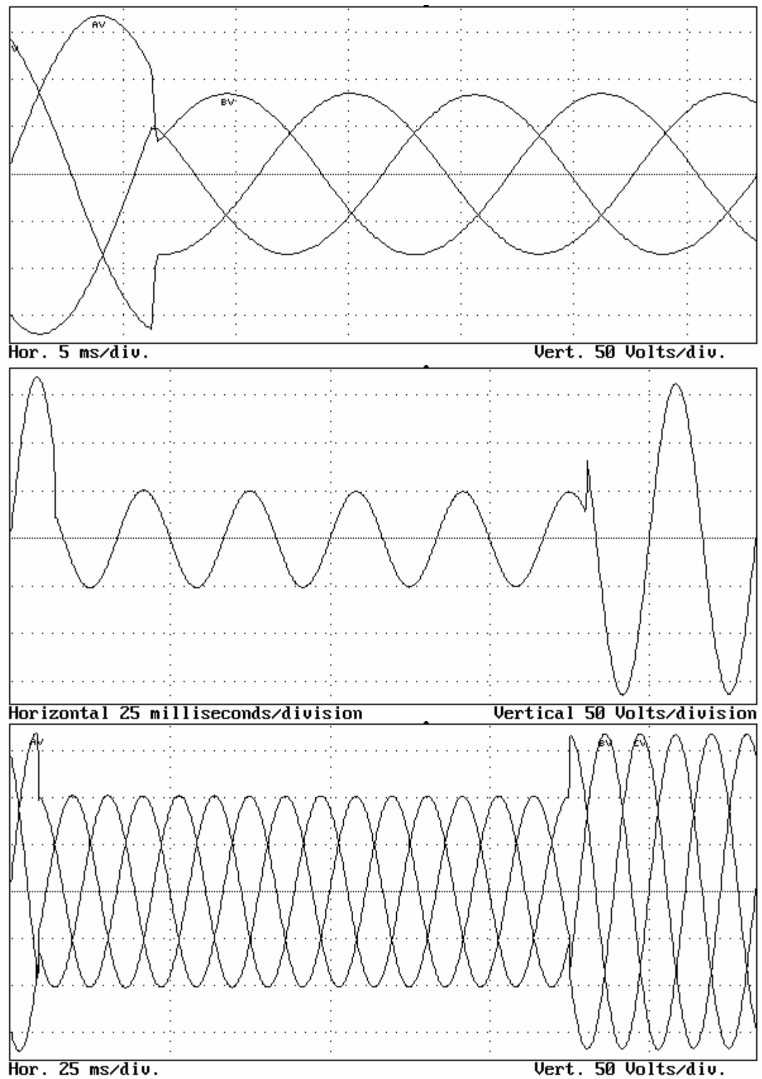


Hor. 5 ms/div. Vert. 50 Volts/div.



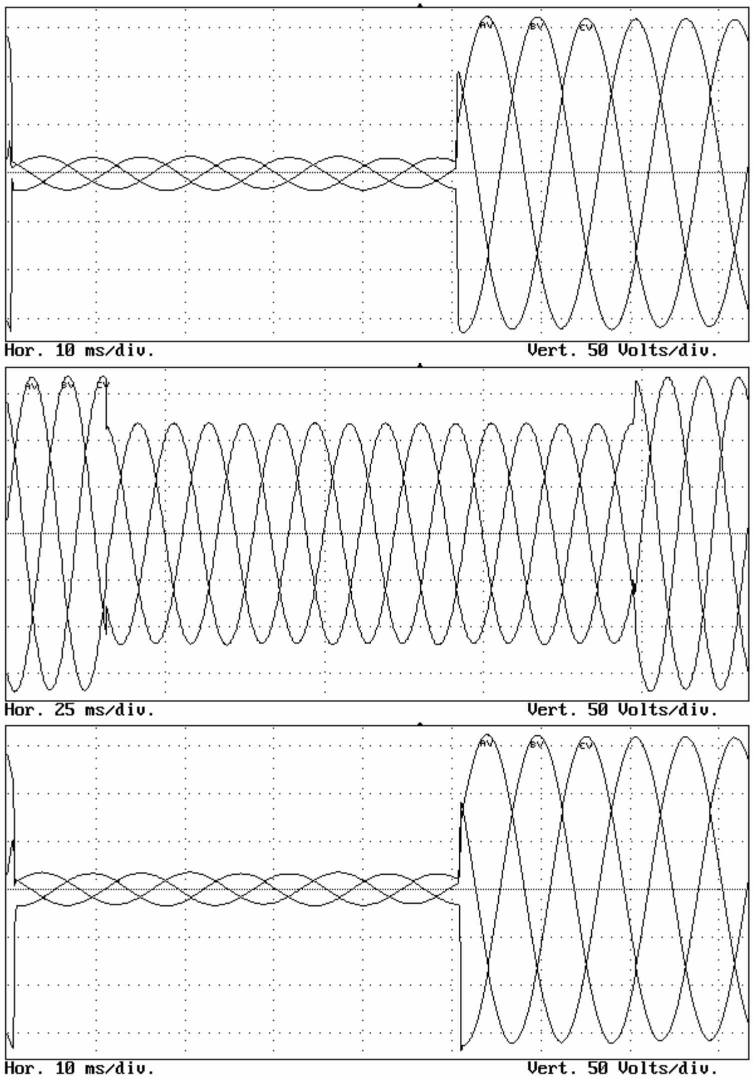
Horizontal 2500 microseconds/division Vertical 500 Volts/division

Waveforms

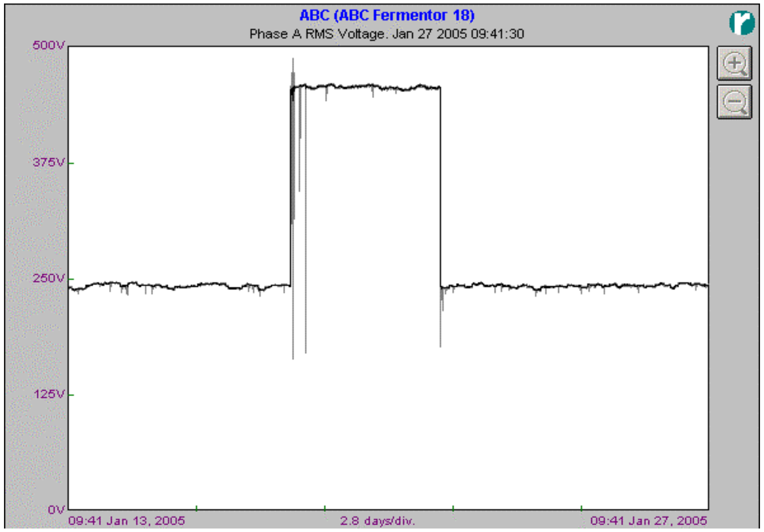


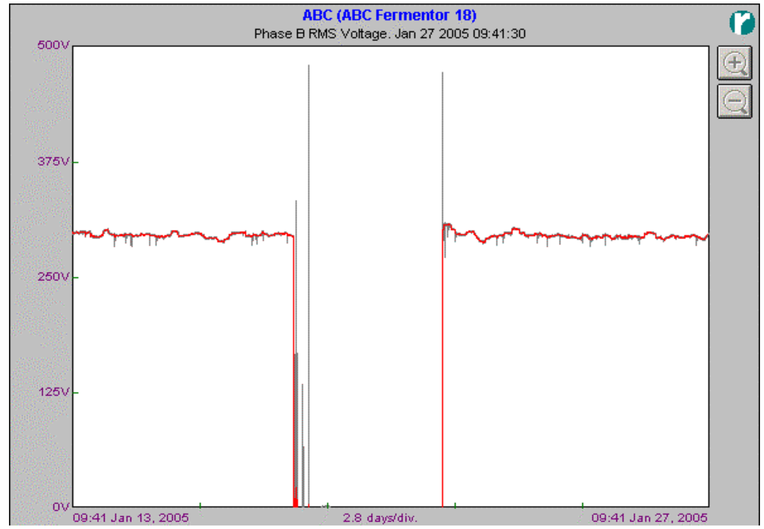
Hor. 5 ms/div.
Vert. 50 Volts/div.
Horizontal 25 milliseconds/division
Vertical 50 Volts/division
Hor. 25 ms/div.
Vert. 50 Volts/div.

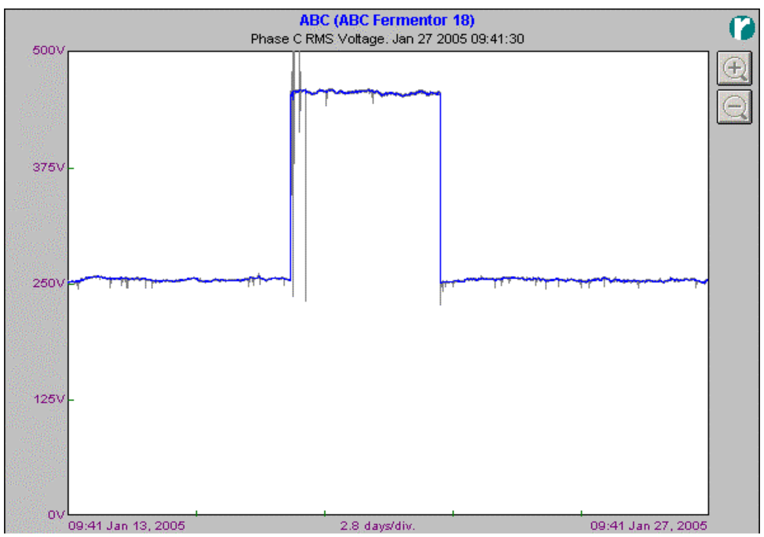
Waveforms

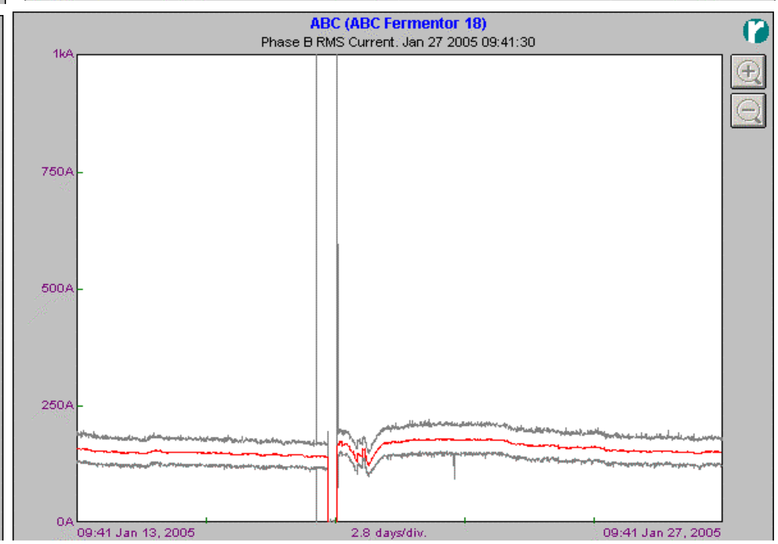

AV
BV
CV
Hor. 10 ms/div.
Vert. 50 Volts/div.
AV
BV
CV
Hor. 25 ms/div.
Vert. 50 Volts/div.
AV
BV
CV
Hor. 10 ms/div.
Vert. 50 Volts/div.

Waveforms

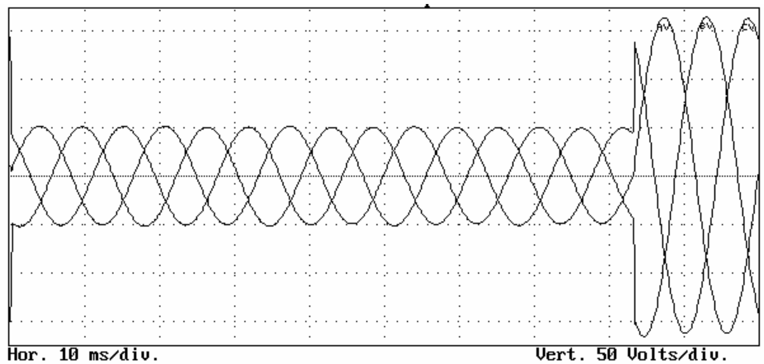

ABC (ABC Fermentor 18)
Phase A RMS Voltage. Jan 27 2005 09:41:30
500V
375V
250V
125V
0V
09:41 Jan 13, 2005
2.8 days/div.
09:41 Jan 27, 2005

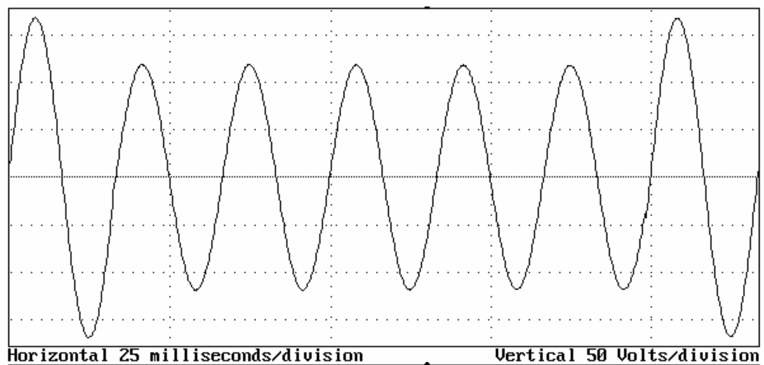

ABC (ABC Fermentor 18)
Phase B RMS Voltage. Jan 27 2005 09:41:30
500V
375V
250V
125V
0V
09:41 Jan 13, 2005
2.8 days/div.
09:41 Jan 27, 2005

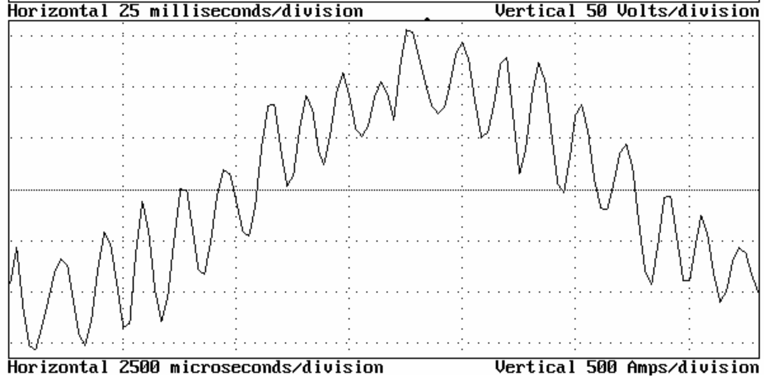

ABC (ABC Fermentor 18)
Phase C RMS Voltage. Jan 27 2005 09:41:30
500V
375V
250V
125V
0V
09:41 Jan 13, 2005
2.8 days/div.
09:41 Jan 27, 2005


ABC (ABC Fermentor 18)
Phase B RMS Current. Jan 27 2005 09:41:30
1kA
750A
500A
250A
0A
09:41 Jan 13, 2005
2.8 days/div.
09:41 Jan 27, 2005

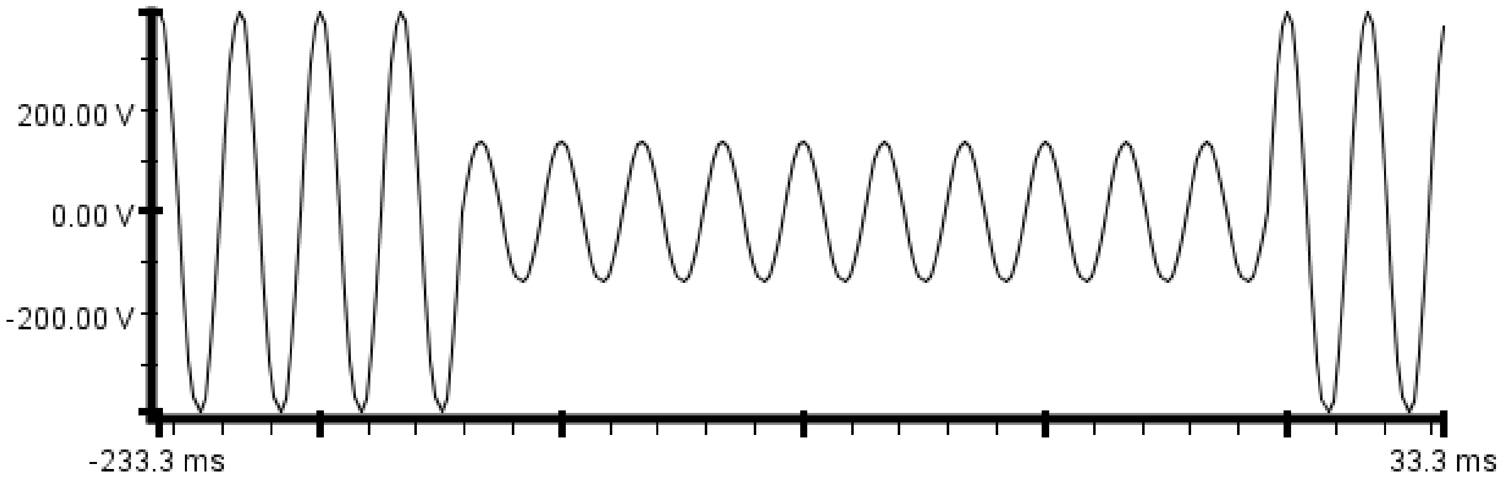
Waveforms


Hor. 10 ms/div.
Vert. 50 Volts/div.

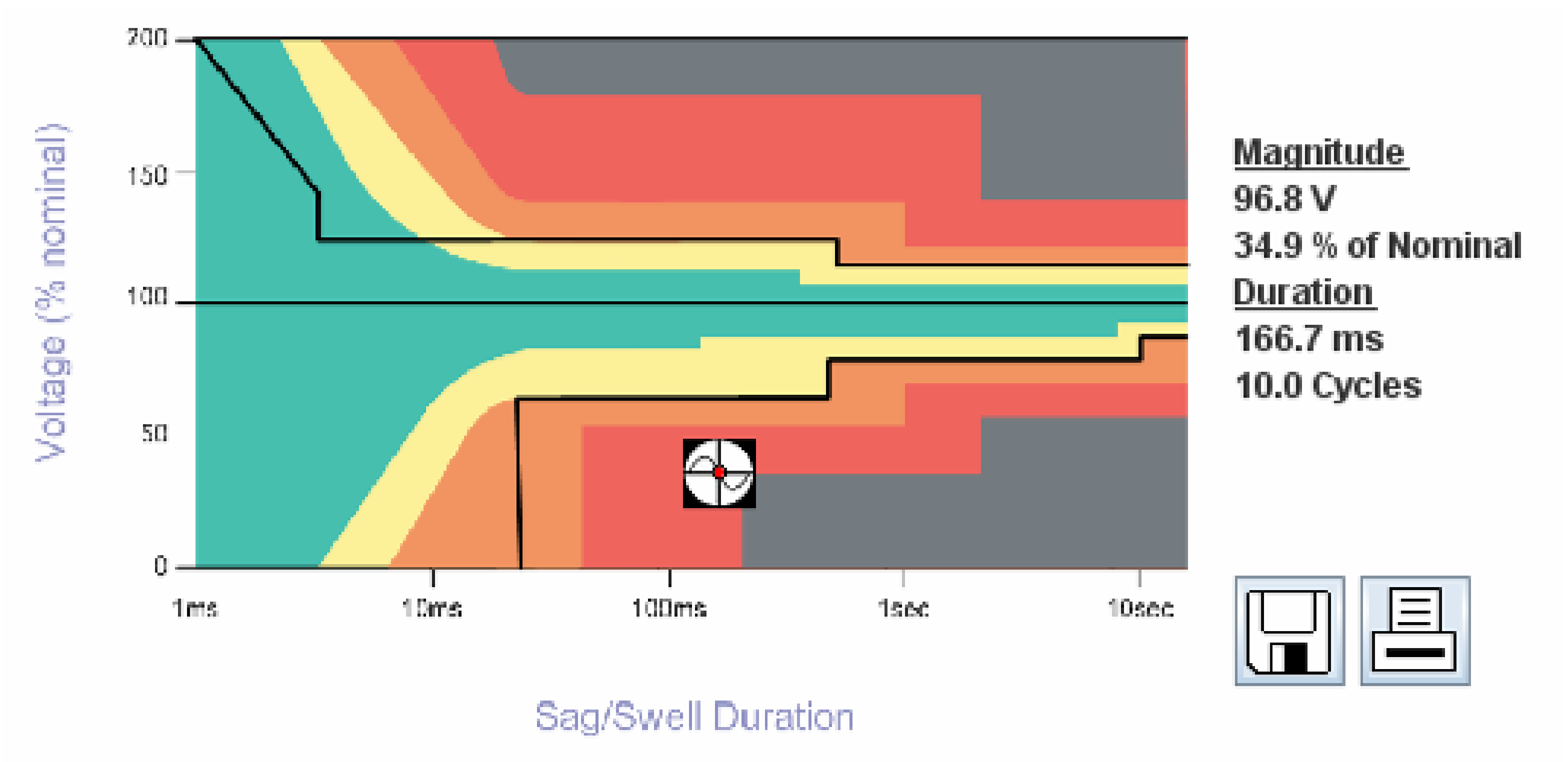

Horizontal 25 milliseconds/division
Vertical 50 Volts/division


Horizontal 2500 microseconds/division
Vertical 500 Amps/division

Waveforms

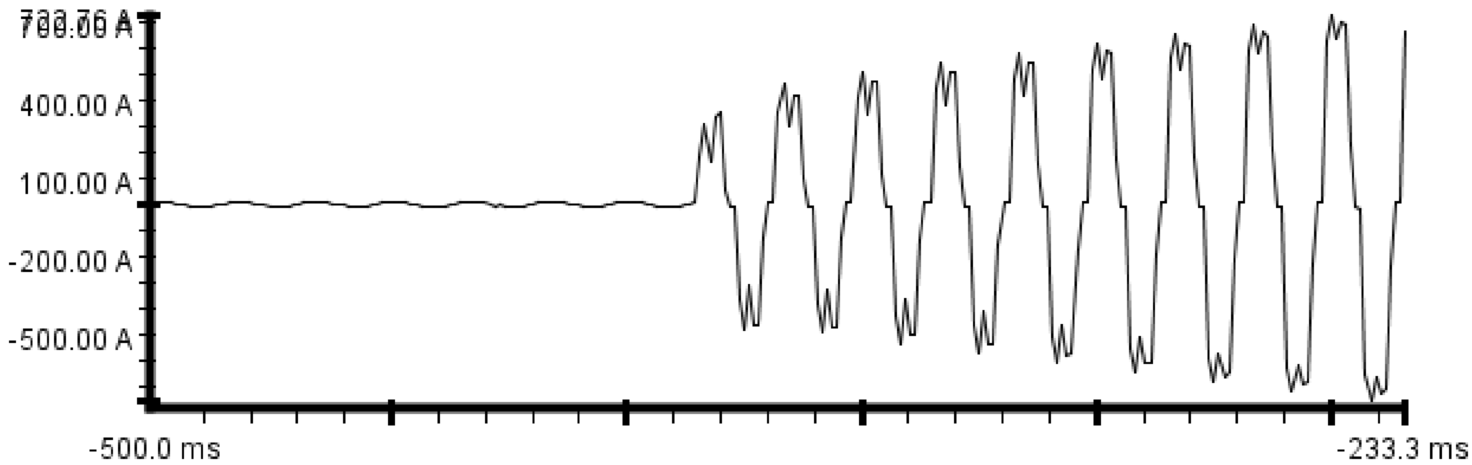


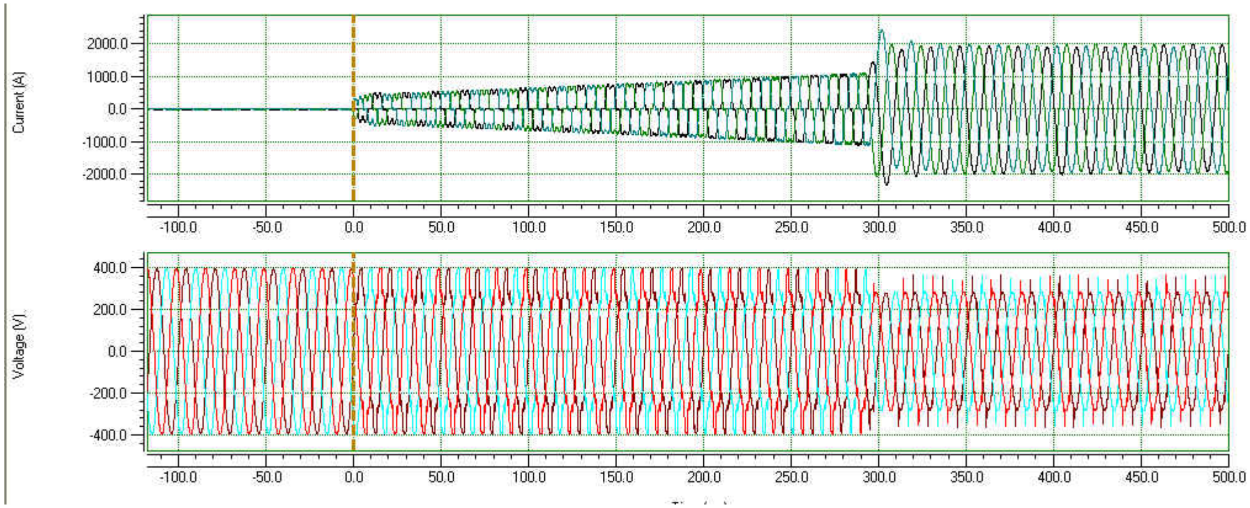
Waveforms



200
150
100
50
0
Voltage (% nominal)
1ms
10ms
100ms
1sec
10sec
Sag/Swell Duration
Magnitude
96.8 V
34.9 % of Nominal
Duration
166.7 ms
10.0 Cycles

Waveforms





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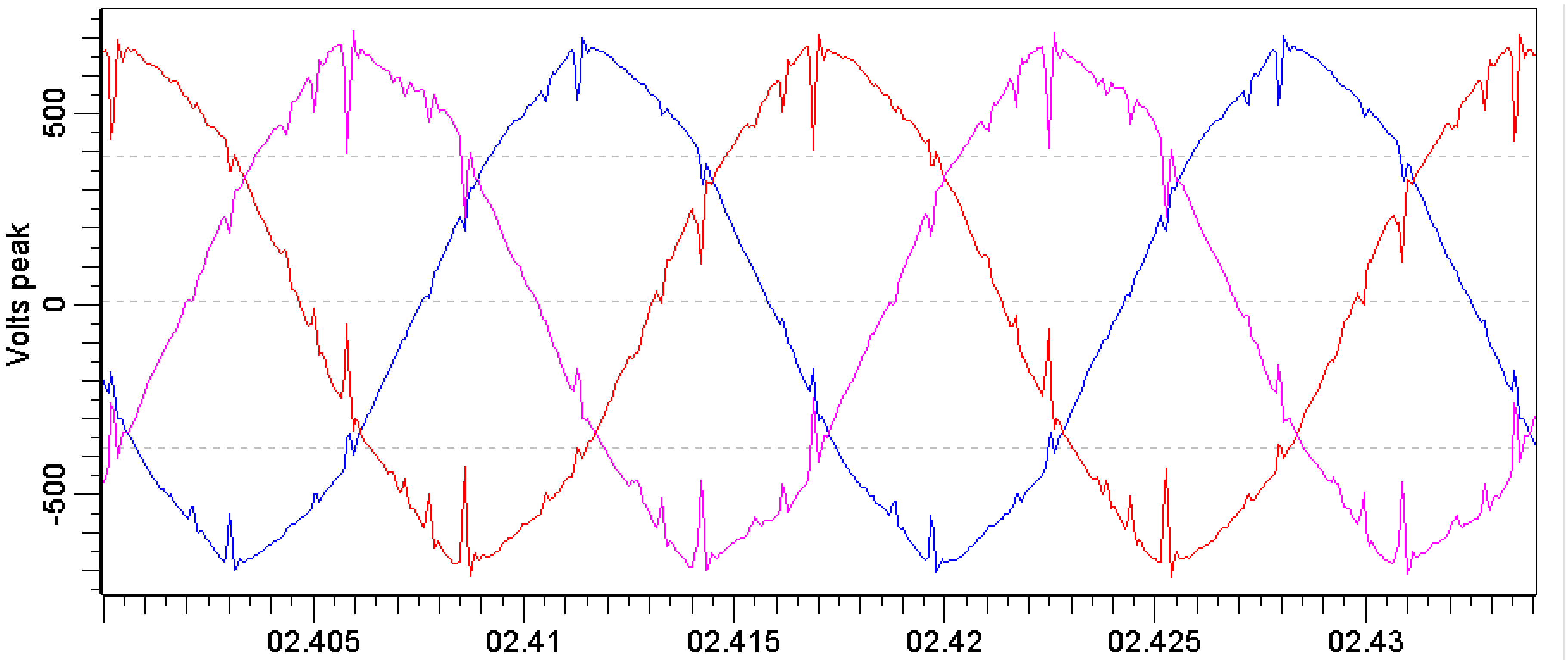
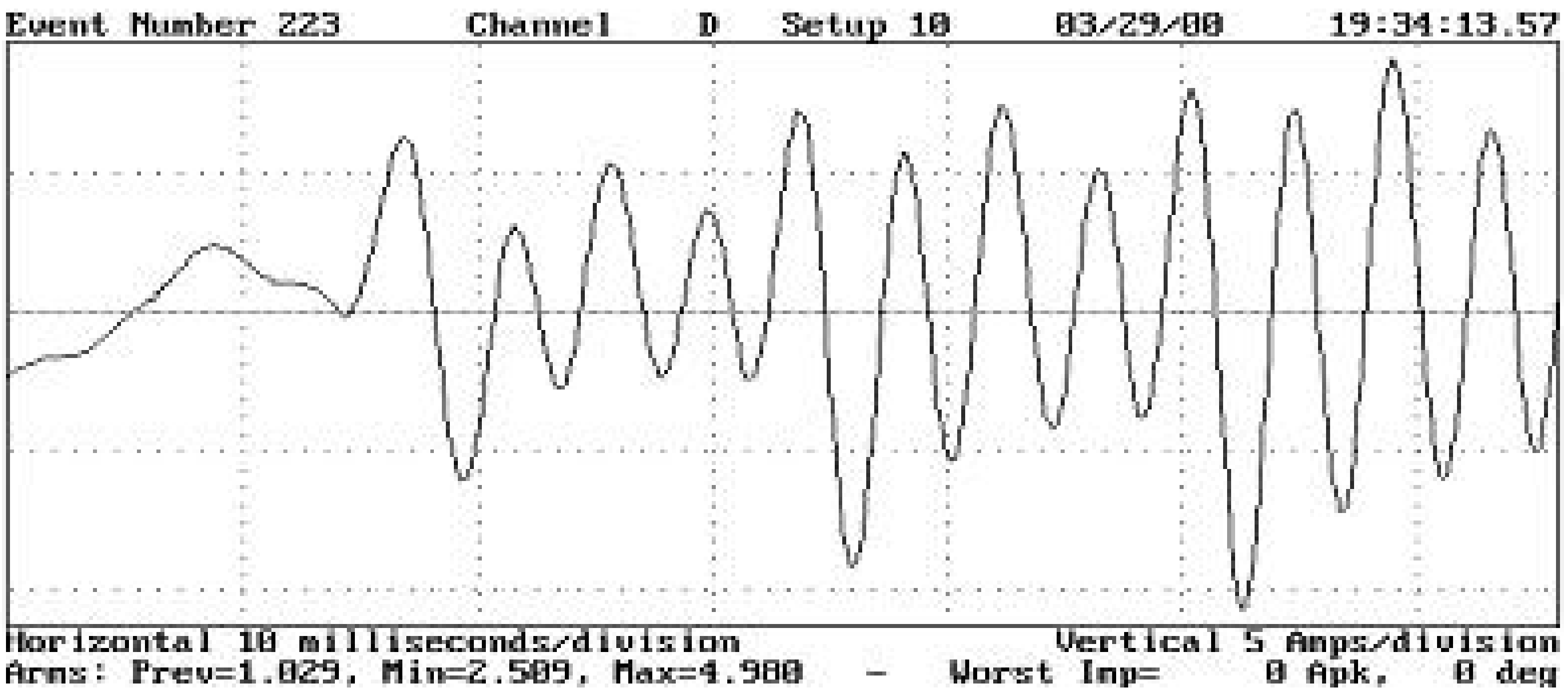
Waveforms



Waveforms


Event Number 223
Channel D
Setup 10
03/29/00
19:34:13.57
Horizontal 10 milliseconds/division
Vertical 5 Amps/division
Arms: Prev=1.029, Min=2.509, Max=4.980 - Worst Imp= 0 Apk, 0 deg

Waveforms

Reference Material

- Eaton Technical Papers:
  - Application of IEEE Std 519-1992 Harmonic Limits Capacitor Application Issues
  - Power Quality Monitoring Considerations
  - The Evolution of Power Quality Data Acquisition Systems
  - Applying Uninterruptible Power Supplies: System Compatibility Issues
- Dranetz – PQ Signature Handbook
- IEEE Std 1100 (Emerald Book)
- IEEE Std 1159 (Power Quality Monitoring)

Thank You!

Questions???

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DanielJCarnovale@eaton.com

412-716-6938

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