Power Monitors, Inc.

Power Quality 102

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Power Monitors, Inc.

55th Annual Minnesota Power Systems Conference
November 14, 2019
St. Paul, MN

Power Quality 102

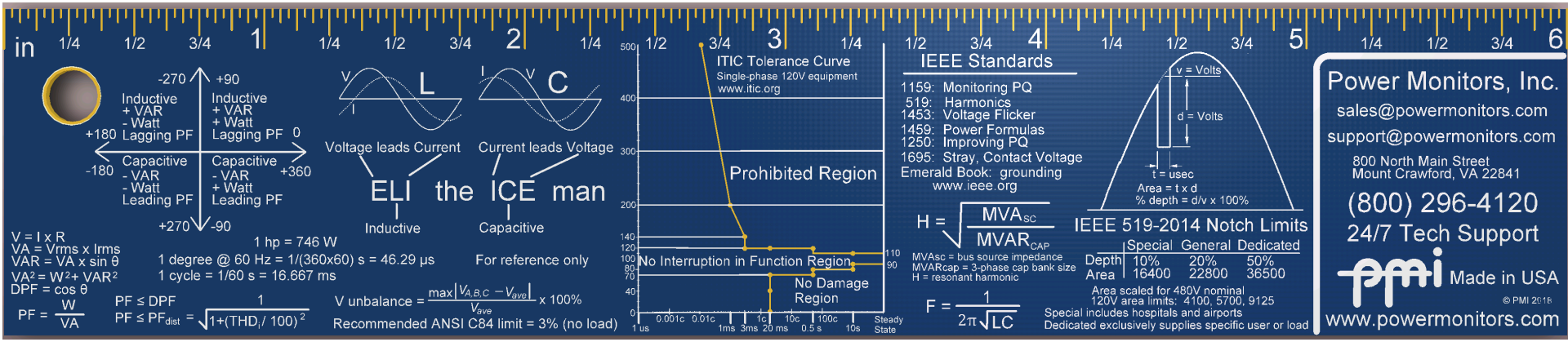
- Transients
- IEEE 519 Harmonic Analysis
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads

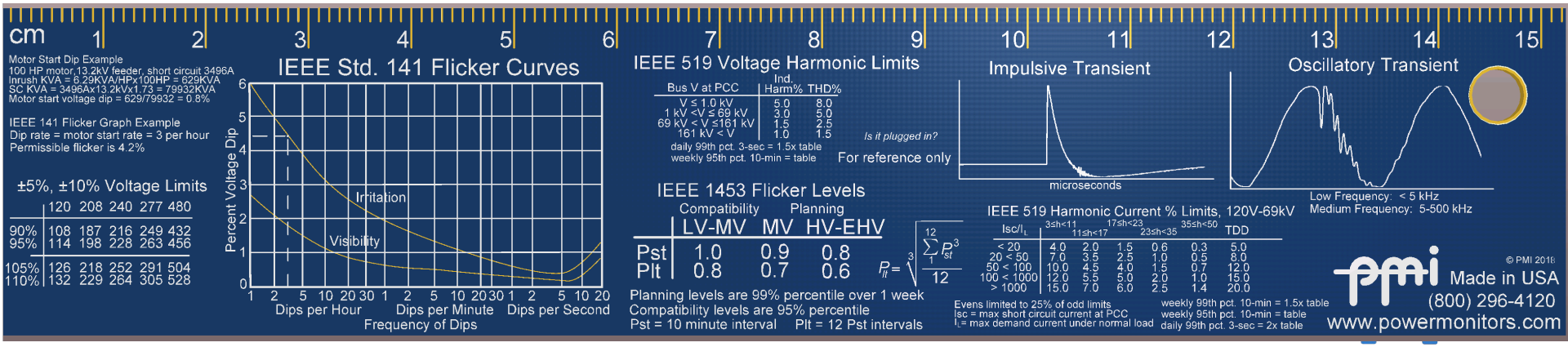
PMI PQ Ruler

Key graphs, thresholds, and formulas from IEEE PQ standards on 6” ruler

White paper explaining all sections on ruler:

http://library.powermonitors.com/pmi-pq-ruler





Power Quality 102

- **Transients**
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads and PQ
- Further Reading

Voltage Quality Variations

Disturbances

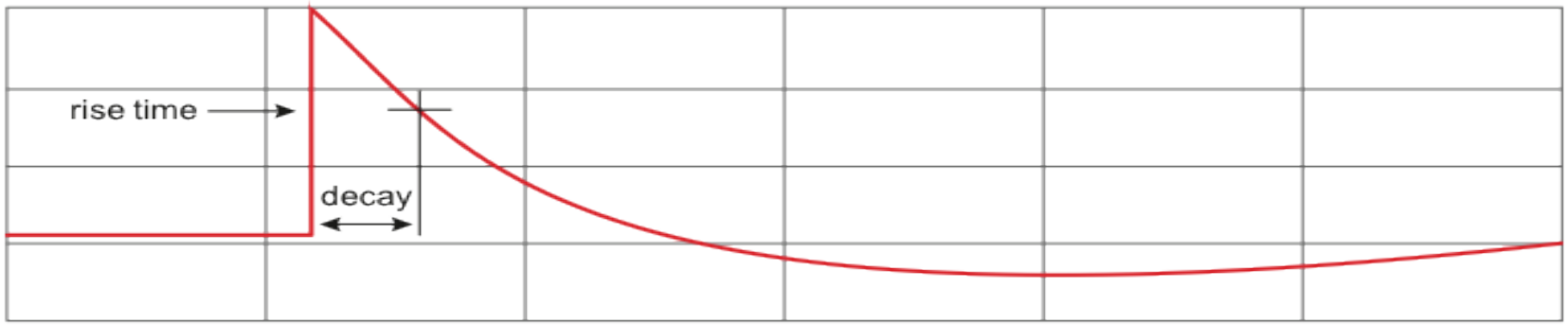
- Occur at Random Intervals
- Transients
- Voltage Sags and Swells
- Voltage Fluctuations
- Momentary and Sustained Interruptions

Steady State Characteristics

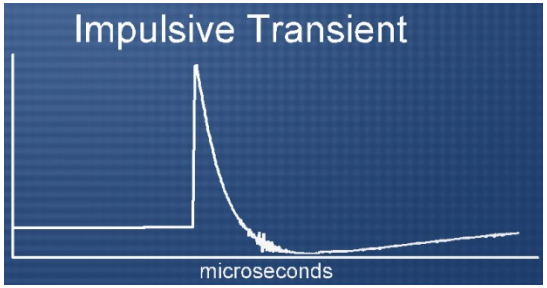
- Quality of Normal Condition Voltage
- Voltage Regulation: Magnitude, Long Term Stability
- Voltage Unbalance
- Voltage Distortion – harmonics, notching, noise

Impulsive Transients

- IEEE 1159–1995, Recommended Practice for Monitoring Electric Power Quality A sudden non-power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity.

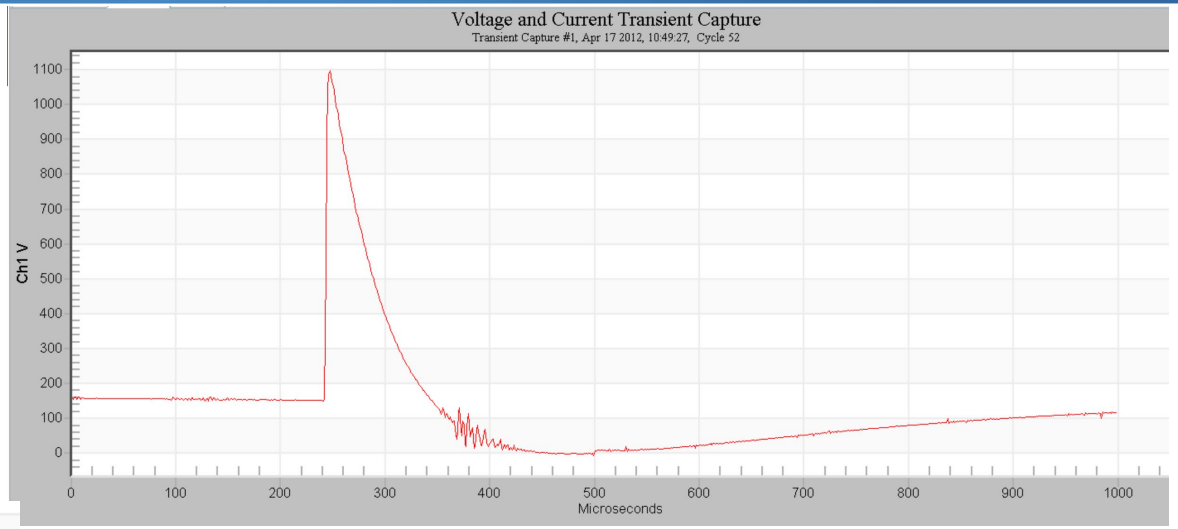


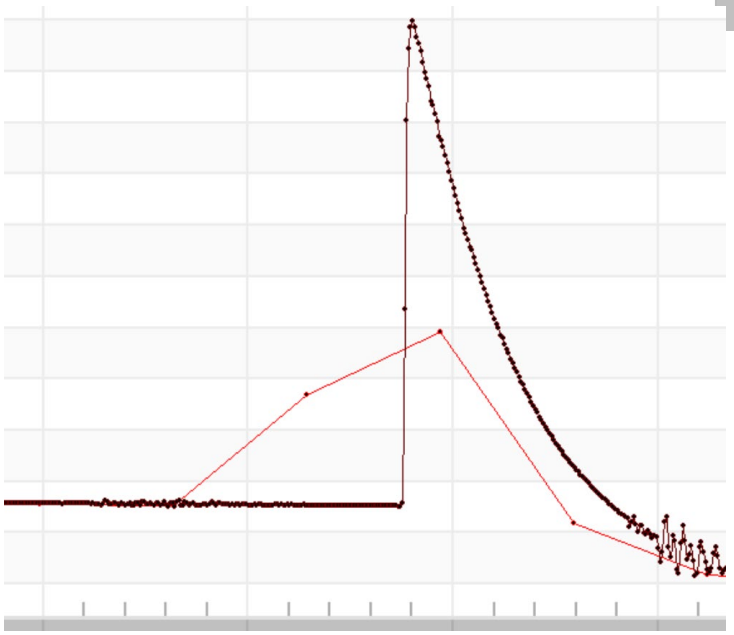
- Rise time and duration can be in nS, µS, mS
- Damped quickly by circuit resistance
- Not conducted far from source (lightning, switching event, etc.)
- Can excite resonances and produce oscillatory transients
- Possible Solution: Surge Suppressors

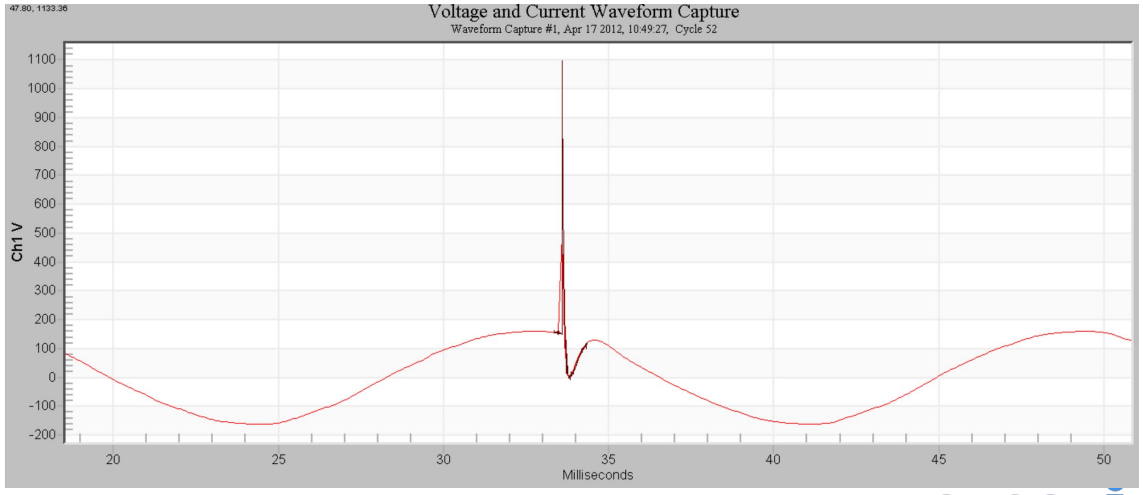


Impulsive Transients

1 ms impulse transient capture with microsecond rise-time

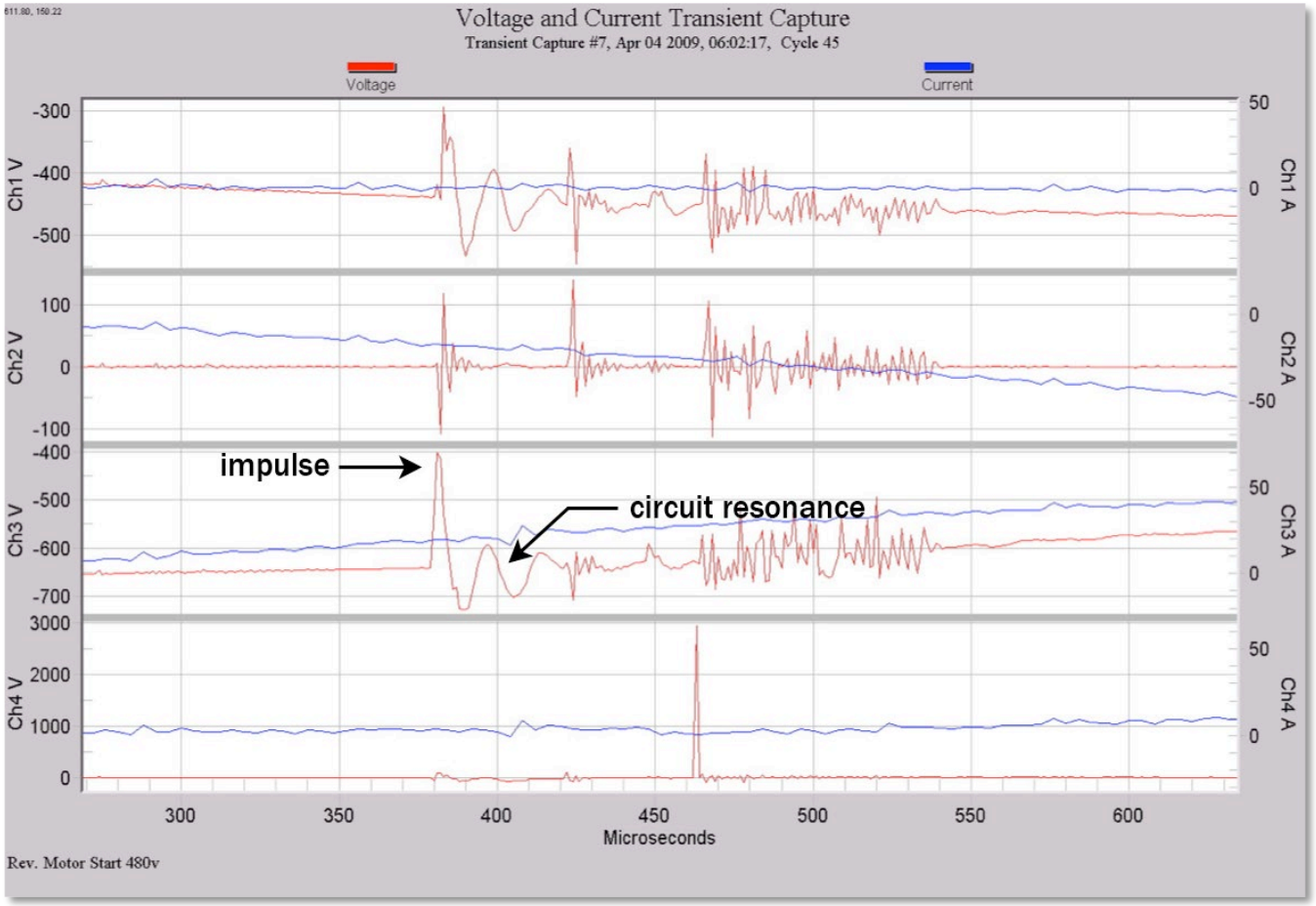






Transient graphed with slower 60 Hz waveform

Impulsive Transients



- Short duration, high frequency voltage impulses – local resonance ringing damped quickly

Oscillatory Transient
Low Frequency < 5kHz

IEEE 1159–1995, Recommended Practice for Monitoring Electric Power Quality

- A sudden, non-power frequency change in the steady-state condition of voltage or current that includes both positive and negative polarity

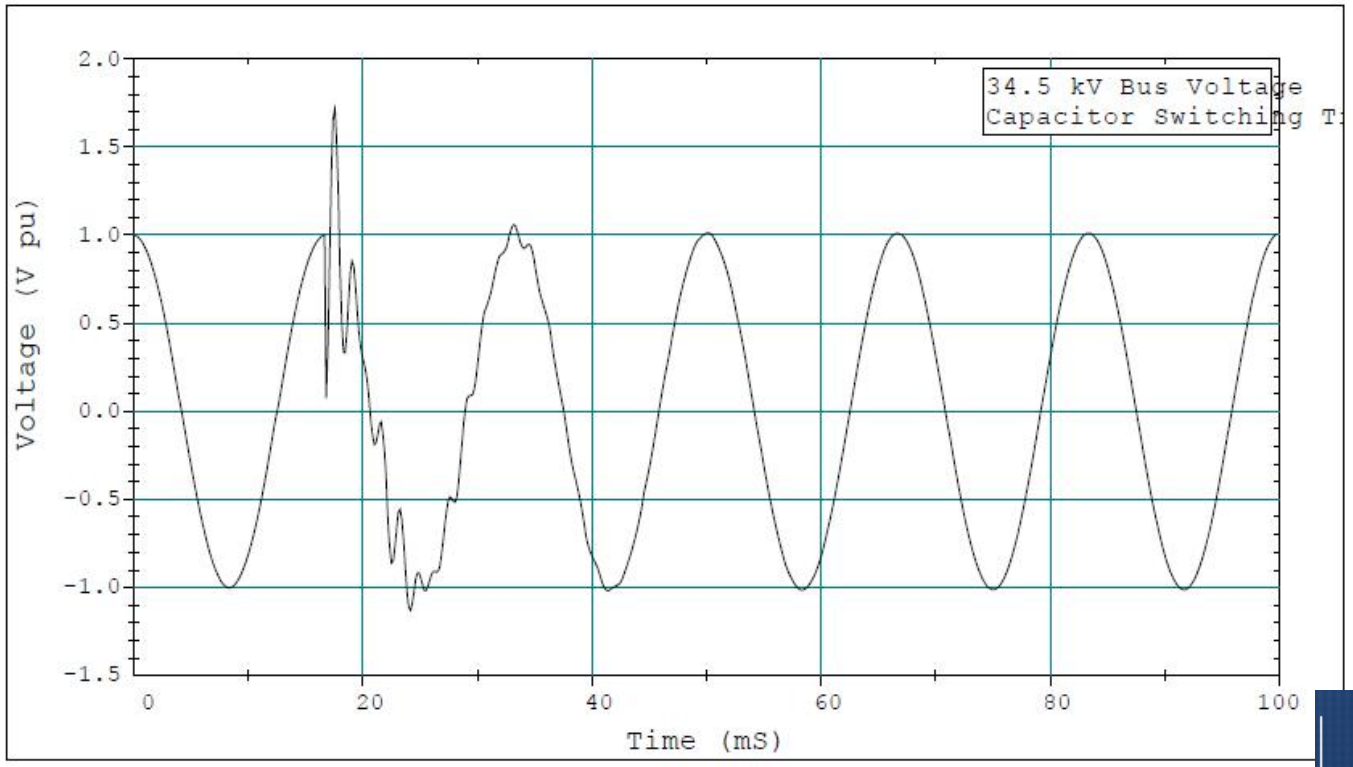
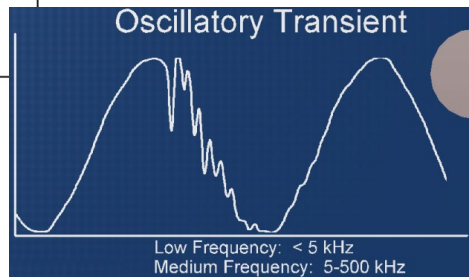


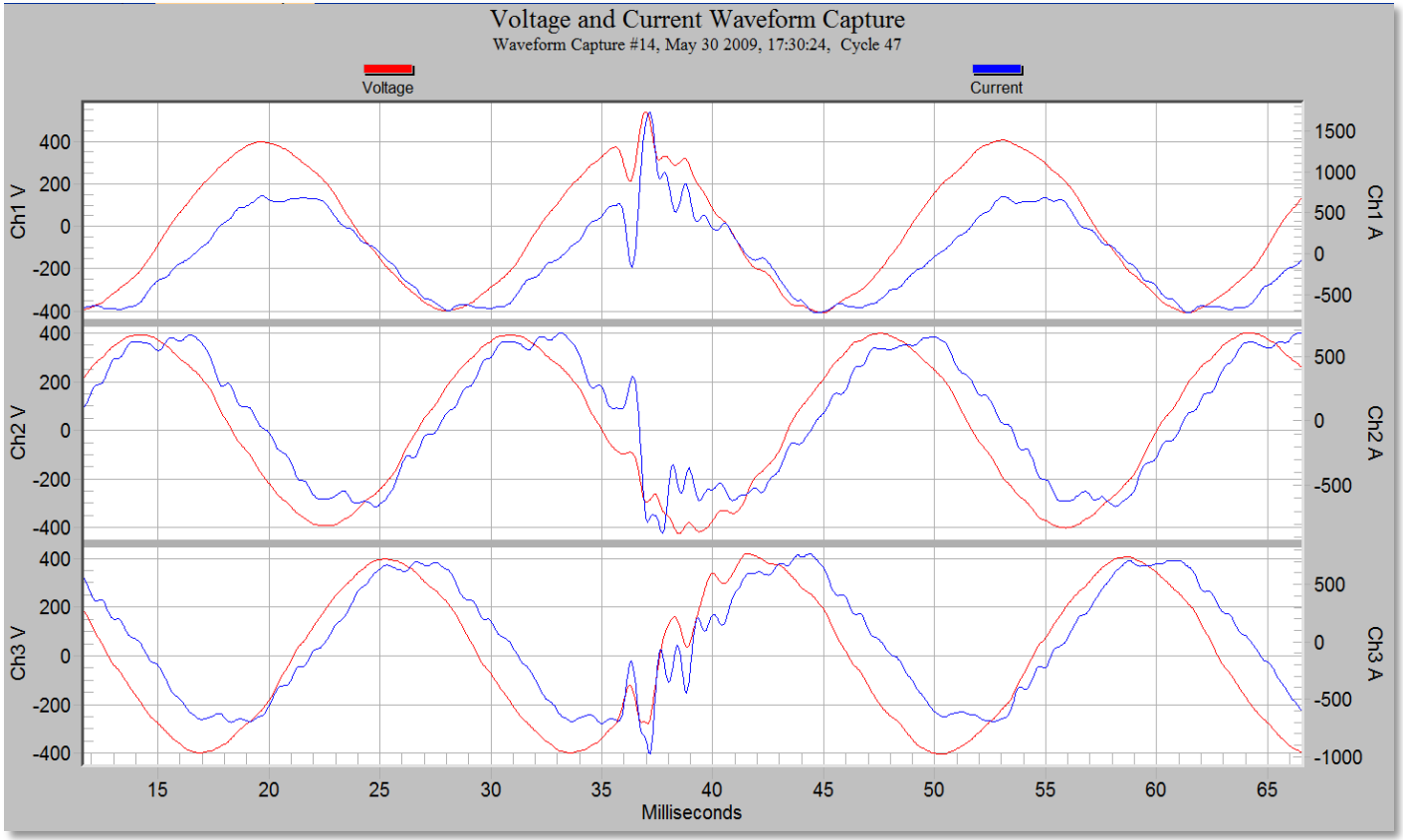
Figure 3: Low frequency oscillatory transient caused by capacitor bank energization

IEEE 1159-1995 Recommended Practice for Monitoring Power Quality © 1995 IEEE

Possible Solutions:
Series Surge Suppressors
Line Reactors



Oscillatory Transient
Low Frequency < 5kHz

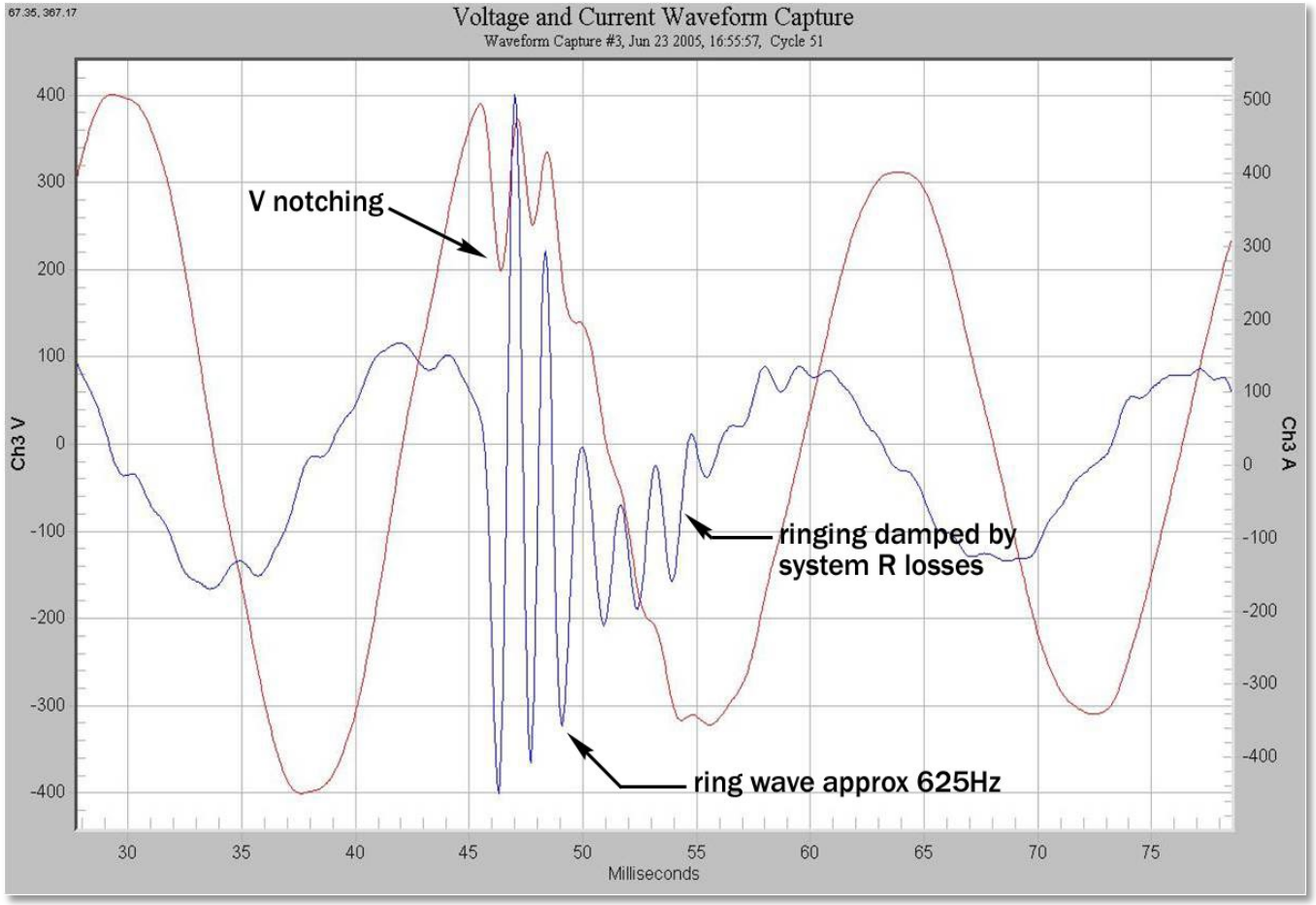


Captured by a PMI Eagle® 440

- Customer load current following voltage variations

Interpreting Captured Waveforms

Oscillatory Transient – Capacitor Energized



Captured by a PMI Eagle® 440

Oscillatory Transient

Medium Frequency 5-500kHz

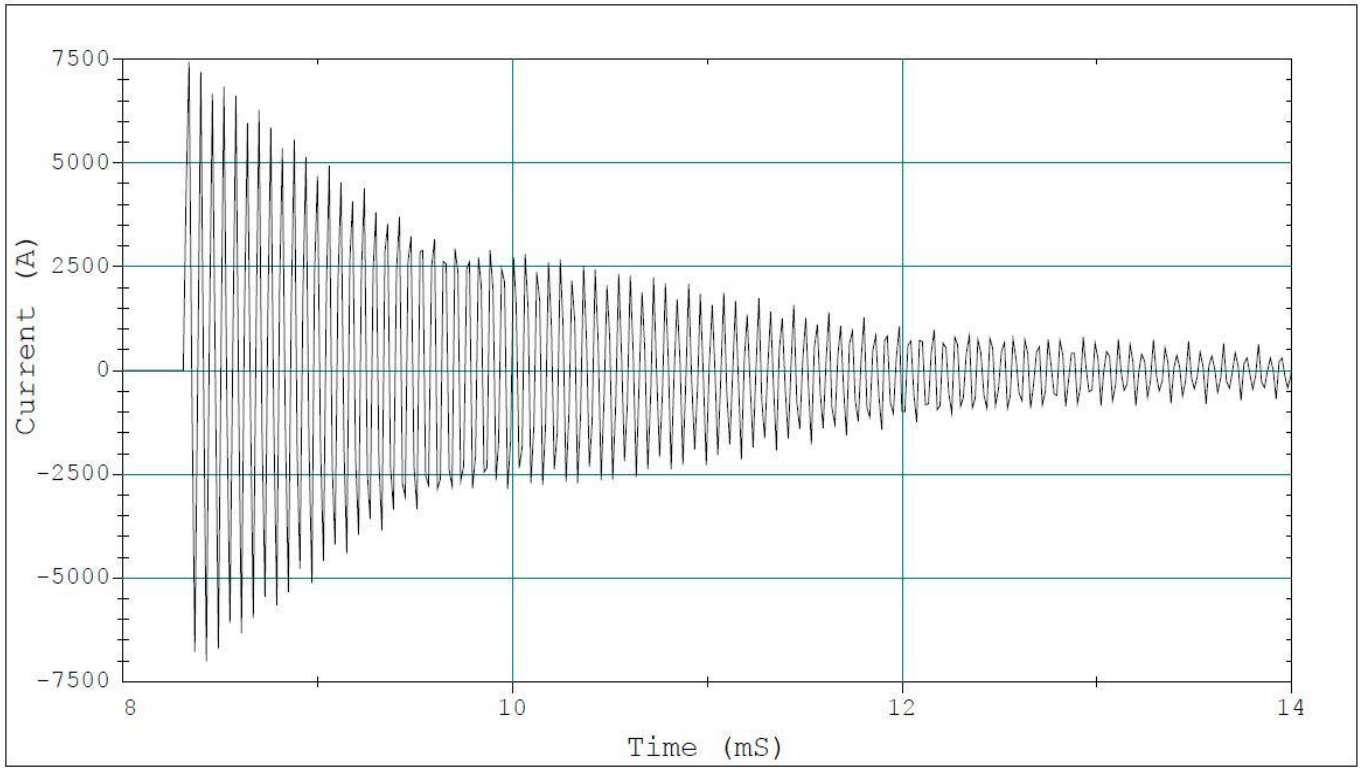
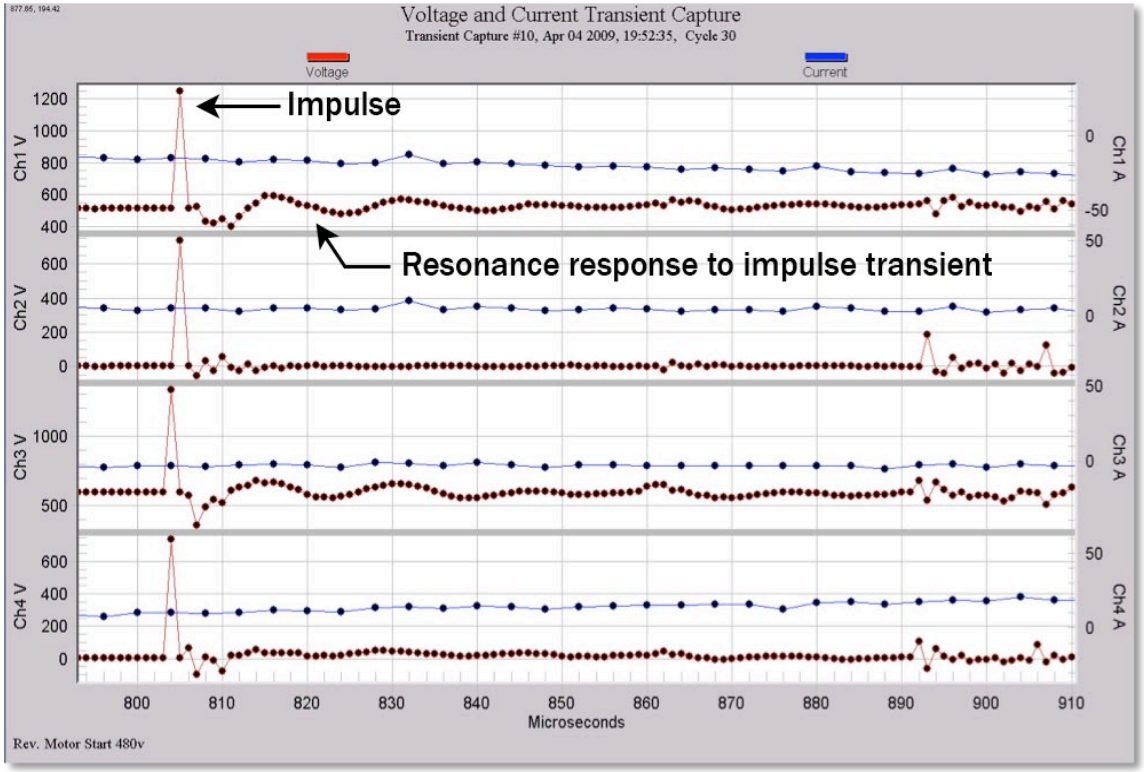


Figure 2: Oscillatory transient caused by back-to-back capacitor switching
IEEE 1159-1995: Recommended Practice for Monitoring Power Quality
© 1995 IEEE

Possible Solutions:
Pre-Insertion resistance or inductance

Oscillatory Transient

Medium Frequency 5-500kHz



Captured by a PMI Revolution®

- 5-500kHz: Med frequency ringing – System response to impulse transient

Voltage Sags

- IEEE 1159–1995, Recommended Practice for Monitoring Electric Power Quality

  A decrease in RMS voltage to between 0.1 and 0.9 pu at the power frequency for durations of 0.5 cycle to 1 min

Typical Causes:

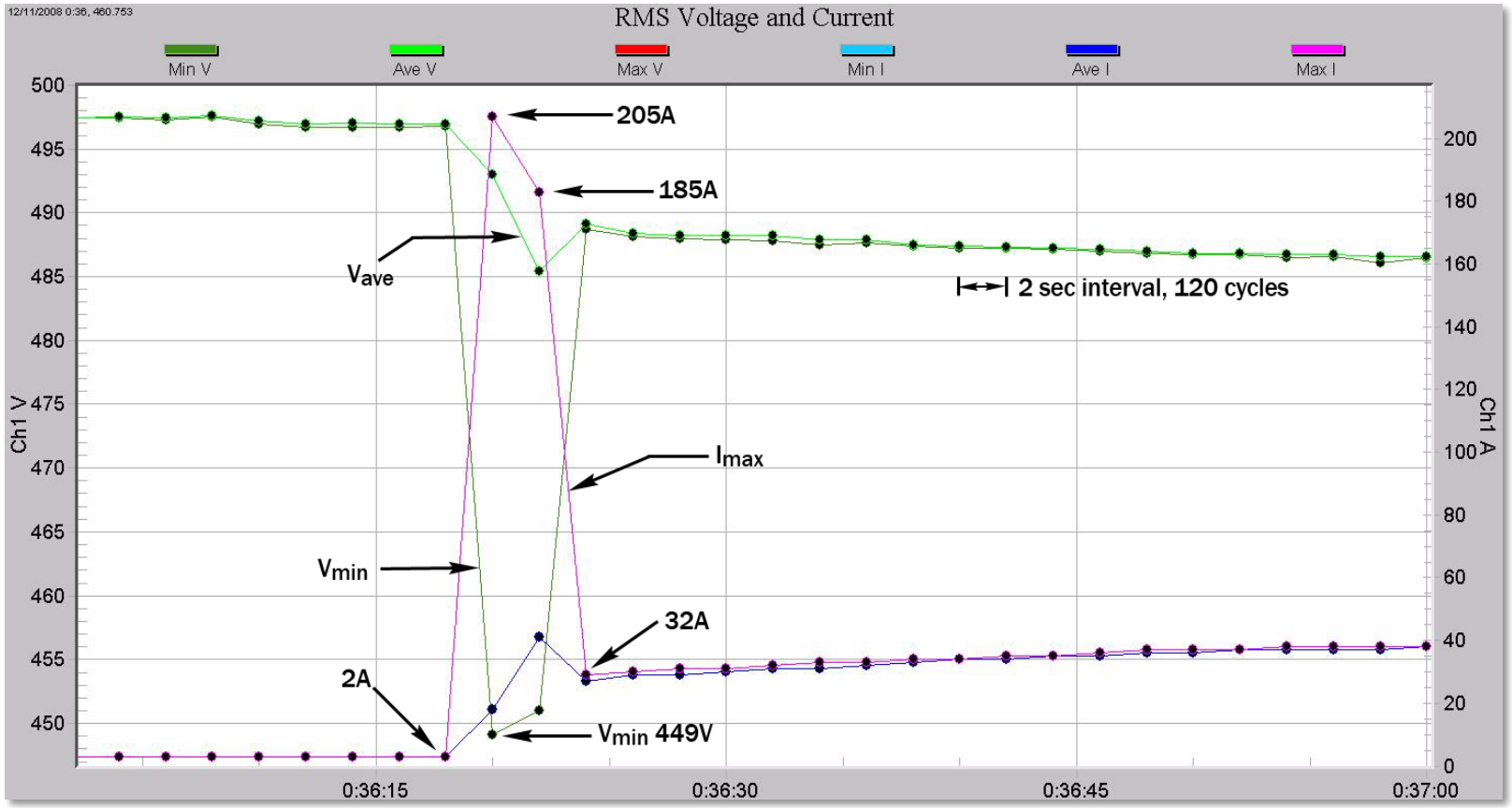
- Power system faults
- Energizing loads that require large currents
- Motor starts

Possible Solutions:

- UPS
- Soft starts on motors
- Lower impedance

Sag with Interval Graphs

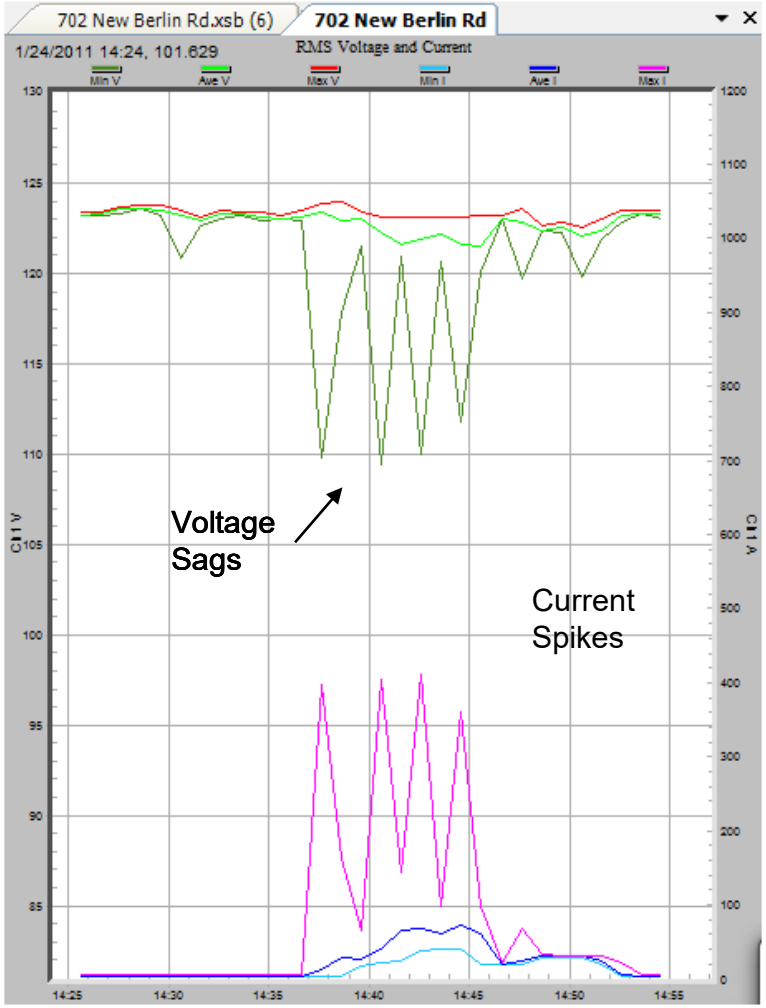
Interval Graph – V sag, 480V motor start



Captured by a PMI Revolution®

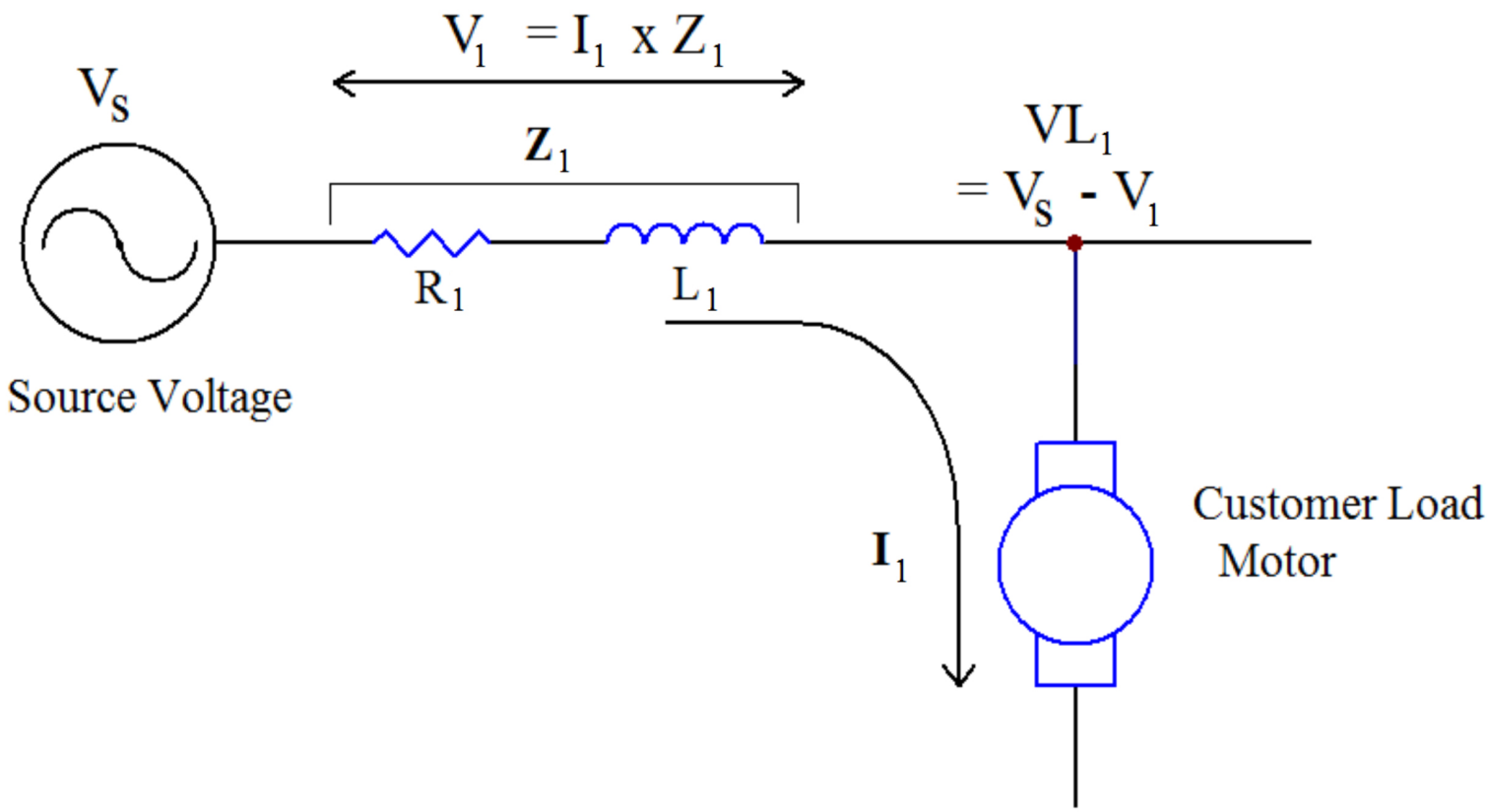
Voltage Sags

- Voltage Sags – can be caused by energizing large loads, starting large motors, loose connections, power system faults
- Can cause equipment trips, mis-operation

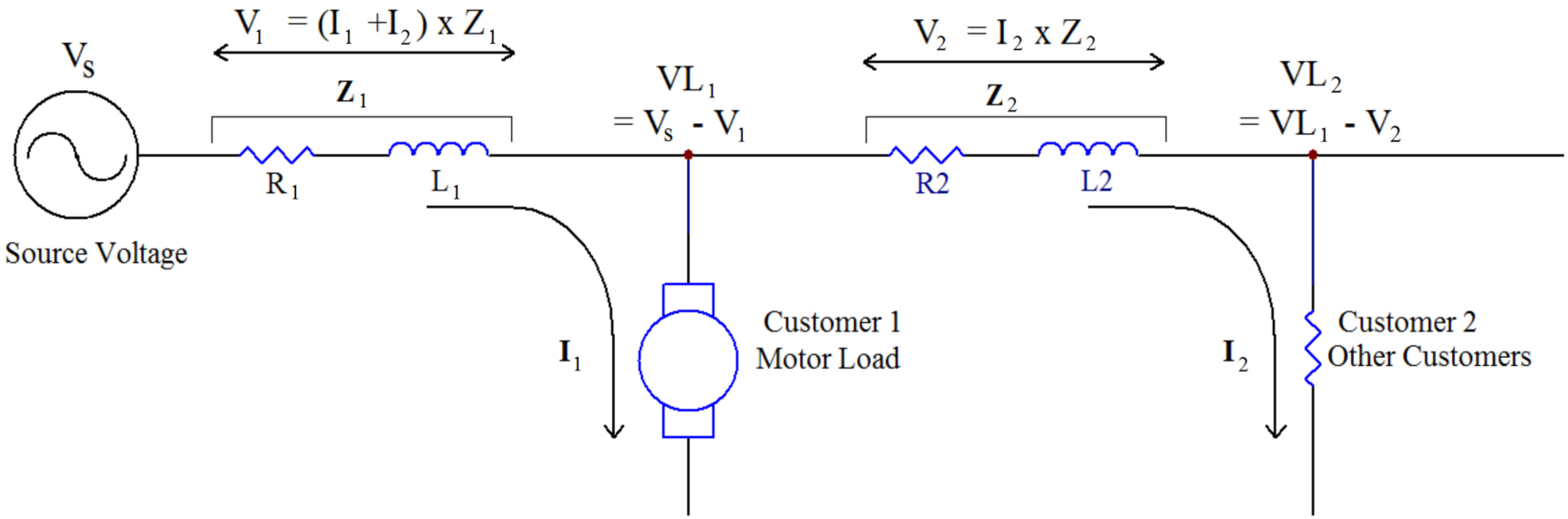


Voltage Sags

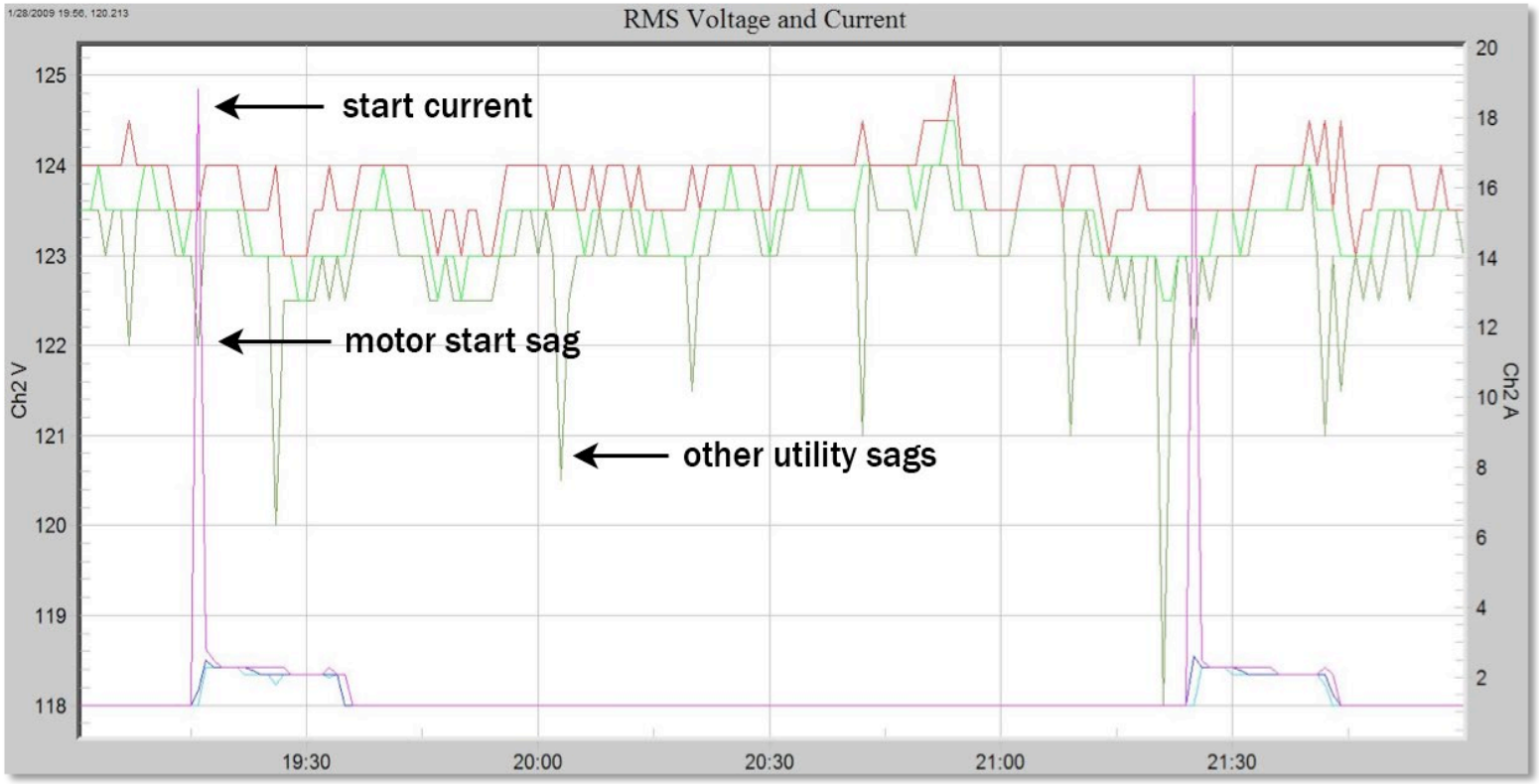
Customer Load Induced



Voltage Sags
Effects of Other Customer Loads



Voltage Sags
120V 1-PH Motor Start

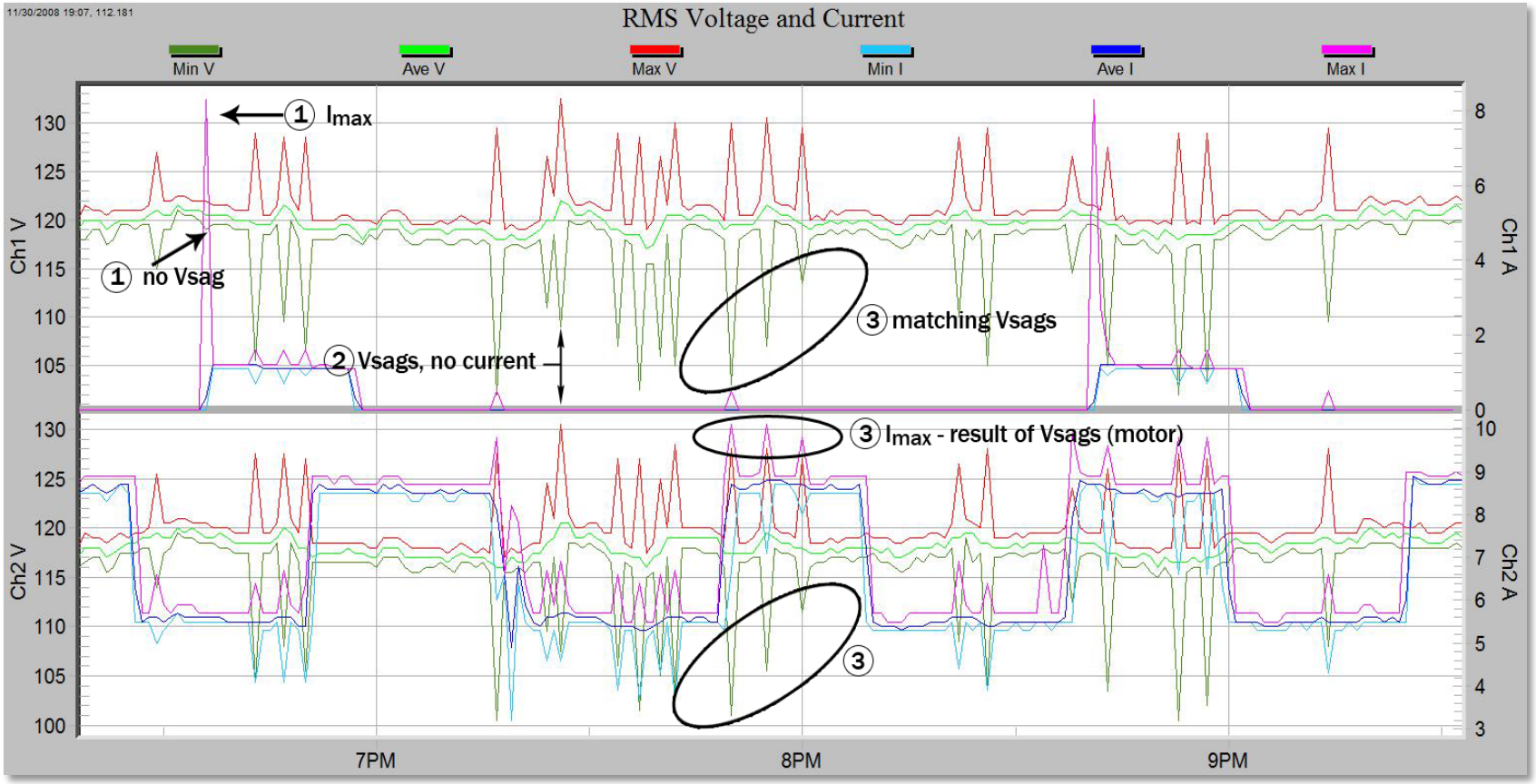


Captured by a PMI Eagle® 440

- Motor start inrush current – 7x running current
- Small momentary Vsag (1.5V) during inrush current

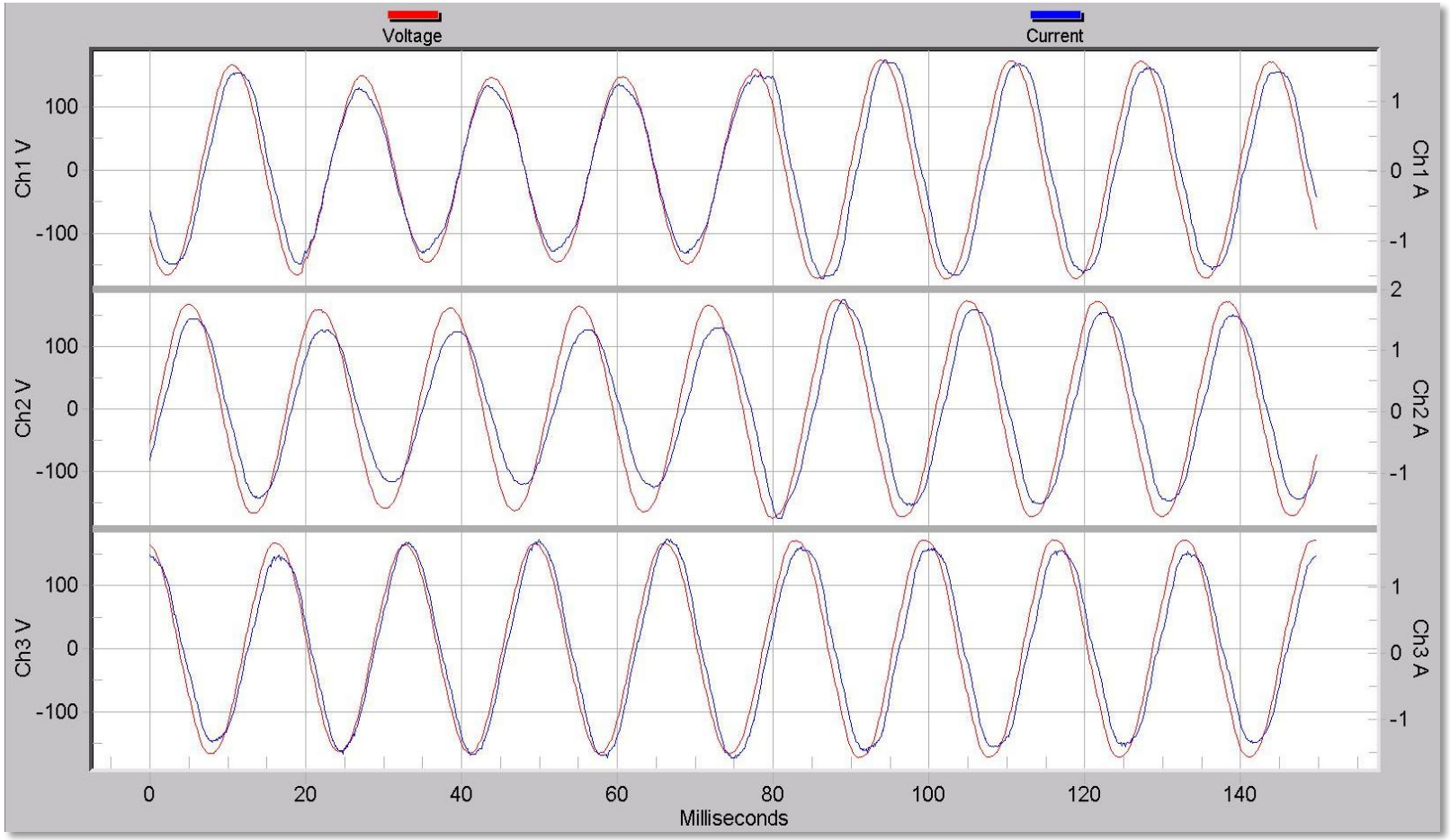
Voltage Sags

Interval Graph – V sags, utility supply or customer induced?



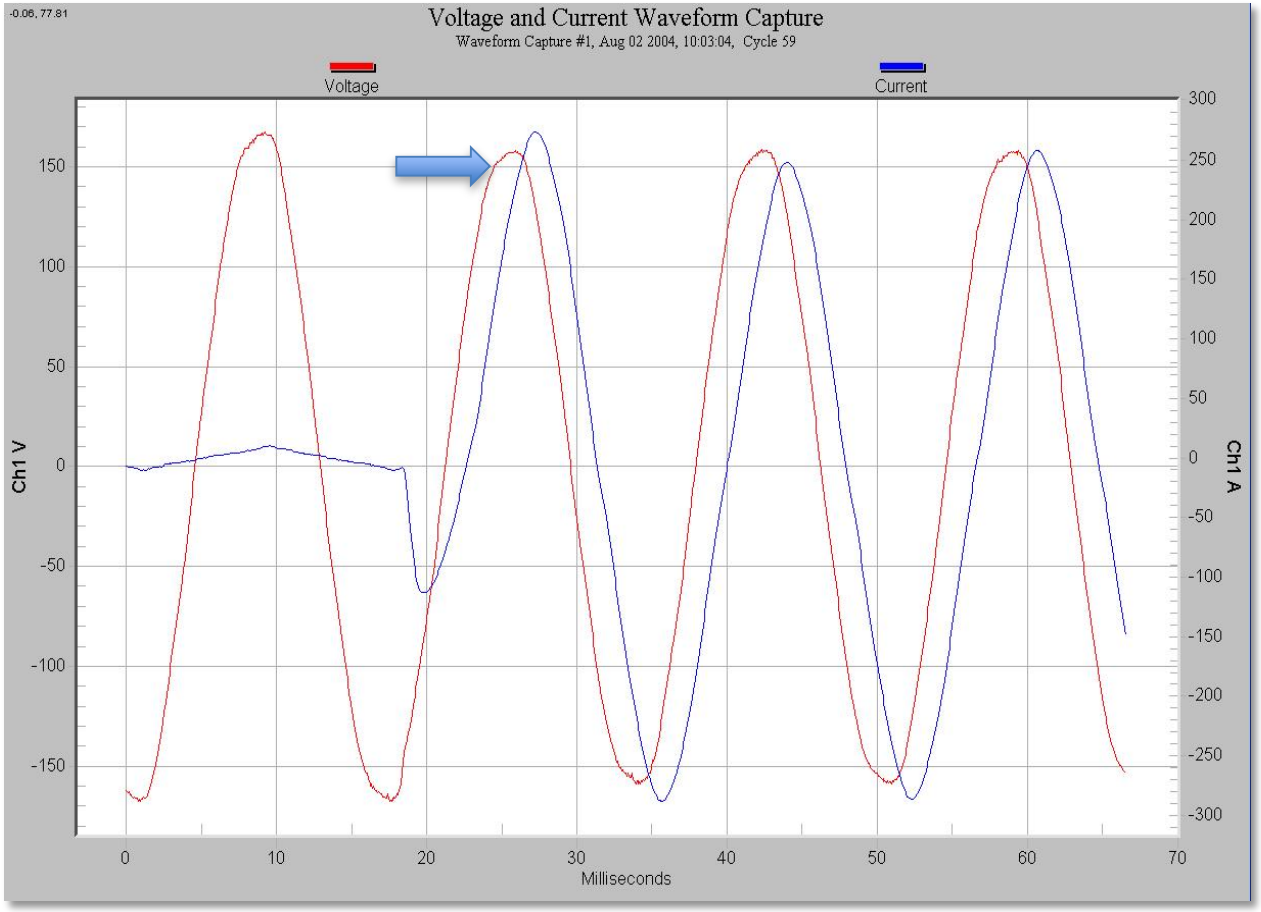
Captured by a PMI iVS-2SX+

Voltage Sag – Utility Side



Captured by a PMI Eagle® 440

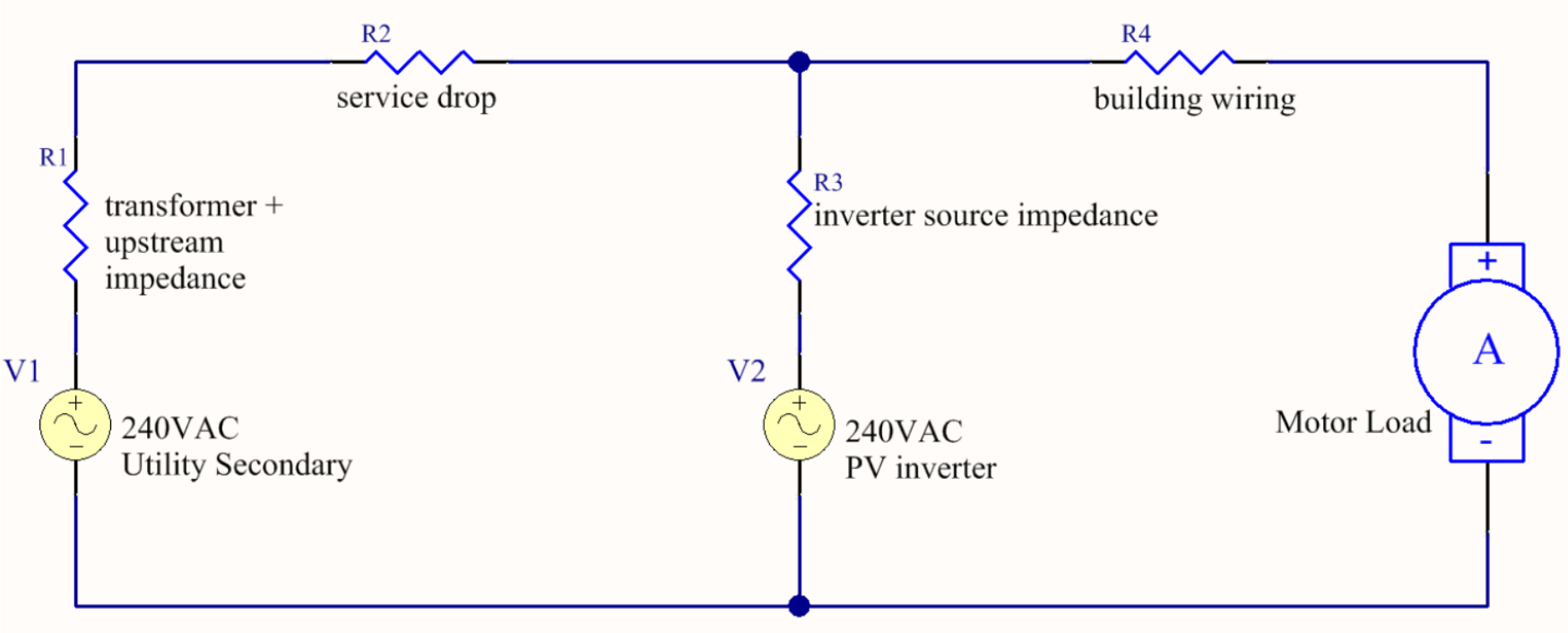
Voltage Sag – Load Induced



Captured by a PMI Eagle® 440

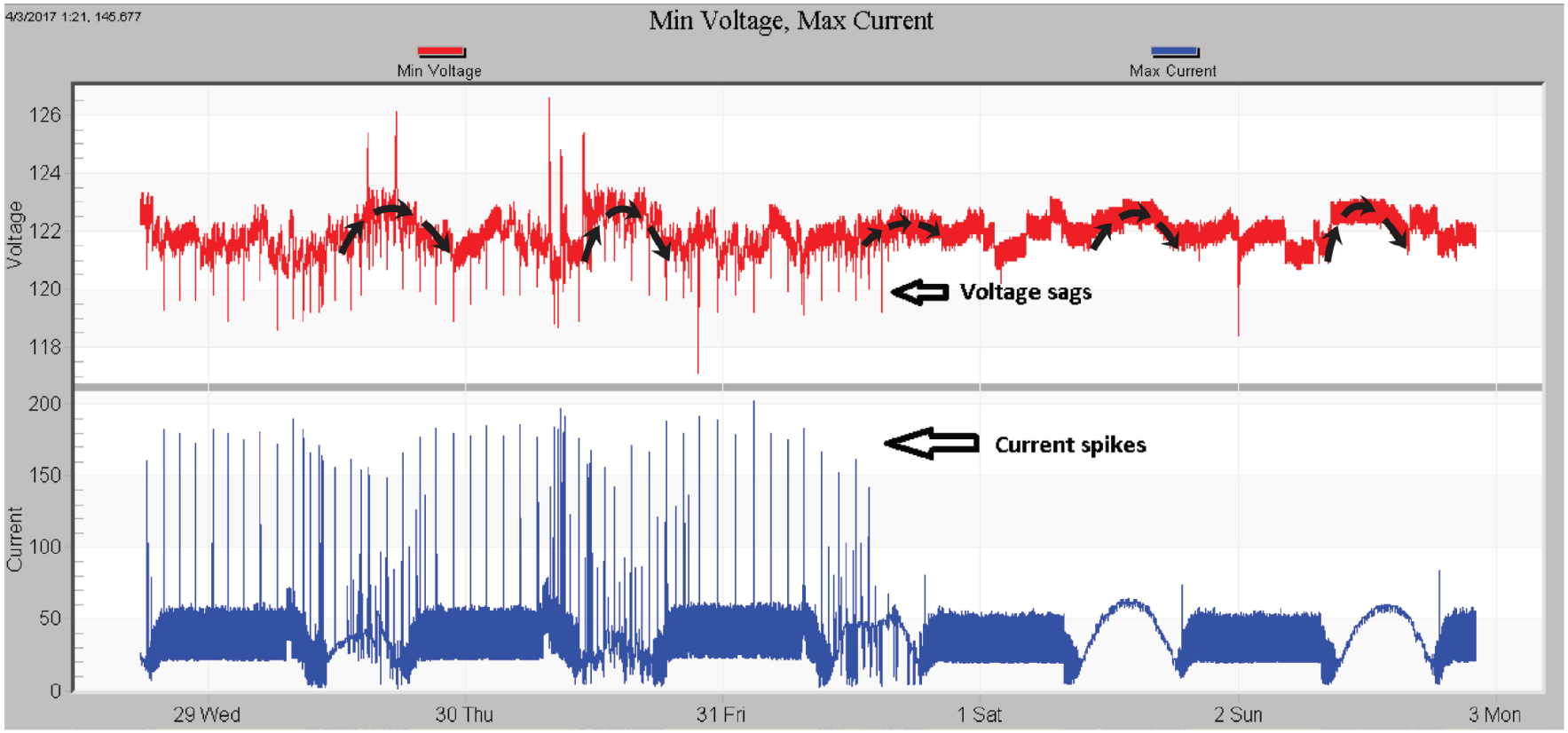
Voltage Sag with PV

Two power sources, with differing impedance



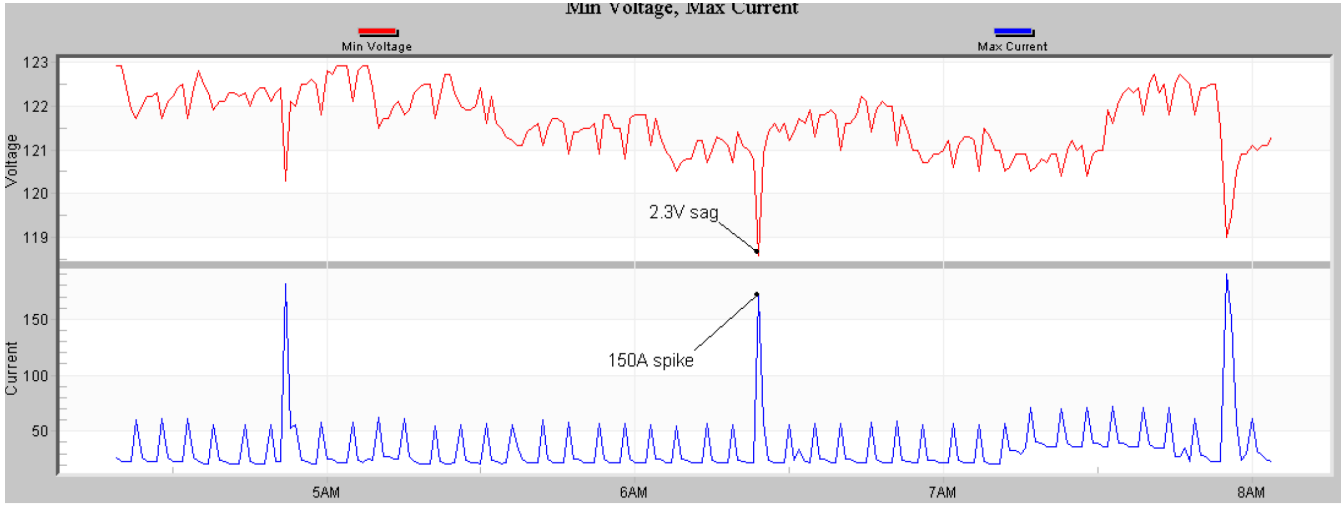
Voltage Sag with PV

Motor starts during day with PV, and also at night with no PV

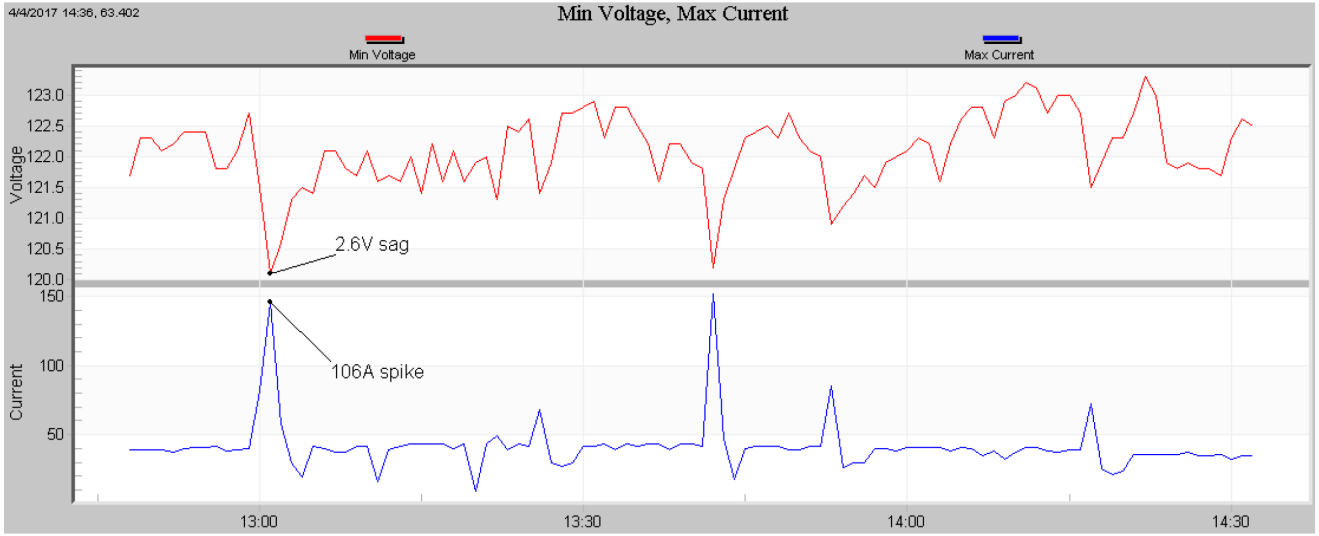


Voltage Sag with PV

150A inrush, 2.3V sag at night



106A inrush, 2.6V sag during day with PV support



Voltage Swell

Cause:

- Can be caused by SLG fault temporary V rise on unfaulted phases, switching events
- Can cause equipment trips, misoperation due to detection of overvoltage condition

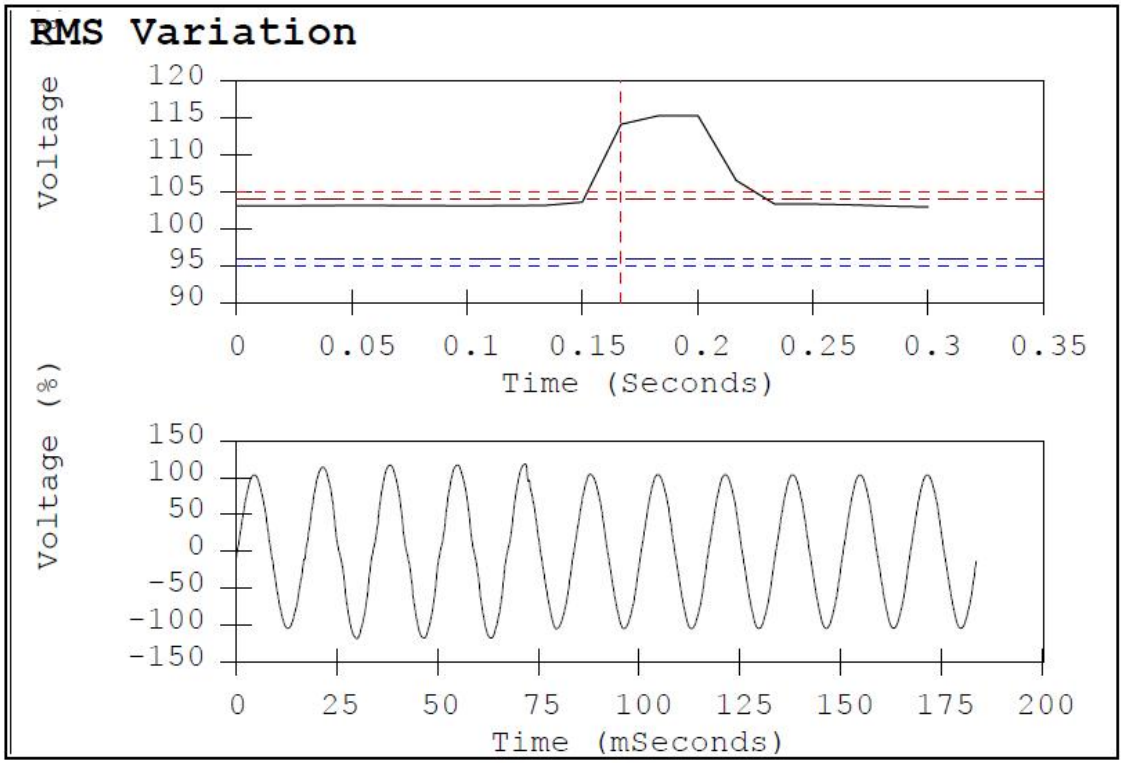


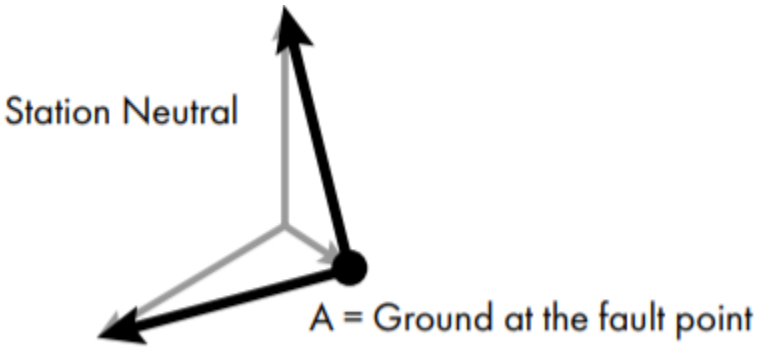
Figure 8– Instantaneous voltage swell caused by SLG fault

IEEE 1159-1995 Recommended Practice for Monitoring Power Quality, © 1995 IEEE

Fault Voltage Swell

ANSI/IEEE C62.92- 1987, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems

System	Overvoltage Factor
Ungrounded System	1.82
Four-Wire Multigrounded System (Spacer Cable)	1.5
Three- Or Four-Wire Unigrounded System (Open Wire)	1.4
Four-Wire Multigrounded System (Open Wire-Gapped Arrester)	1.25
Four-Wire Multigrounded System (Open-Wire Metal-Oxide Arrester)	1.35

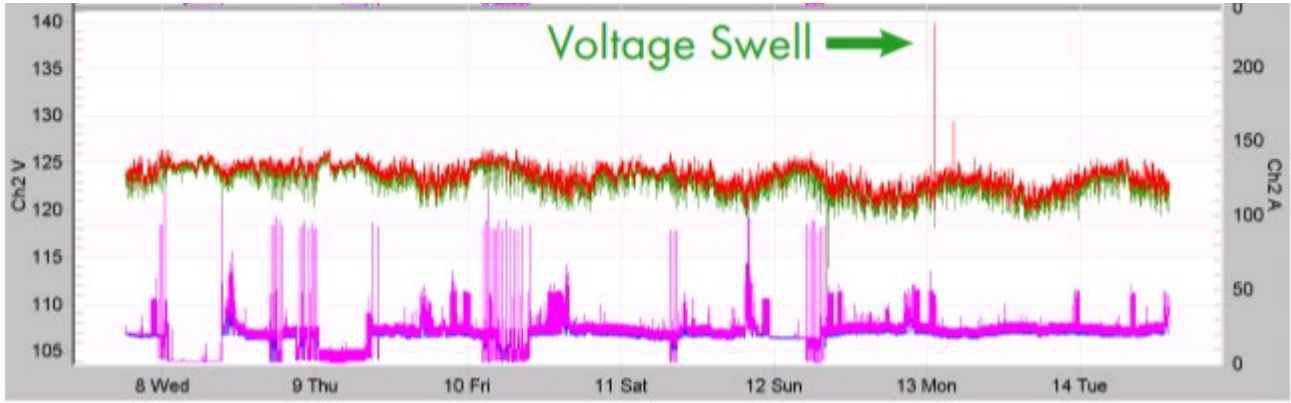


Cause:

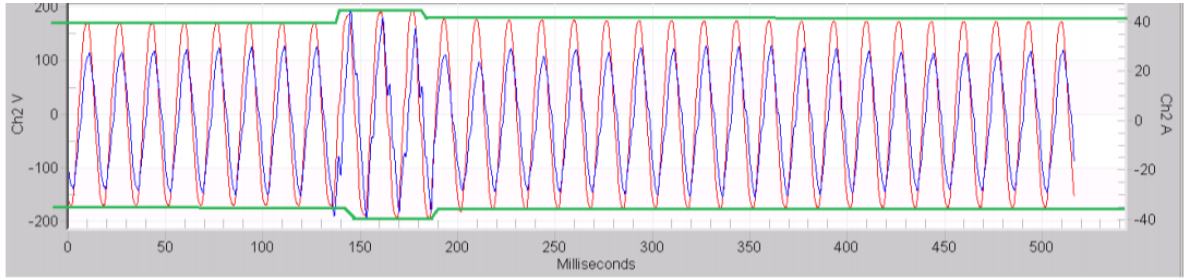
- Fault pulls local ground away from substation ground potential, increasing ground-phase voltage on other phases
- Overvoltage factor depends on circuit grounding method

Recloser Voltage Swell

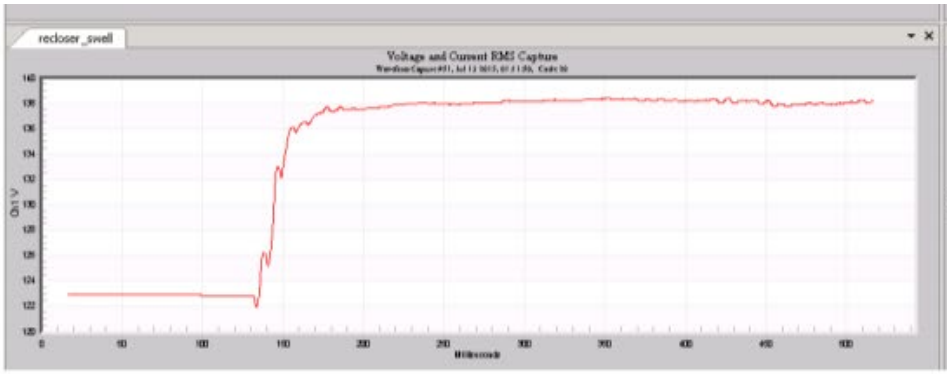
- Multiple recloses appear as single stripchart max voltage point
- Waveform captures give more timing detail

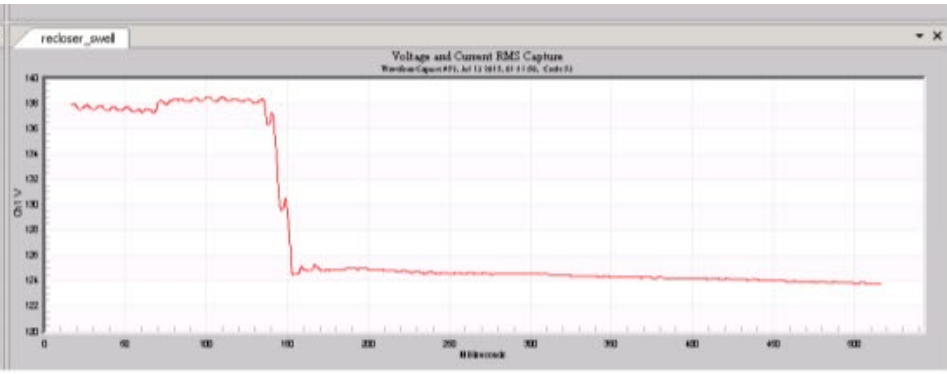


3 cycle reclose



30 cycle reclose





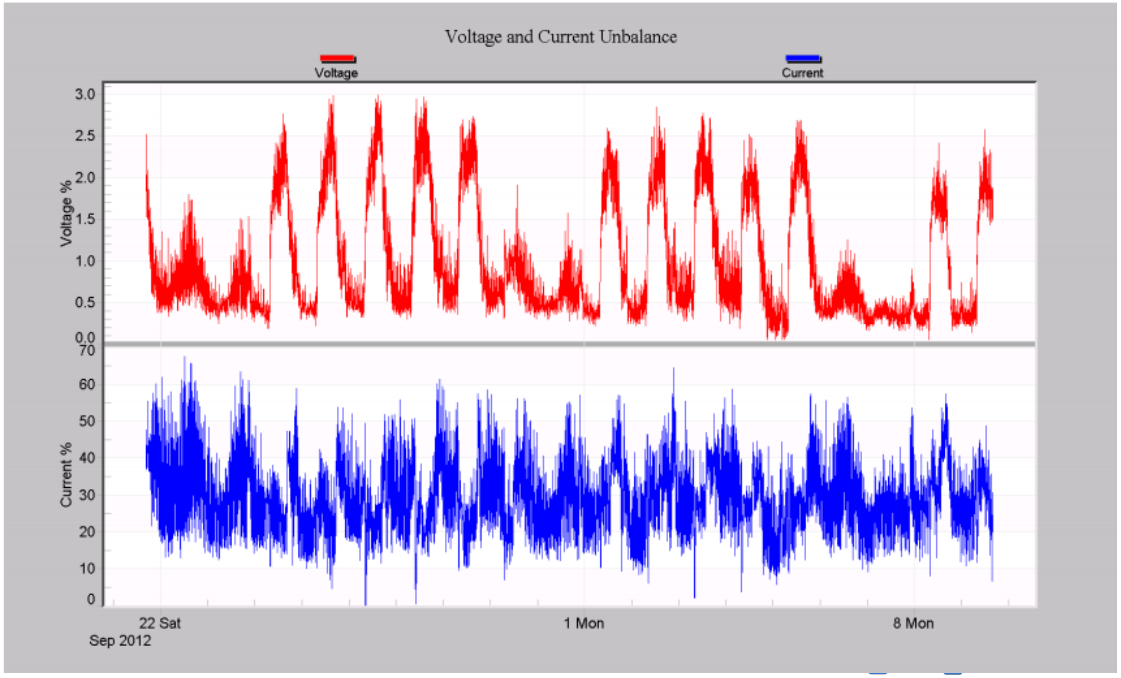
Voltage Unbalance

- Max deviation from ave, divided by ave.
- A, B, C = 124V, 119V , 112V
- Ave = (124+119+112)/3 = 118.3V
- dVmax = |112-118.3| = 6.3V
- Vu = 6.3/118.3 x 100% = 5.3%

$$dV_{max} = \max_{n=1,2,3} |V_n - V_{ave}|$$

$$V_u = \frac{dV_{max}}{V_{ave}} \times 100\%$$

ANSI C84 limit = 3% voltage unbalance, with no load



Delta Voltage Unbalance

- Voltage phase angle shifts can cause unbalance in delta circuit, not seen in wye!

$$V_{AB} = V_{AN} - V_{BN}$$
$$V_{BC} = V_{BN} - V_{CN}$$
$$V_{CA} = V_{CN} - V_{AN}$$

$$V_{AB} = |V_{AN}|\angle\theta_A - |V_{BN}|\angle\theta_B$$

$$V_{AB} = |V_{AN}|\angle\theta_A - |V_{BN}|\angle\theta_B$$
$$V_{AB} = |V_{AN}|cos(\theta_A) - |V_{BN}|cos(\theta_A) + j(|V_{AN}|sin(\theta_A) - |V_{BN}|sin(\theta_A))$$
$$|V_{AB}| = \sqrt{(|V_{AN}|cos(\theta_A) - |V_{BN}|cos(\theta_A))^2 + (|V_{AN}|sin(\theta_A) - |V_{BN}|sin(\theta_A))}$$

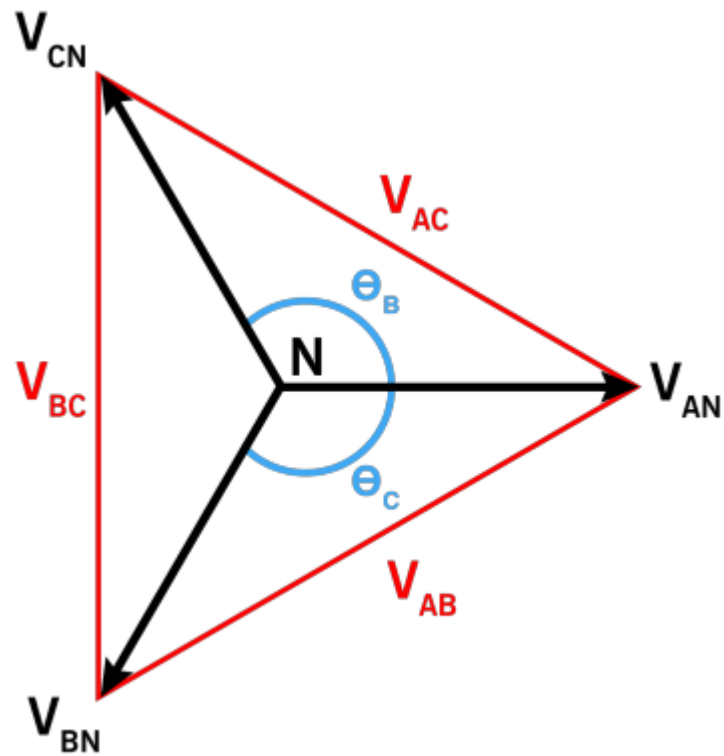
Ex. 277/480V ideal system, 120 degrees

$$\begin{aligned}|V_{AB}| &= \sqrt{(|V_{AN}|cos(\theta_A) - |V_{BN}|cos(\theta_A))^2 + (|V_{AN}|sin(\theta_A) - |V_{BN}|sin(\theta_A))^2}\\ &= \sqrt{(277\cos(0) - 277\cos(120))^2 + (277\sin(0) - 277\sin(120))^2}\\ &= \sqrt{((277 - -138.5)^2 + (0 - 239.9)^2}\\ &= \sqrt{415.5^2 + (-239.9)^2}\\ &= \sqrt{230192.26}\\ &= 479.8 \text{ Volts}\end{aligned}$$

Add 5 degree phase B shift:

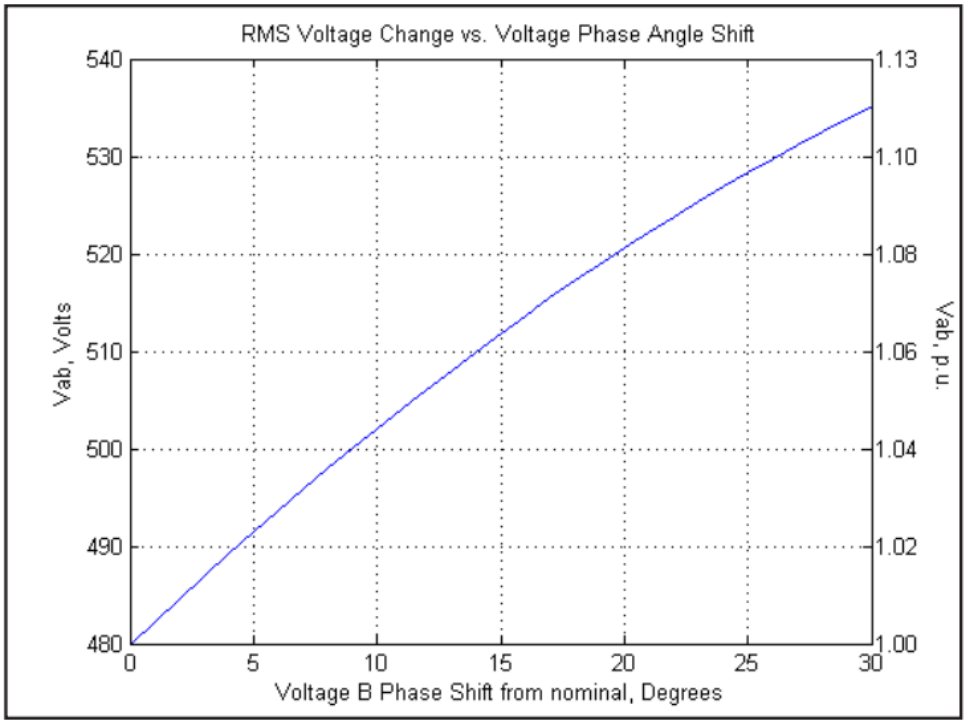
$$\begin{aligned}|V_{AB}| &= \sqrt{(277\cos(0) - 277\cos(125))^2 + (277\sin(0) - 277\sin(125))^2}\\ &= \sqrt{435.9^2 + (-226.9)^2}\\ &= \sqrt{241477.9}\\ &= 491.4 \text{ Volts}\end{aligned}$$

11.6V shift = 2.4% change!



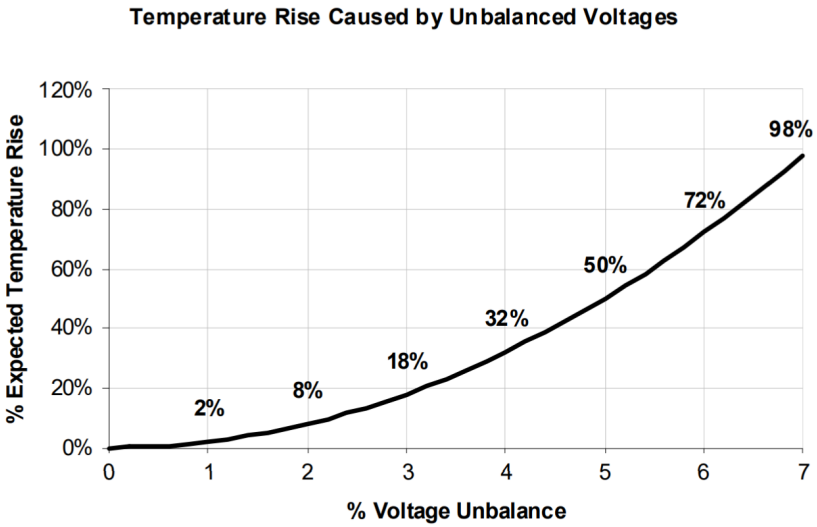
Delta Voltage Unbalance

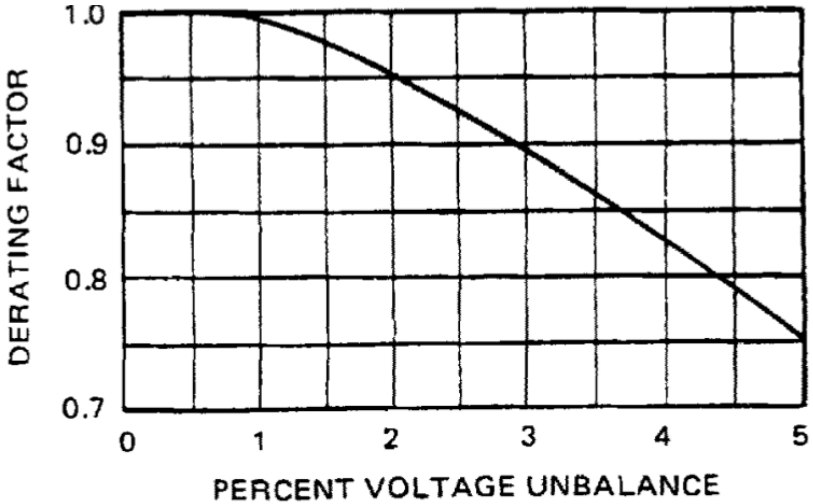
- Be aware of delta voltage unbalance
- Utility limits are generally line-neutral, but most equipment is line-line connected
- Connect PQ recorder with same hookup type as sensitive equipment in some cases
- Unbalance may require phase angle fixes in addition or instead of voltage regulator adjustments
- Blown cap bank fuse in one phase
- Open deltas
- Neutral reactors and unbalanced feeders



Unbalance and AC Motors

- Motors are mostly unaffected by unbalance until 70% loaded or higher
- Loaded motor's current unbalance is ~ 6-10 times voltage unbalance
- Lightly loaded motor's current unbalance can be 20-30 times voltage unbalance – can false trip protection
- Increased heating may damage motor, may have to derate
- VFDs are often more sensitive



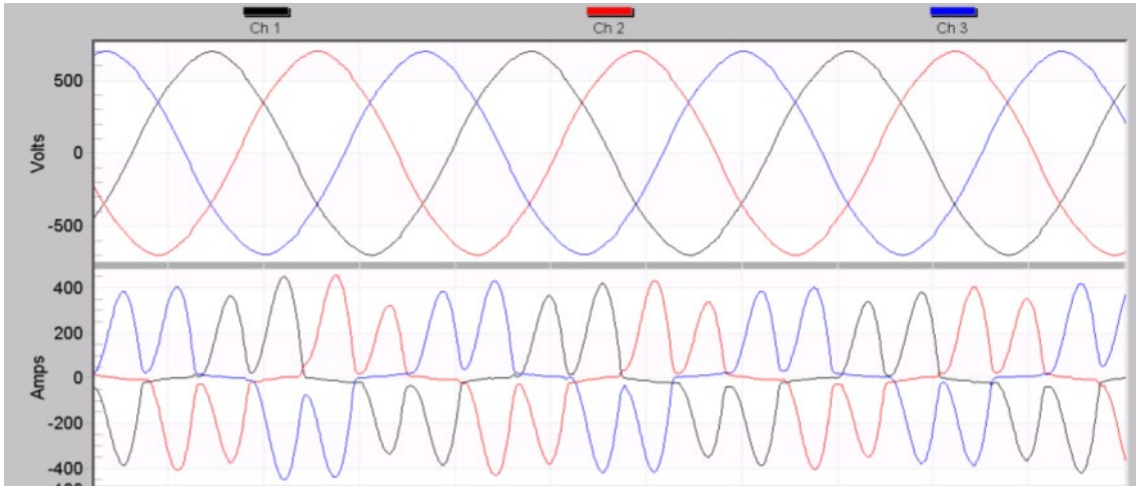


NEMA MG-1 derating curve

VFD Unbalance

Voltage Unbalance

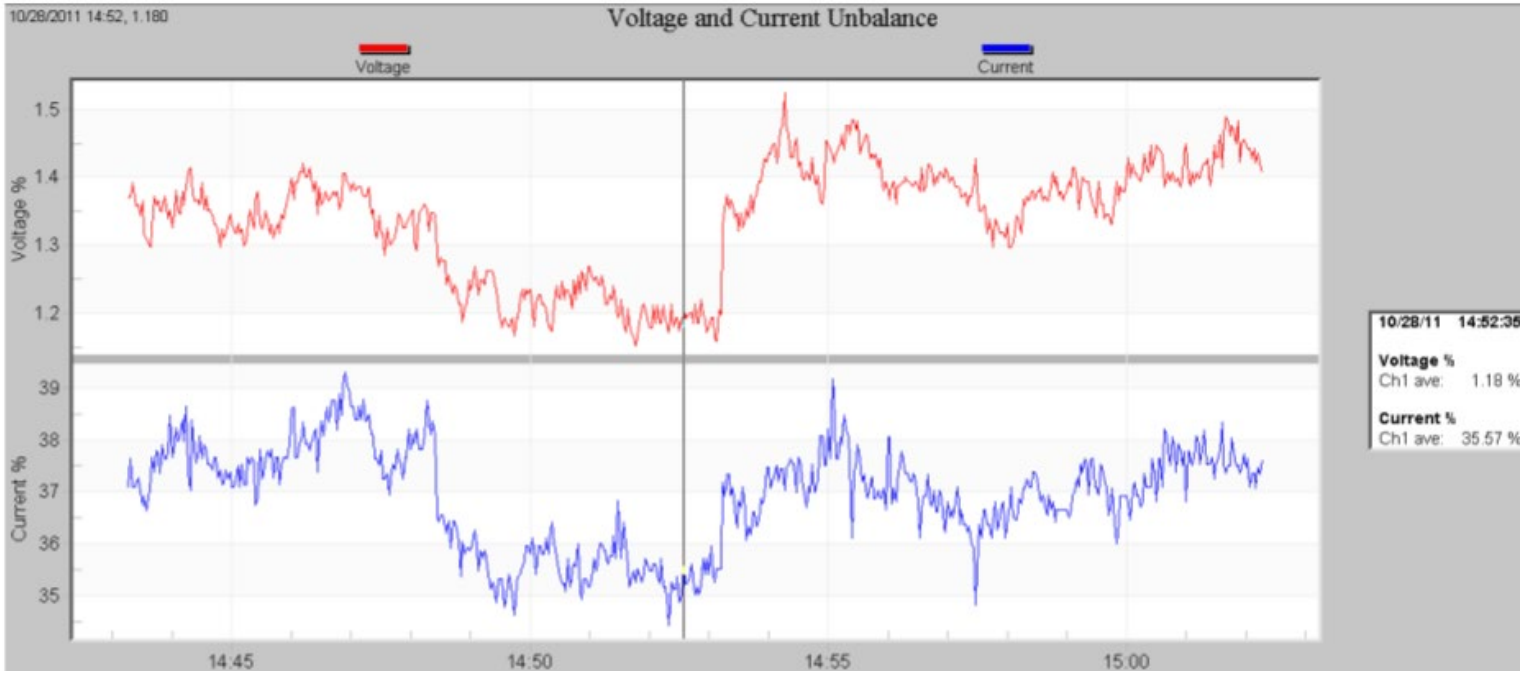
- Causes unequal currents through 3-phase rectifiers
- Increased heating can lead to “thermal runaway”, causing the rectifier to fail



Voltage Unbalance

Unbalance ratio – Current unbalance / Voltage unbalance

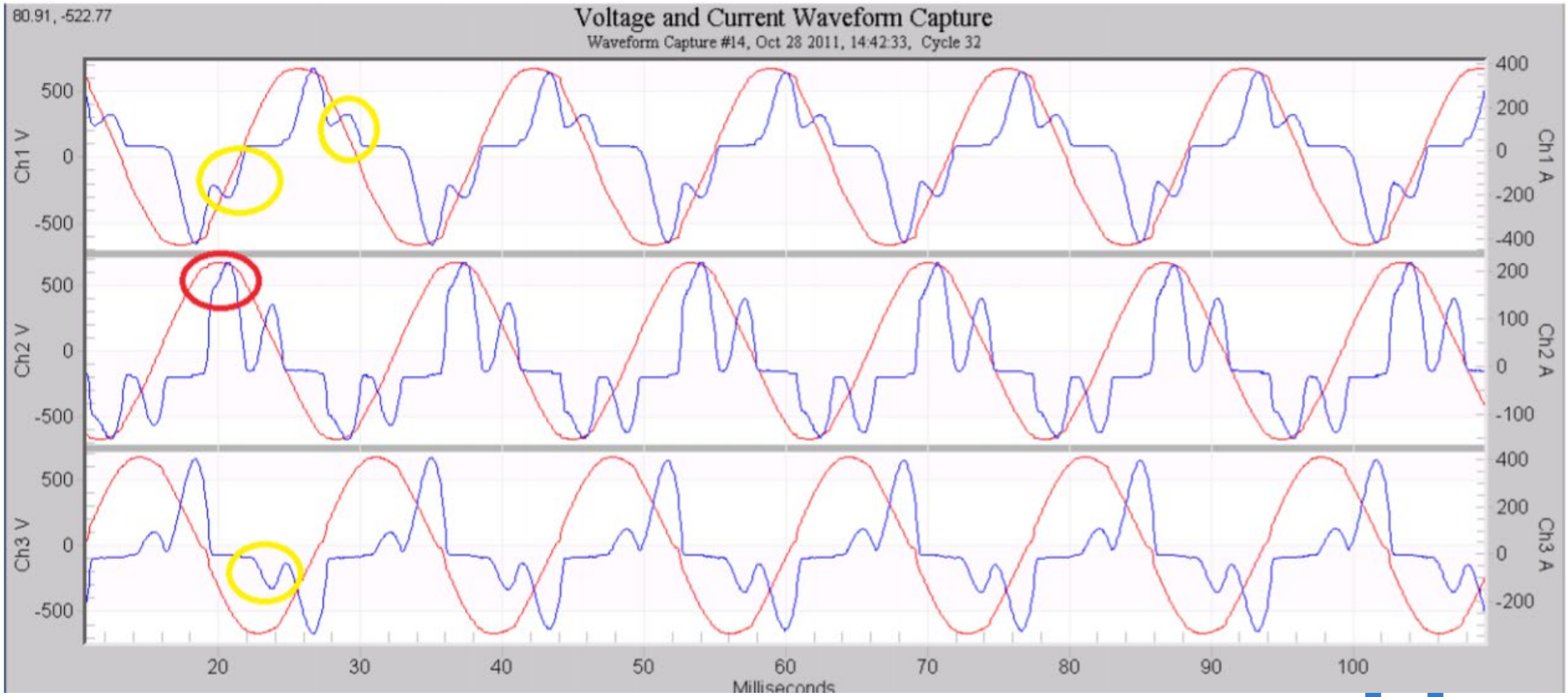
- Typical VFD ratio is 10-20
- Ratio is over 30 below (1.18% voltage, 35% current) – indicates possibly failing VFD bridge input



Voltage Unbalance

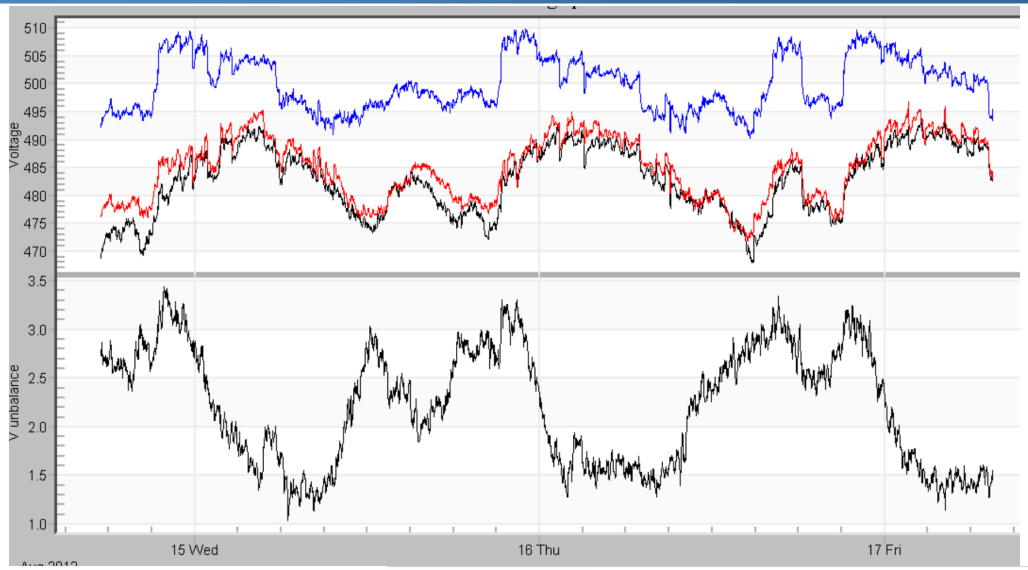
Unbalance ratio – Current unbalance / Voltage unbalance

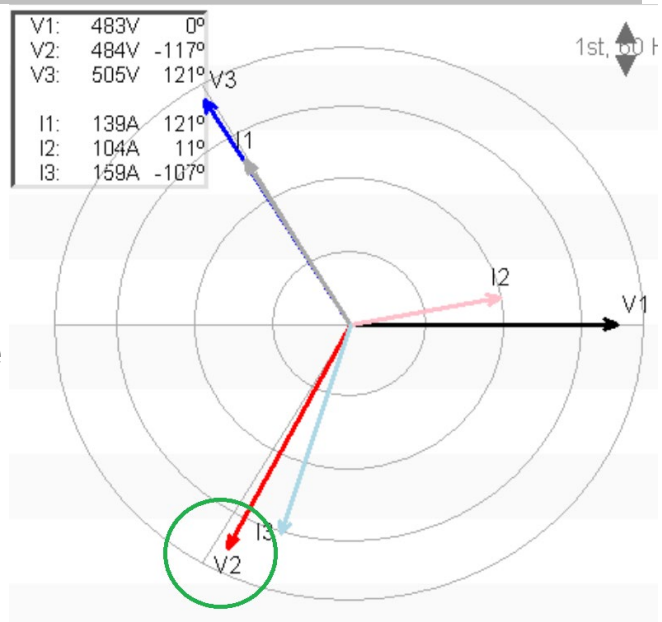
- Waveform analysis – high and runt current pulses – failing VFD rectifier



Case: Delta Voltage Unbalance

- Phase B: -117 degrees
- Phase C: 121 degrees
- 3.4% voltage unbalance
- Half is from phase shift
- Line reactor in substation combined with > 100A neutral current from unbalanced feeders





Check vector diagram for voltage phasors shifted from 120 degree marks

Power Quality 102

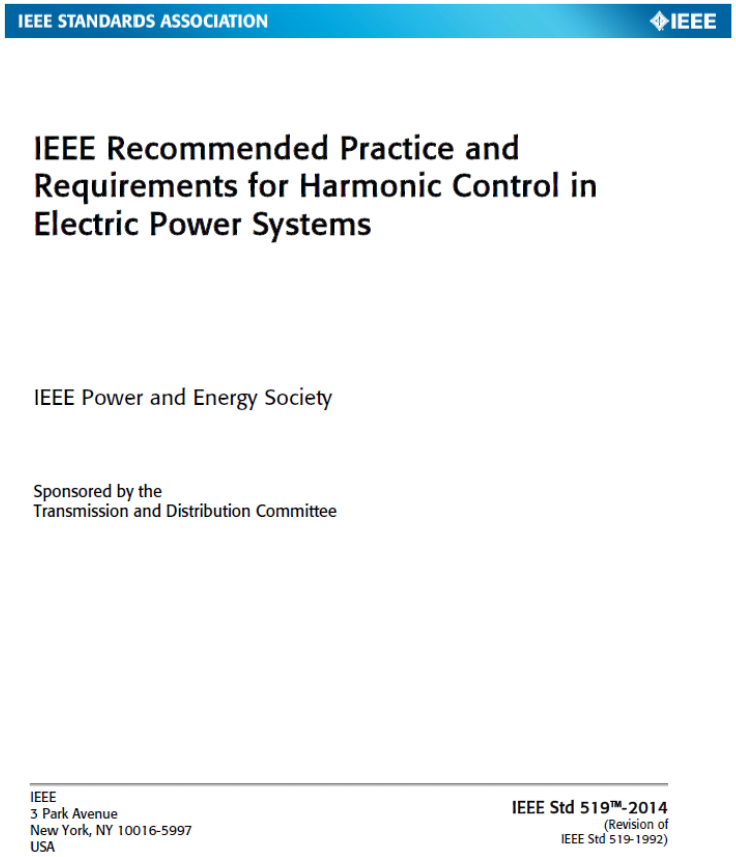
- Transients
- **IEEE 519 Harmonics**
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads

Harmonics - IEEE 519:2014

- Recommended practice for measuring and applying limits to voltage and current harmonics
- Applies at utility level – not an equipment spec
- Limits for utilities (voltage) and end-users (current)

Important to have a copy as the normative reference!

IEEE 519:1992 is also an excellent reference


IEEE STANDARDS ASSOCIATION IEEE

IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

IEEE Power and Energy Society

Sponsored by the
Transmission and Distribution Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 519™-2014
(Revision of
IEEE Std 519-1992)

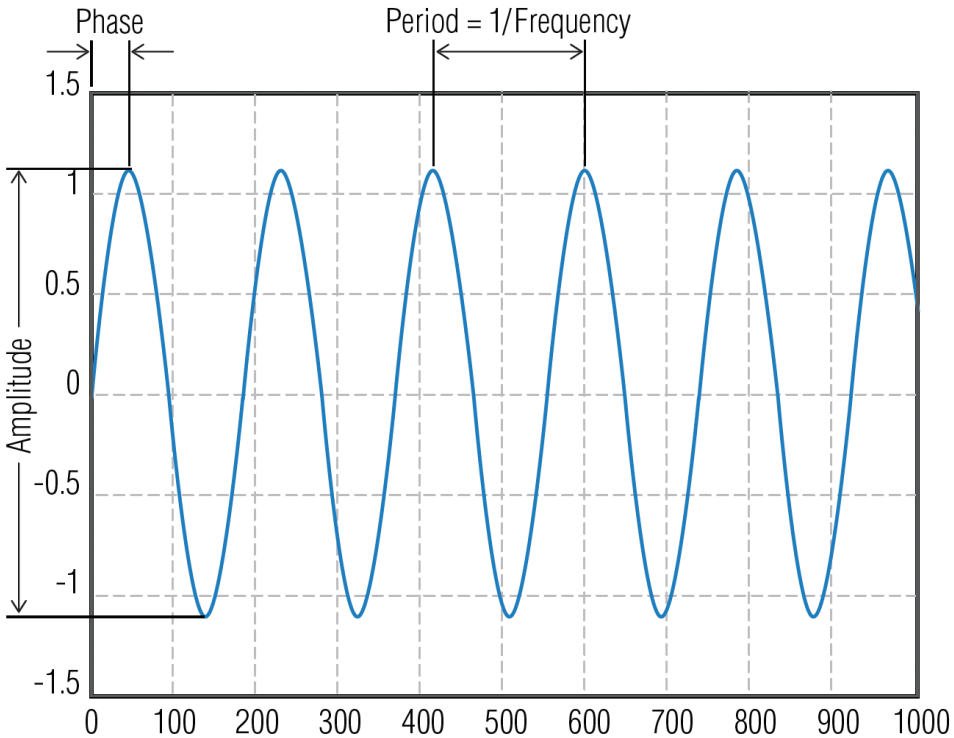
Sine waves

Sinusoid: $V(t) = A\sin(2\pi Ft+\theta)$

Sine properties:

A = amplitude
F = frequency
θ = phase angle

- Periodic
- Frequency unchanged by a linear system
- Orthogonal: $\int_{-\pi}^{\pi} \sin(Mt)\sin(Nt) = 0, \quad M \neq N$



120 VAC = $167\sin(2\pi 60t)$ $(167 = 120 \times \sqrt{2})$

What are Harmonics?

Fourier theorem: Any periodic waveform may be uniquely decomposed into a summation of sine waves of amplitude A_k, phase θ_k, and frequency kF

$$V(t) = \sum_k A_k \sin(2\pi kFt + \theta_k)$$

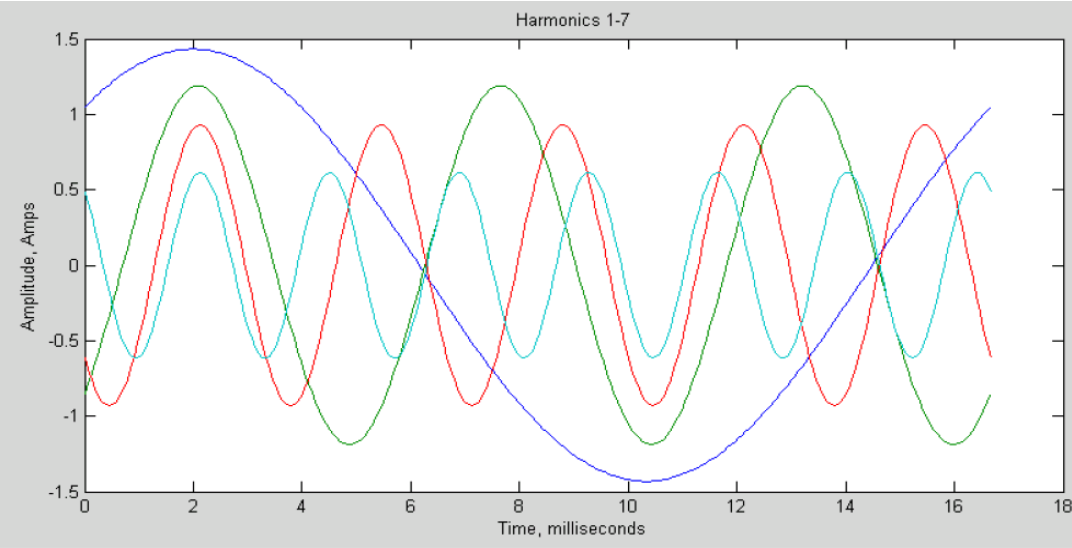
kF = multiple of the base frequency F, or fundamental.

If F=60 Hz, kF = 2x60, 3x60 = 120, 180 Hz, etc.

A_k = amplitude of the kth sine wave

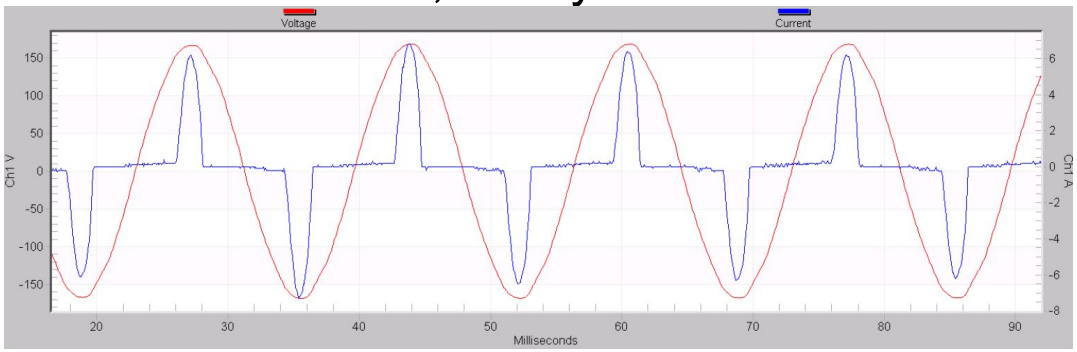
θ_k = phase angle of the kth sine wave, relative to the fundamental

k^{th} sine wave is the kth harmonic of the fundamental

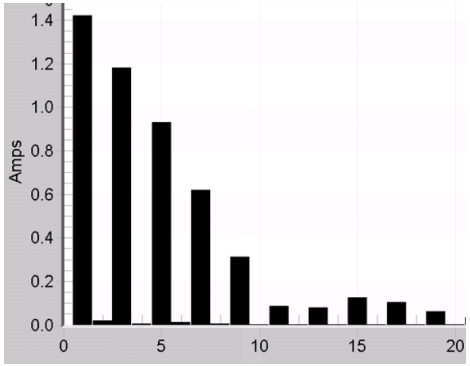


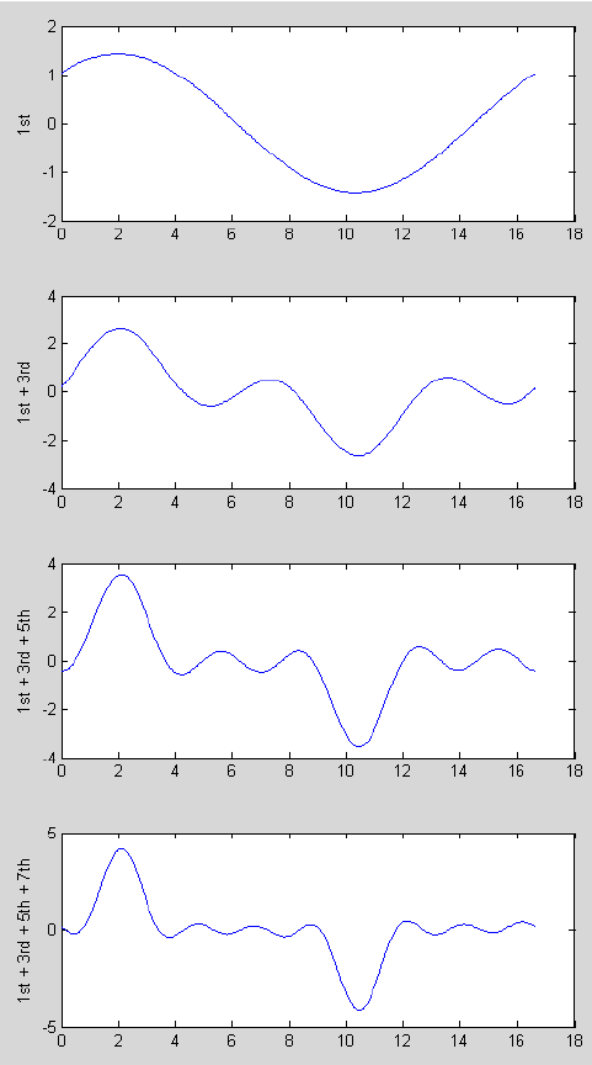
Why use Harmonics?

Most waveform distortion is periodic, driven by the 60 Hz voltage waveform – these are nonlinear, but synchronous loads



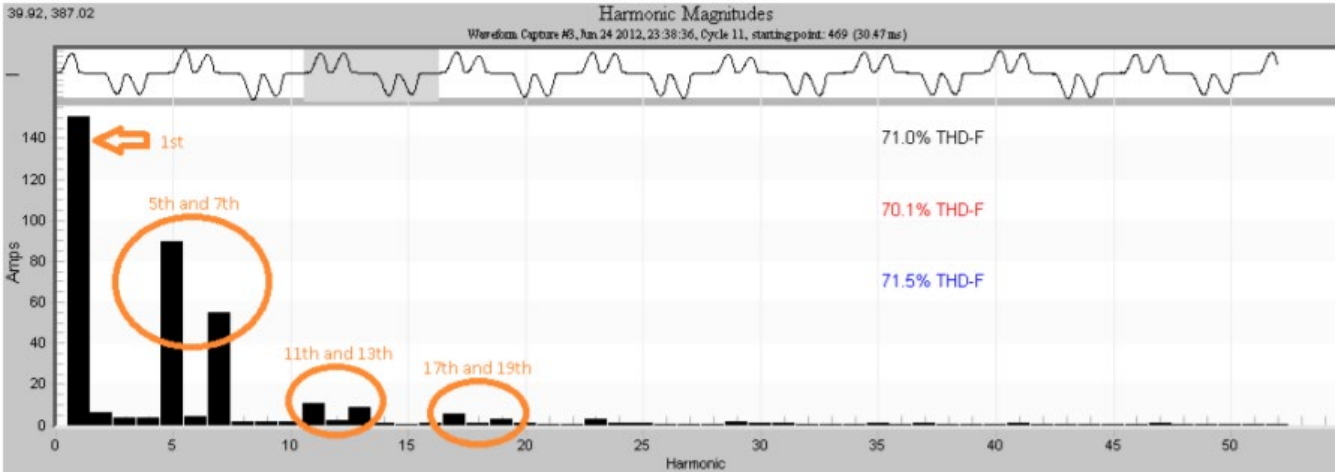
- Any complex, but periodic waveform shape has a unique harmonic representation
- Harmonic breakdown is parsimonious – most real-world waveforms are described by a few large harmonics
- Harmonics may be filtered by circuits tuned to specific frequencies – cf. linear system theory





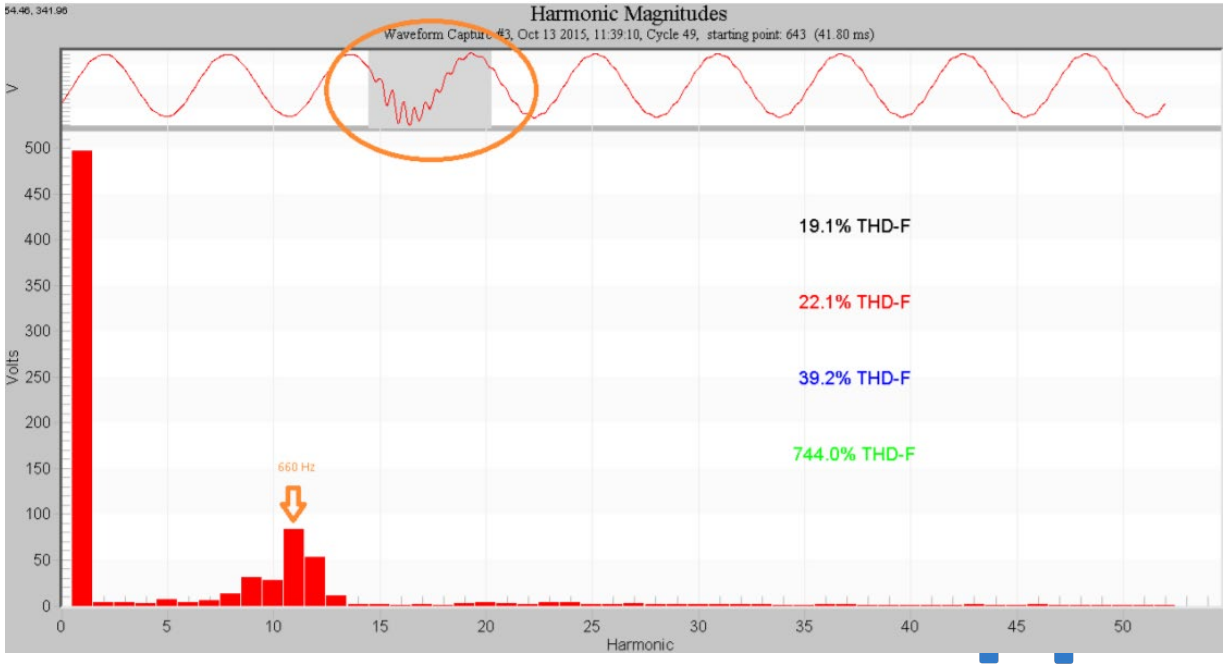
Harmonics are Steady State

Distortion repeated every cycle - harmonics



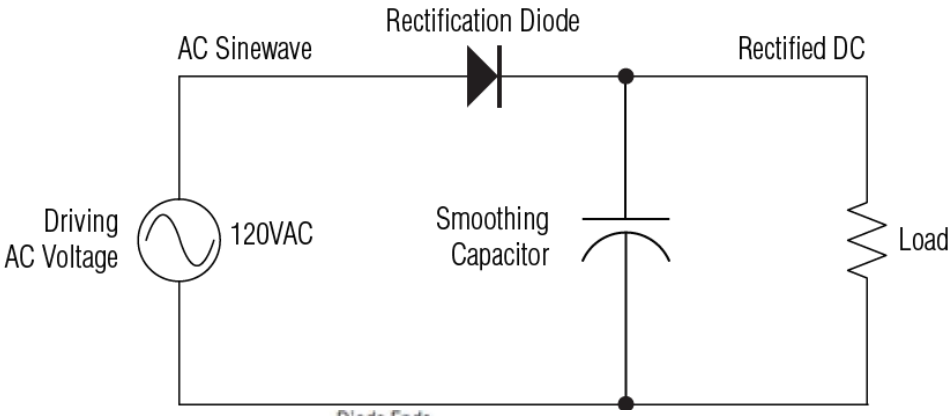
Vs

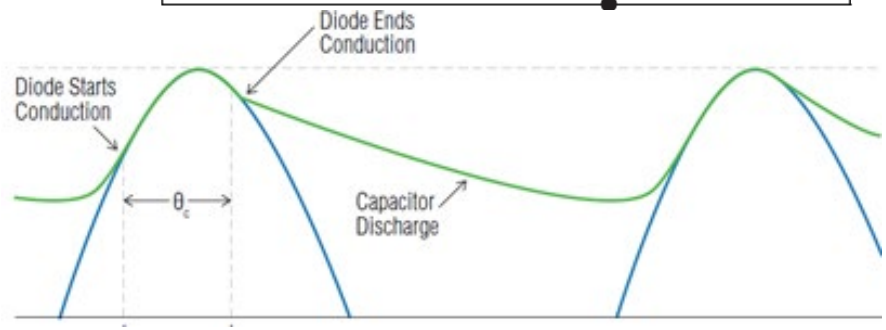
Oscillatory transient – NOT harmonics

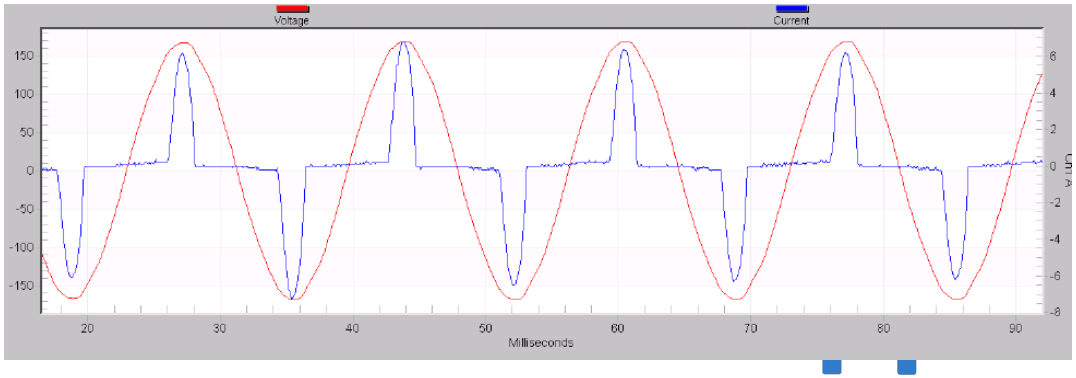


What Causes Current Distortion?

- Nonlinear circuit elements dynamically change impedance at different points on the voltage waveform
- Most modern loads convert 60 HZ AC into DC with rectifiers
- Nonlinearity is memoryless – repeats every 60 Hz cycle

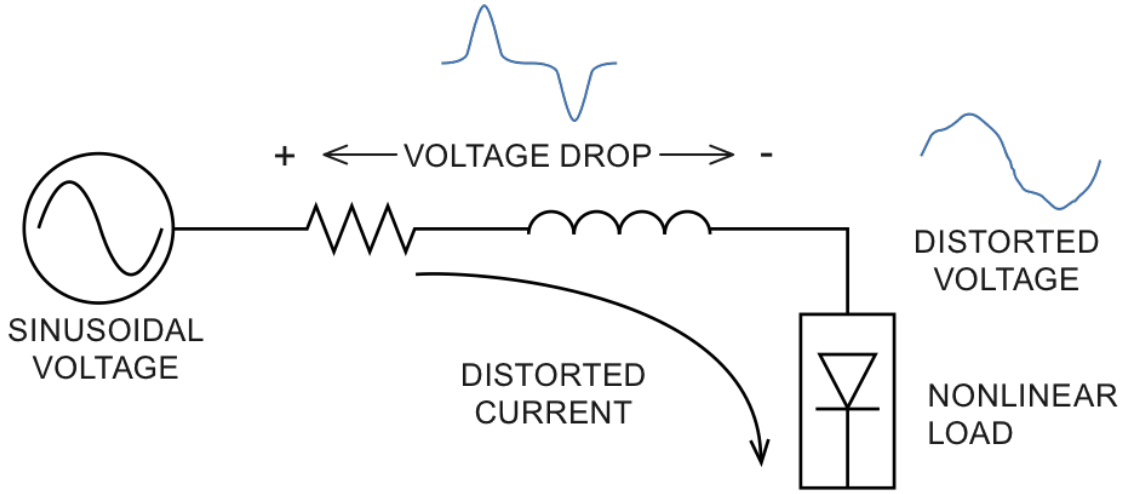






What Causes Voltage Distortion?

- Harmonic load current flowing through system impedance causes nonlinear voltage drop.
- Harmonic voltage drop combines with and reduces supply voltage resulting in a distorted voltage applied to the load.
- Resulting voltage harmonics depend on system impedance and harmonic load current



IEEE 519:1992

Don't throw away the 1992 edition! Removed in 2014:

- Harmonic Generation
- System Response Characteristics
- Effects of Harmonics
- Reactive Power Compensation and Harmonic Control
- Analysis Methods

IEEE 519:1992: 101 pages

IEEE 519:2014: 29 pages

1992 edition contained background discussion, examples – still great info

2014 edition is tightly focused on just the limits and statistical analysis

IEEE 519:2014 Philosophy

Limiting distortion is a “shared responsibility” – utility and end users

- Utility – keep system impedance low to minimize voltage distortion with “acceptable” harmonic currents

- Users – keep load harmonics “acceptable” to allow a utility to operate with reasonable impedances

Harmonic voltage distortion limits are provided to reduce the potential negative effects on user and system equipment. Maintaining harmonic voltages below these levels necessitates that

— All users limit their harmonic current emissions to reasonable values determined in an equitable manner based on the inherent ownership stake each user has in the supply system and

— Each system owner or operator takes action to decrease voltage distortion levels by modifying the supply system impedance characteristics as necessary.

IEEE 519:2014 Definitions

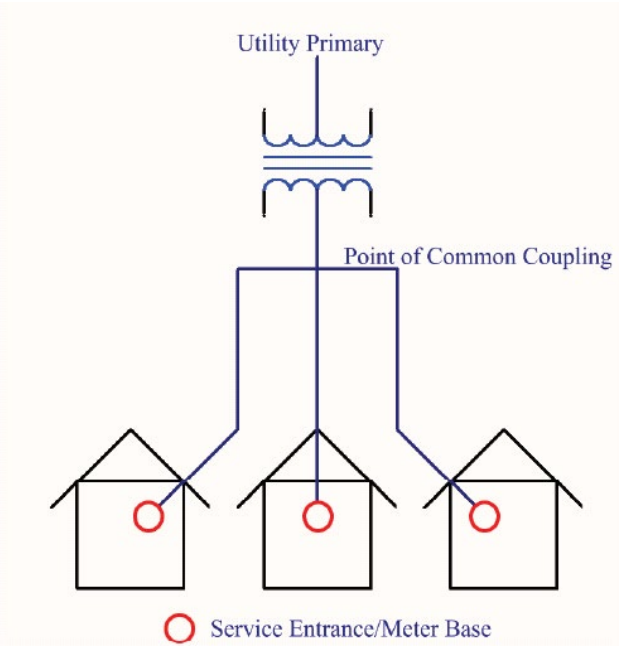
Point of Common Coupling – "Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation."

- Often at the revenue meter/service entrance
- Can be at transformer primary for industrial customers

Voltage harmonics are worse on transformer secondary, so when in doubt, use that to be conservative

Tricky cases:

- Single customer on a dedicated feeder – at substation, or transformer?
- Large industrial customer with a small 2nd customer tapped off one phase



IEEE 519:2014 Definitions

Max demand load current - sum of the currents at PCC, corresponding to the max demand during each of the 12 previous months, divided by 12

- Difficult to measure, must often be estimated
- For planning/design stages, cannot be measured!

- One approach is to use worst case full load current of all nonlinear loads
- I THD may be better at full load, but total harmonic contribution is usually highest at full load

IEEE 519:2014 Definitions

Total Harmonic Distortion, Total Demand Distortion (THD, TDD) –

Harmonic subgroups used in calculations

Excludes interharmonics, but allows for harmonic modulation

THD is only synchronous distortion – no interharmonic (non-synchronous) effects

Voltage THD not relative to a nominal system voltage

$$X_{THD} = \frac{\sqrt{X_2^2 + X_3^2 + \cdots + X_{50}^2}}{X_1} \times 100\%$$

X_k is the kth voltage or current harmonic

$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + \cdots + I_{50}^2}}{I_L} \times 100\%$$

I_k is the kth current harmonic
I_L is the max demand current

IEEE 519:2014 "VS" Harmonics

Very Short Time = 3 seconds

- Aggregation of 15 consecutive harmonic measurements F_n for harmonic n
- 12 cycles/measurement = 0.2 seconds x 15 = 3 seconds
- $F_{n,vs}$ = very short time harmonic n
- RMS addition
- 3 seconds is the smallest time interval used for limiting
- Harmonics are a steady-state problem- hence 3 seconds = "very short"

$$F_{n,vs} = \sqrt{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^2}$$

IEEE 519:2014 “SH” Harmonics

Short Time = 10 minutes

- Aggregation of 200 consecutive very short time measurements $F_{n,vs}$ for harmonic n
- 3 seconds x 200 = 10 minutes
- $F_{n,sh}$ = short time harmonic n
- 10 minutes is the largest time interval used for limiting
- If you have a recording at 3 second intervals, can compute 10 minute short time values from that – don’t need to record both

$$F_{n,sh} = \sqrt{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^{2}}$$

IEEE 519:2014 Voltage Limits

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

- Line-to-neutral voltage limits at PCC
- Daily 99th percentile very short time (3 sec) values should be less than 1.5 times Table 1
- Weekly 95th percentile short time (10 min) values should be less than Table 1

IEEE 519:2014 Current Limits

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

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

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

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

where

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

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

- Current limits at PCC
- Daily 99th percentile very short time (3 sec) values should be less than 2.0 times Table 2
- Weekly 99th percentile short time (10 min) values should be less than 1.5 times Table 2
- Weekly 95th percentile short time (10 min) values should be less than Table 2

IEEE 519:2014 Current Limits

Table 3—Current distortion limits for systems rated above 69 kV through 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) [a, b]						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4.0
50 < 100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

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

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

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

where

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

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

- Current limits at PCC
- Daily 99th percentile very short time (3 sec) values should be less than 2.0 times Table 3
- Weekly 99th percentile short time (10 min) values should be less than 1.5 times Table 3
- Weekly 95th percentile short time (10 min) values should be less than Table 3

IEEE 519:2014 Current Limits

Table 4—Current distortion limits for systems rated > 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 25[c]	1.0	0.5	0.38	0.15	0.1	1.5
$25 < 50$	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

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

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

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

where

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

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

- Current limits at PCC
- Daily 99th percentile very short time (3 sec) values should be less than 2.0 times Table 4
- Weekly 99th percentile short time (10 min) values should be less than 1.5 times Table 4
- Weekly 95th percentile short time (10 min) values should be less than Table 4

IEEE 519:2014 PQ Ruler Limits

- Voltage Limits complete on ruler
- Current limits given for 120V-69kV

IEEE 519 Voltage Harmonic Limits

Bus V at PCC	Ind. Harm%	THD%
V ≤ 1.0 kV	5.0	8.0
1 kV <V ≤ 69 kV	3.0	5.0
69 kV < V ≤161 kV	1.5	2.5
161 kV < V	1.0	1.5

daily 99th pct. 3-sec = 1.5x table
weekly 95th pct. 10-min = table

IEEE 519 Harmonic Current % Limits, 120V-69kV

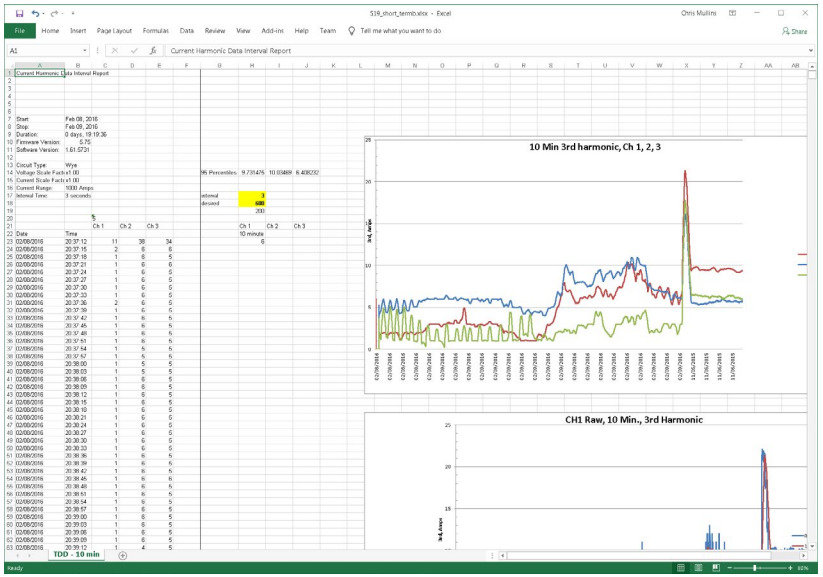
Isc/I_L	3≤h<11	11≤h<17	17≤h<23	23≤h<35	35≤h<50	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Evens limited to 25% of odd limits
Isc = max short circuit current at PCC
I_L= max demand current under normal load

weekly 99th pct. 10-min = 1.5x table
weekly 95th pct. 10-min = table
daily 99th pct. 3-sec = 2x table

Manual IEEE 519:2014 Analysis

A. Determine Point of Common Coupling
B. Record data
    1. Voltage, current individual harmonic subgroups, 1-50
    2. Voltage, current harmonic subgroup THDs
    3. RMS voltage, current highly recommended
    4. Use 3 second recording interval
    5. Record for at least one normal week
C. Determine parameters
    1. max demand current I_L – estimate, use historical data
    2. Find short circuit current I_{SC}
D. Compute statistics
    1. Compute TDD
    2. Compute percentiles of all 3 second data
    3. Compute 10 minute short time harmonic values
    4. Compute 10 minute percentiles
E. Apply limits
    1. Determine correct voltage, current tables from bus voltage and I_{SC}/I_L
    2. Compute table multipliers for each percentile
    3. Apply limits to each harmonic, THD, TDD
F. Declare pass or fail



Helpful Excel functions:

- SUMPRODUCT
- PERCENTILE
- SQRT

Automatic Software Analysis

A. Record for 1 week with Revolution IEEE 519 config

B. Enter I_L, I_{sc}, bus voltage category (stored with recording)

C. Run 519 compliance report – ProVision computes:

- TDD
- 3 second, 10 minute percentiles
- Voltage, current limits from 519 tables
- Pass/fail for each harmonic, and overall

IEEE 519 Daily Compliance Report

Start: Dec 04, 2018 13:54:45
Stop: Dec 04, 2018 13:55:23
Duration: 0 days, 00:00:38
Firmware Version: 5.85 Unit Type: Revolution
Software Version: 1.72.6911 Serial No.: 61147

Circuit Type: Wye
Voltage Scale Factor: x1.00
Current Scale Factor: x1.00
Current Range: 1000 Amps
Interval Time: 3 seconds

Maximum Demand Current (Amps): 256
Maximum Short Circuit Current (Amps): 512
Compliance Status: Failed

Failed Voltage Channels:	Failed Voltage Harmonics:	Failed Current Channels:	Failed Current Harmonics:
1,2,3	1,5	1,2,3	1,3,5,7

% harmonic at the 99 percentile

	Voltage				Current			
Harmonic	Ch 1	Ch 2	Ch 3	Limit	Ch 1	Ch 2	Ch 3	Limit
THD/TDD	0.010	0.040	0.310	1.500	1.010	1.040	**1.710**	1.500
2nd	0.035	0.035	0.035	0.250	0.400	0.900	0.500	1.000
3rd	0.760	0.759	0.759	1.000	**9.800**	**12.000**	**14.300**	1.000
4th	0.036	0.036	0.036	0.250	0.400	0.700	0.500	1.000
5th	**1.119**	**1.119**	**1.120**	1.000	0.900	**1.200**	**1.300**	1.000
6th	0.024	0.024	0.024	0.250	0.400	0.400	0.500	1.000
7th	0.492	0.492	0.496	1.000	0.900	0.900	**1.100**	1.000
8th	0.028	0.028	0.028	0.250	0.400	0.400	0.400	1.000
9th	0.252	0.248	0.248	1.000	0.400	0.500	0.500	1.000
10th	0.024	0.024	0.024	0.250	0.400	0.400	0.400	1.000
11th	0.424	0.420	0.420	0.500	0.500	0.500	0.500	1.000
12nd	0.024	0.024	0.024	0.125	0.400	0.400	0.400	1.000
13th	0.164	0.160	0.160	0.500	0.400	0.400	0.400	1.000
14th	0.024	0.024	0.024	0.125	0.400	0.400	0.400	1.000
15th	0.080	0.080	0.080	0.500	0.400	0.400	0.400	1.000
16th	0.024	0.024	0.024	0.125	0.400	0.400	0.400	1.000
17th	0.200	0.200	0.200	0.200	0.400	0.400	0.400	1.000

IEEE 519:2014 Simplified

In many cases, harmonics are low enough to enable a simplified approach.

Given three observations:

1. THD is always ≥ than any single harmonic – true for 3 sec and 10 min. readings.

$$\mathrm{THD}_{vs} \geq \max F_{n,vs}$$

2. 3 sec values are always ≥ 10 minute values.

$$\max F_{n,vs} \geq \max F_{n,sh}$$

3. A percentile is always ≤ the max value. The max value is the 100th percentile.

Nth percentile ≤ 100th percentile = max value

If the "largest" measurement type (3 second THD/TDD) is lower than the strictest threshold (10 minute THD/TDD), then all harmonics are under their thresholds.

If not, still some possible simplifications ….

IEEE 519:2014 Simplified

Follow flowchart to check for immediate compliance in 1 week recording

If max 3 second THD < 5% - voltage is OK

Else if max 3 second THD < 8% AND max 3 second harmonic is < 7.5%, voltage is OK

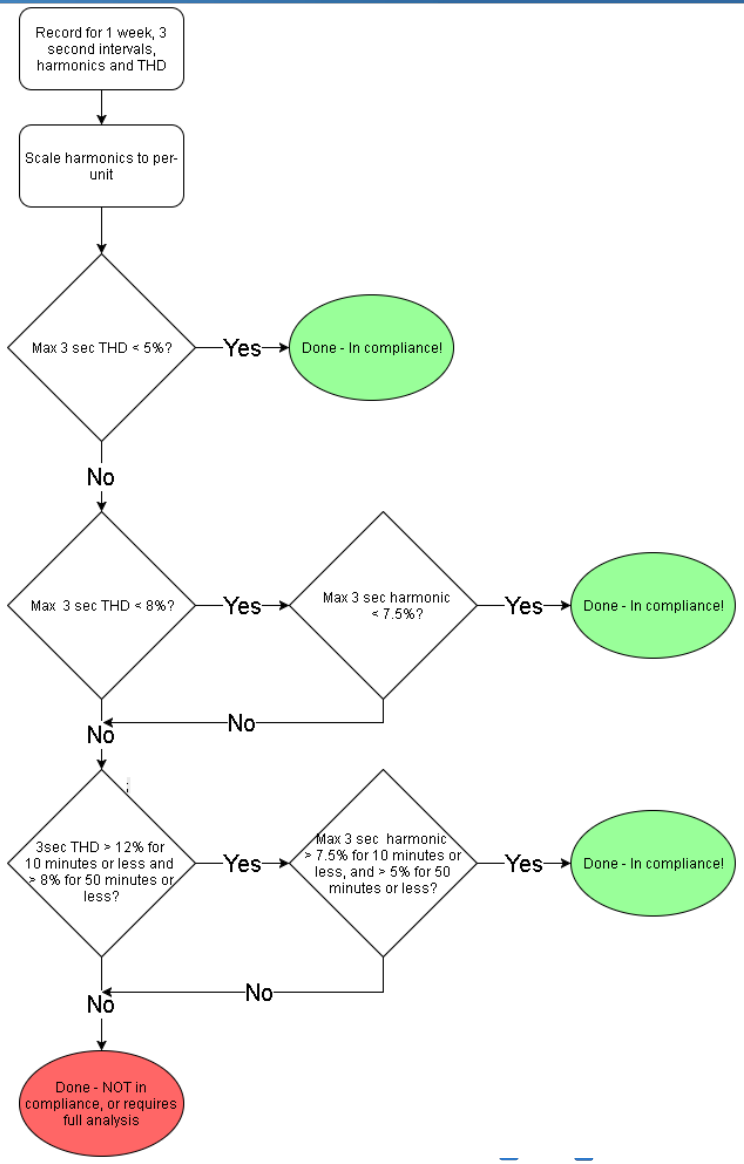
Else if 3 sec THD > 12% for less than 10 minutes AND > 8% for less than 50 minutes AND max 3 sec harmonic > 7.5% for under 10 minutes, AND > 5% for less than 50 minutes, voltage is OK

Else – must do full analysis

In many cases, voltage THD is under 5% everywhere – automatically in compliance – no need to check harmonics!

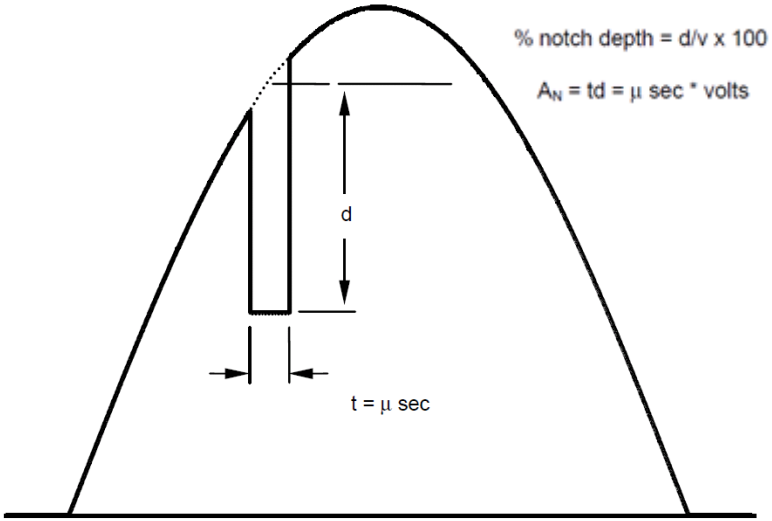
Table 1—Voltage distortion limits

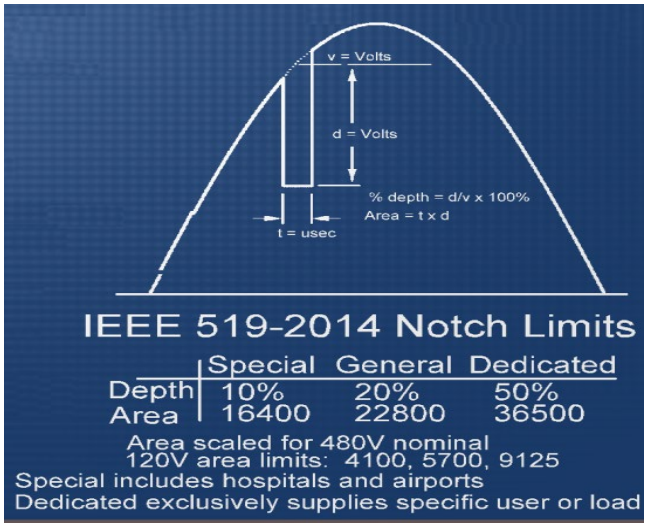
Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0



IEEE 519:2014 Voltage Notching

- A periodic distortion that's best analyzed in the time domain due to special shape
- Limit is based on area of missing voltage waveform
- Not an event-based limit – only for sustained notching in every cycle
- Commonly seen with commutation problems in VFDs and other active 3 phase rectifiers





	Special Applications[a]	General System	Dedicated System[b]
Notch Depth	10%	20%	50%
Notch Area (A_N)[c,d]	16400	22800	36500

a Special applications includes hospitals and airports.

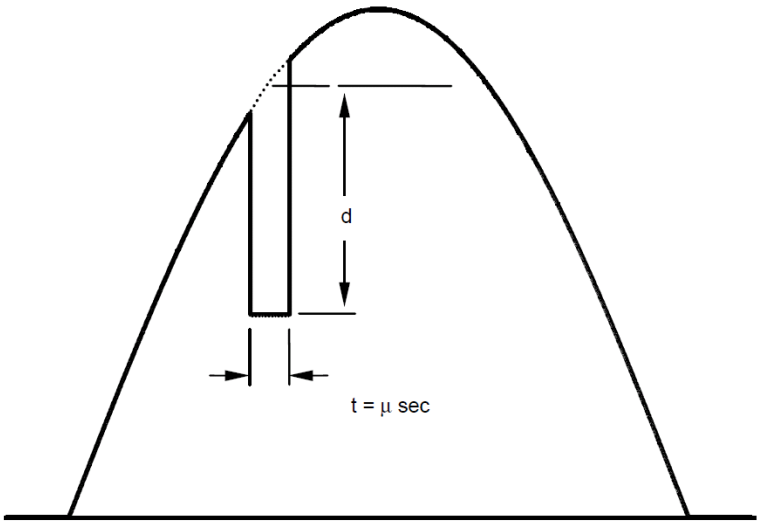
b A dedicated system exclusively supplies a specific user or user load.

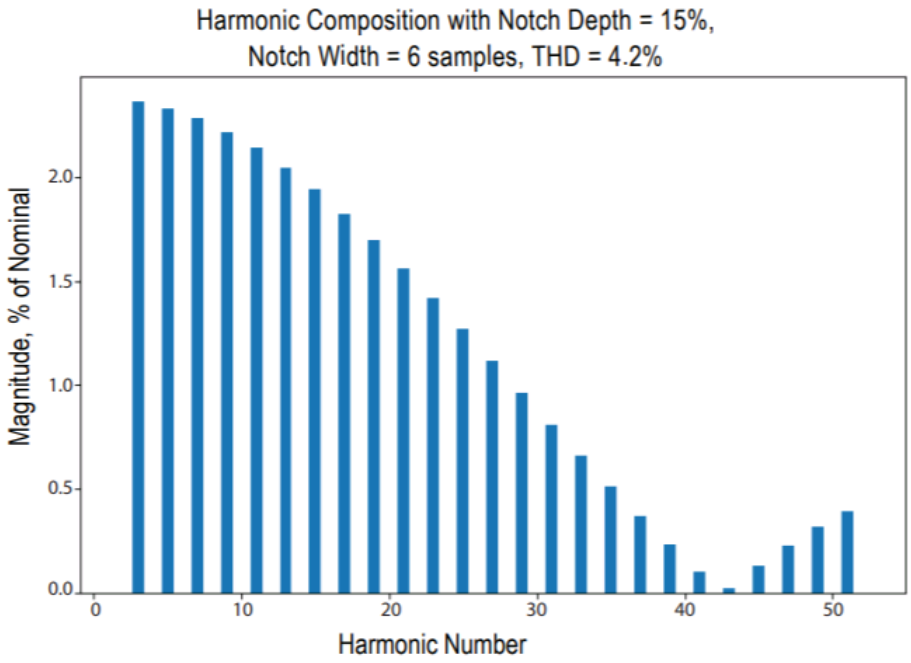
c In volt-microseconds at rated voltage and current.

d The values for AN have been developed for 480V systems. It is necessary to multiply the values given by V/480 for application at all other voltages.

IEEE 519:2014 Voltage Notching

- Since notching is a periodic distortion, it could be analyzed with harmonics
- Notching show broadband harmonics – mitigation is difficult with filtering
- Harmonic breakdown is more complex than time-domain volts x seconds notch analysis





Harmonic Guidelines

Just because utility voltage is under limits doesn't mean you shouldn't monitor and limit current!

- Out-of-compliance customers should still be mitigated – could cause problems later when feeder is more loaded
- Underloaded feeder doesn't give high harmonic customers a pass …
- More difficult to enforce limits later if high harmonic customers start affecting others later, but nothing on their load changed

This means proactive current monitoring – don't let a customer be the first to tell you there are problems

Harmonic Guidelines

Just because customers are under limits doesn't mean there isn't a problem lurking

- With normal system impedance, all customers under limits -> utility voltage is under limits
- Resonance condition with PFCs and specific harmonic can cause localized elevated voltage THD and peak voltage
- Useful to measure voltage THD with and without PFCs
- Resonance frequency can change with load
- Good background in IEEE 519:1992, and PMI whitepapers Feeder Resonance and PFCs and Resonances

As an example, consider the substation transformer in Figure 1. This is an 18 MVA LTC transformer with a 12,470Y/7200V secondary. This transformer has a known MVA_{SC} of 140 MVA at nominal line voltage and tap position. The substation has 1.4 MVAR capacitance installed per phase, or 4.2 total. Using equation (4) gives:

$$H = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}} = \sqrt{\frac{140}{4.2}} = 5.8$$

This gives a resonant frequency of 5.8 x 60 Hz 350 Hz. This transformer's actual circuit inductance is also known to be around 3 mH (per phase).

$$F = \frac{1}{2\pi\sqrt{LC}}$$

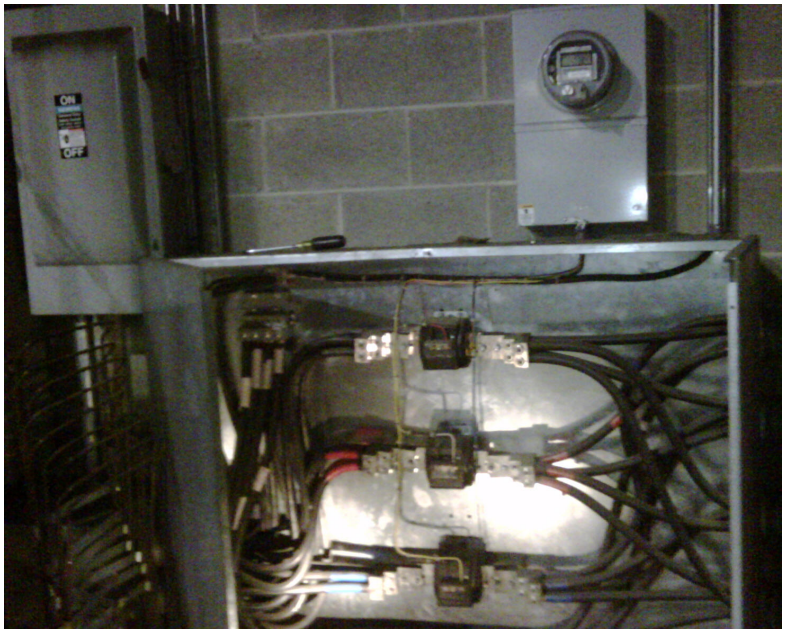
$$H = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}}$$

MVAsc = bus source impedance
MVARcap = 3-phase cap bank size
H = resonant harmonic

Guidelines

PCC issues

- Not always clear where the PCC actually is
- May be difficult to record on primary side



If in doubt, advantages to customer transformer secondary or metering cabinet:

- Voltage harmonics are higher due to transformer impedance – conservative choice
- Allows for easy isolation of customer current

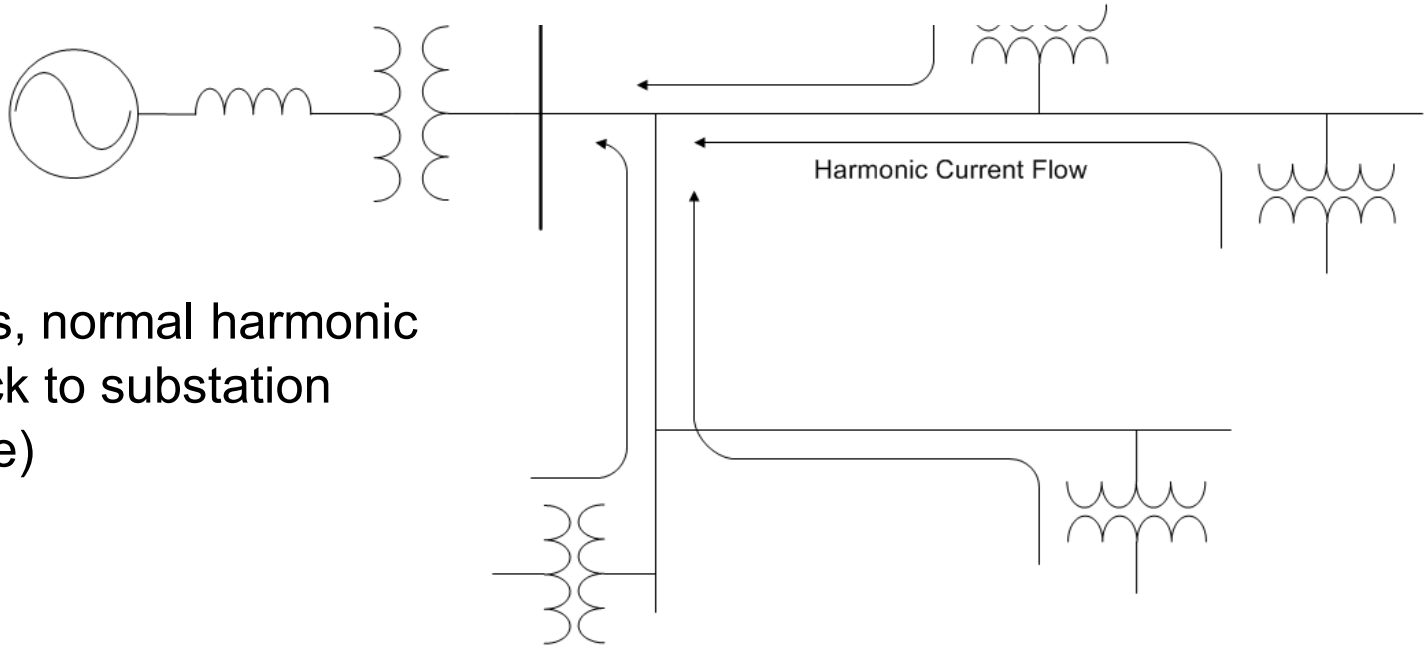
Ask about any customer PFCs

Finding Source of Harmonics

- Harmonic Current Flow - “follow the current”
- Harmonic Power Sign (negative W) - beware of “IF’s”
- Relative Magnitudes approach
- Common sense approach - evaluate likely sources, customers
- Correlation of voltage distortion (VTHD) with customer load characteristics, time variations
- Resonance clues

Finding Source of Harmonics

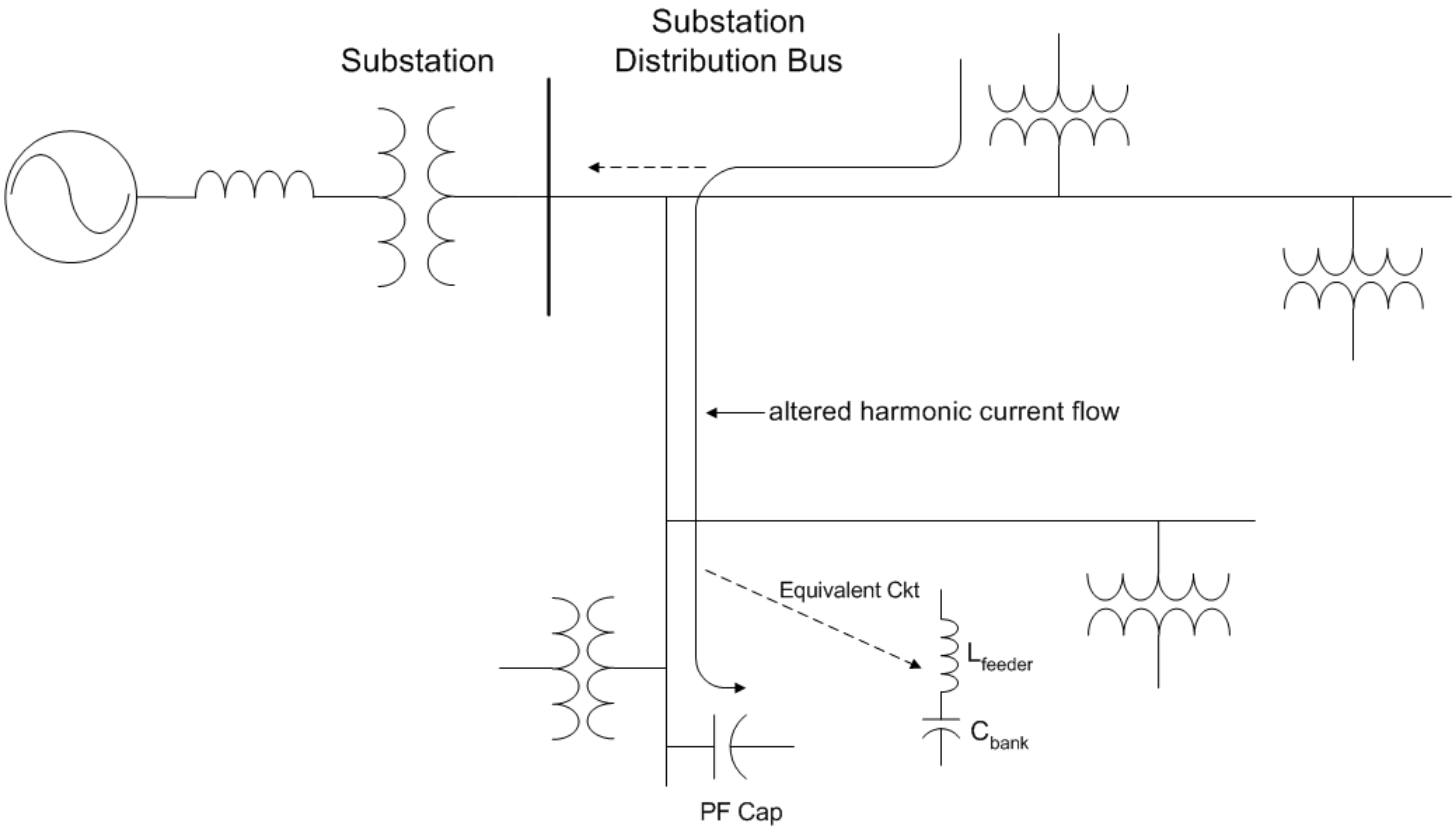
Harmonic Current Flow



Without capacitors, normal harmonic current flow is back to substation (lowest impedance)

Finding Source of Harmonics
Harmonic Current Flow With Capacitors

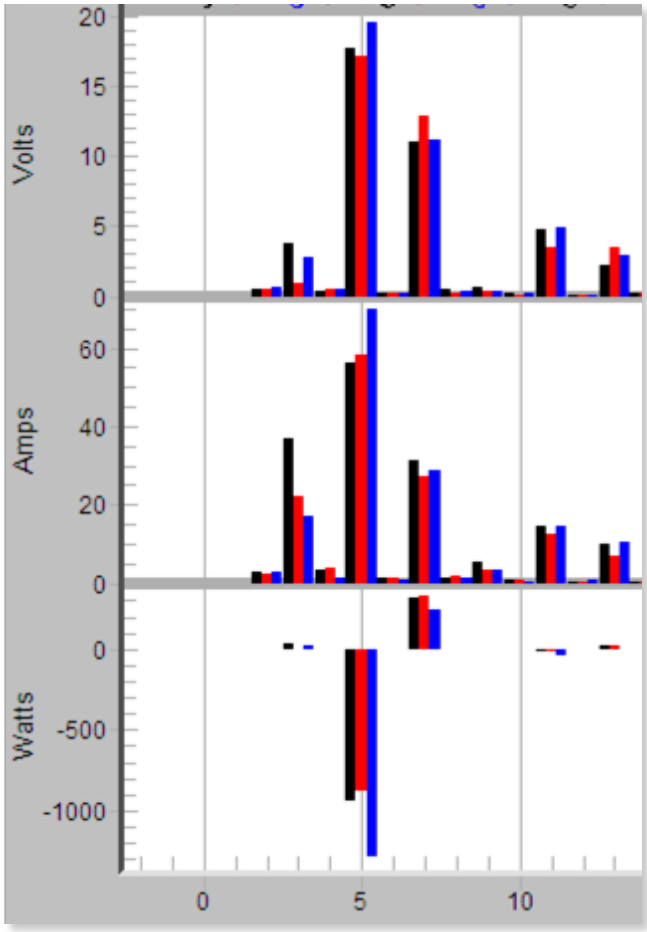
Majority of harmonic current flow can be toward series resonance (low Z) formed by capacitor and feeder impedance. Can cause blown capacitor fuses.



Finding Source of Harmonics

Harmonic Power Sign

- Negative power of significant magnitude can indicate that load is source of harmonic current injection
- Phase angle between V_h and I_h greater than ±90 degrees = negative harmonic power, flow from load to source - opposite direction of 60Hz power flow
- Requires proper CT polarity



Finding Source of Harmonics

Common Sense Approach

Evaluate likely sources: Larger industrial, commercial customers – *look for nonlinear loads, not just large loads*

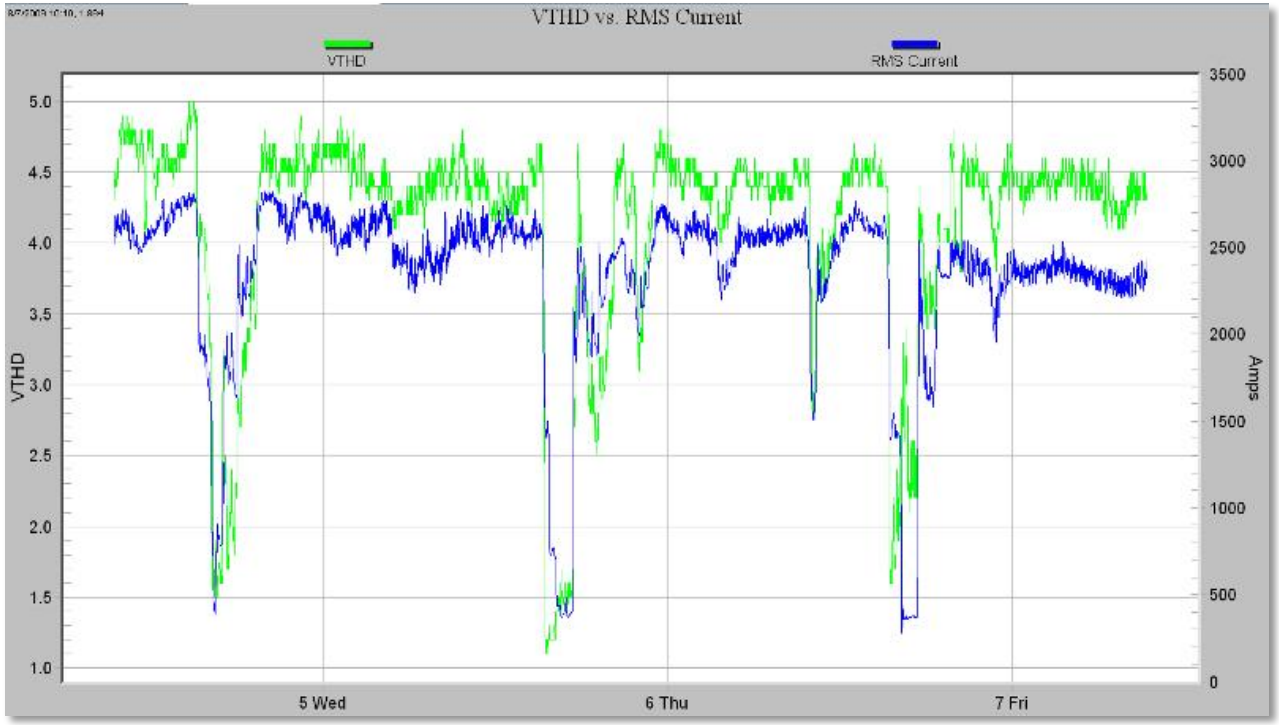
On customer side of transformer:

- Look for significant harmonic currents
- Elevated VTHD (greater than 5%) usually indicates resonance condition
- Check capacitor currents
- Correlation of VTHD with customer RMS and harmonic currents

Finding Source of Harmonics
Evaluate Customer Loads

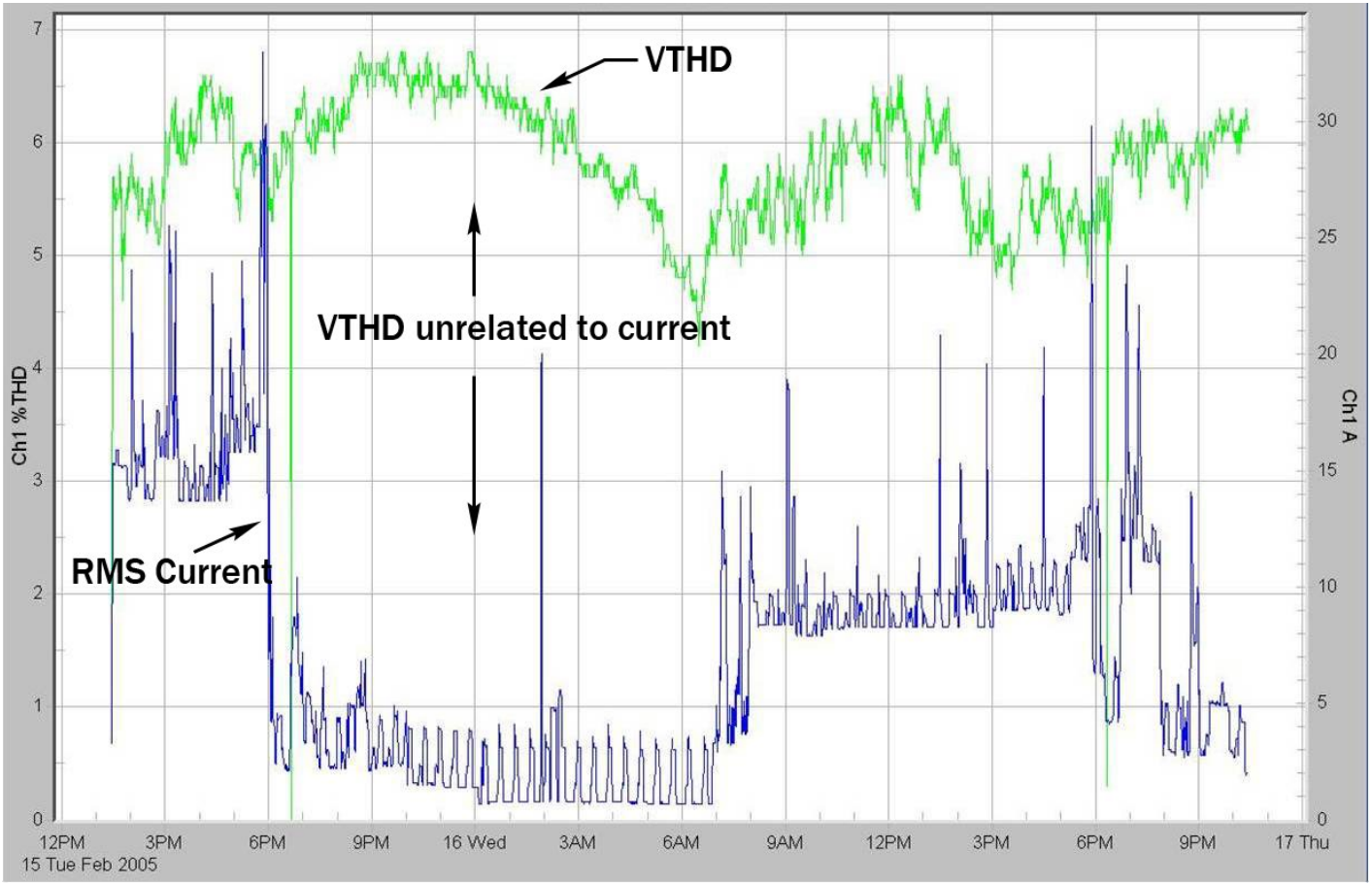
Correlation of voltage distortion with customer load

- VTHD interval graph - does VTHD vary with customer shift changes, breaks, etc. – commercial/industrial customers
- Correlate VTHD patterns with customer load characteristics - equipment types, use patterns - VTHD vs RMS and harmonic load currents



Finding Source of Harmonics

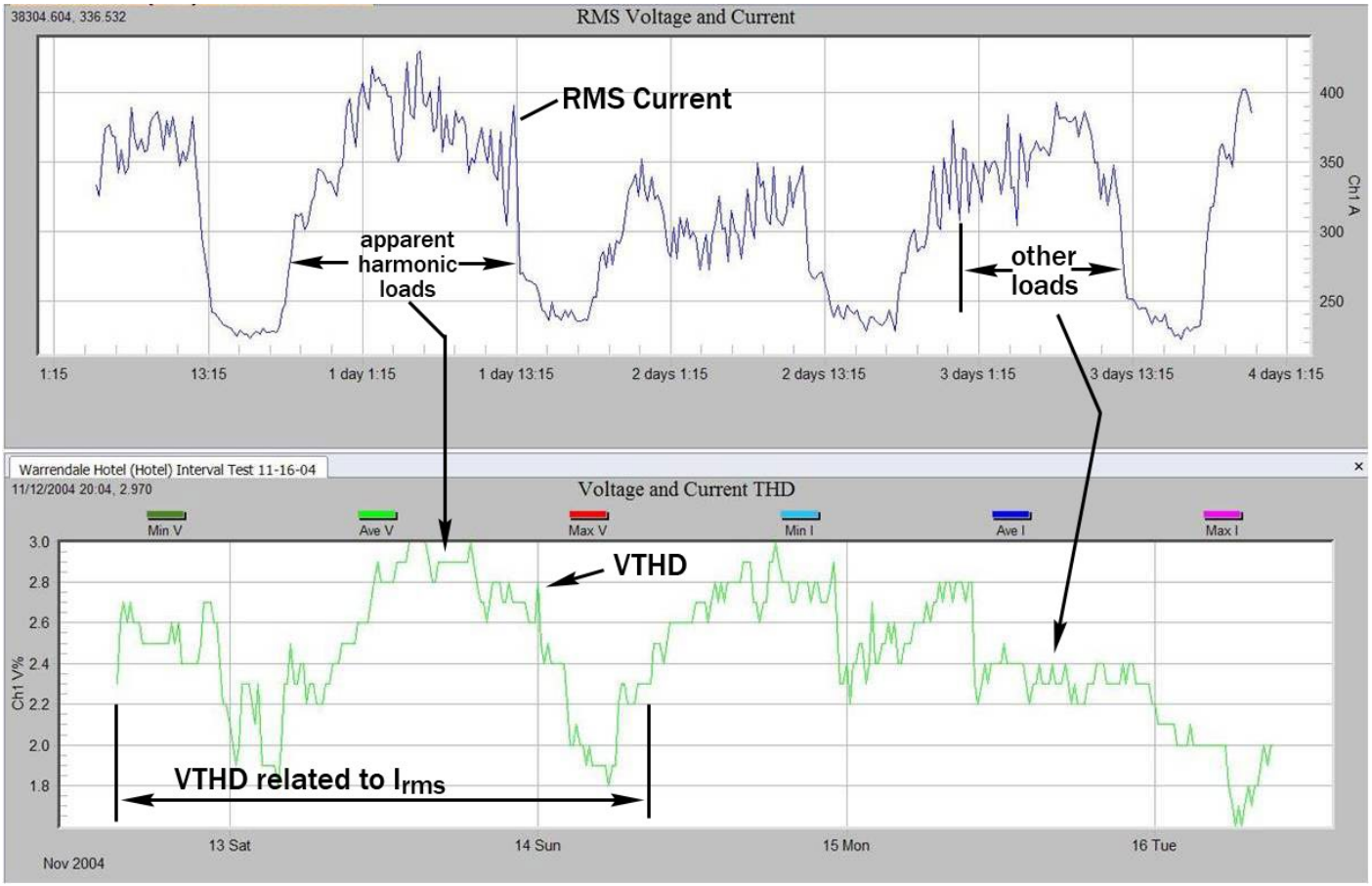
Compare VTHD to customer load



VTHD uncorrelated with load current

Finding Source of Harmonics

Correlation - Compare VTHD to customer load



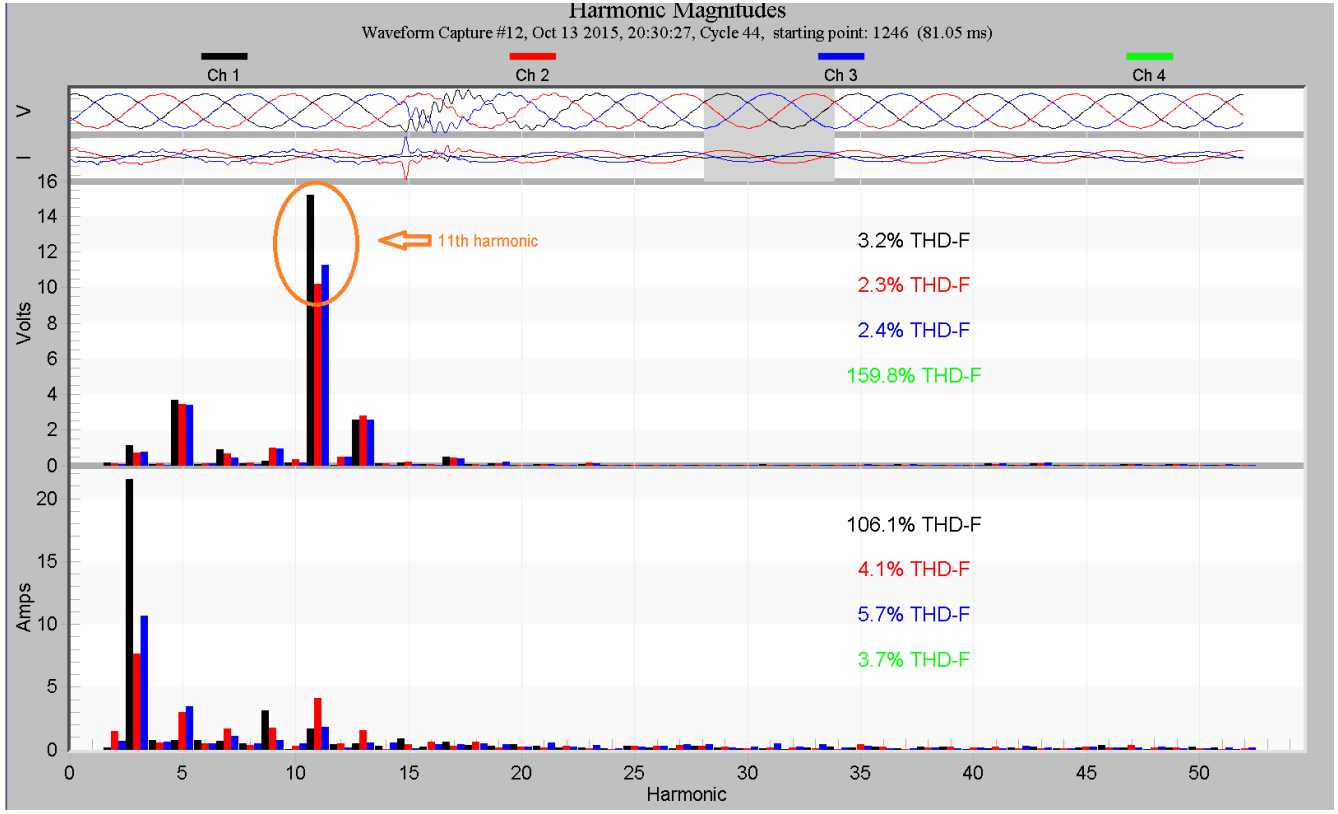
VTHD Correlated with load current

Finding Source of Harmonics

Resonance Clues

- Resonance induced problem typically has one dominant harmonic
- Where harmonic problems exist, measure current in capacitors – single, large harmonic current nearly always indicates capacitor is in resonance with system impedance
- High voltage THD – usually a combination of excessive harmonic current injection and system response that magnifies harmonic currents, VTHD

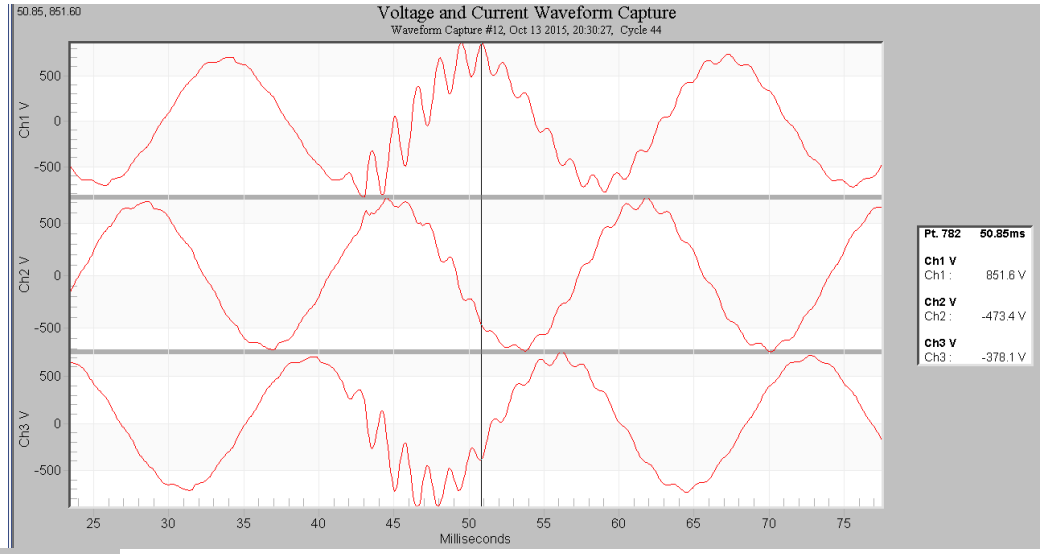
Single Resonance

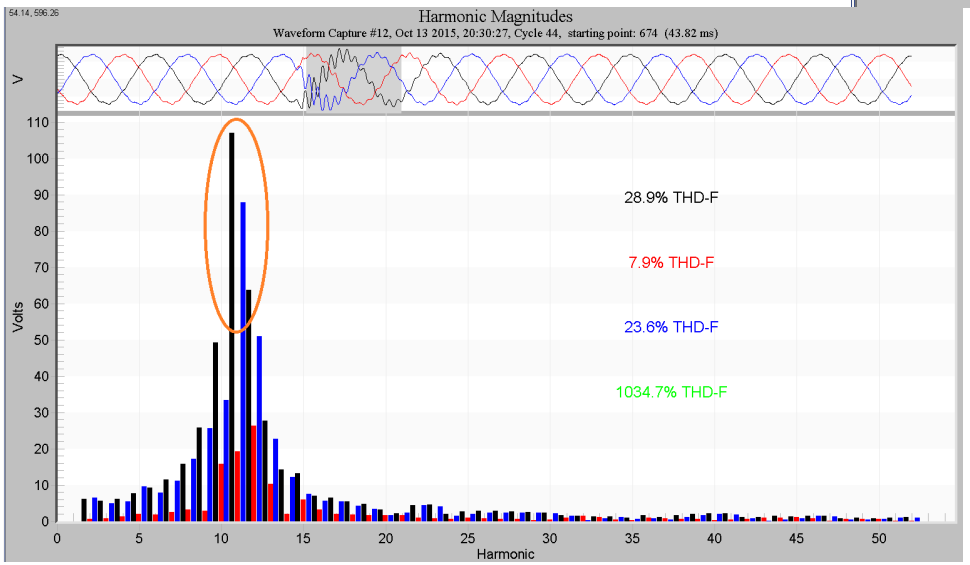


- 11th harmonic dominant on voltage – sign of a resonance near 660 Hz
- Most of the 3% voltage THD is from this single harmonic

Single Resonance

Oscillatory period measurement gives 1.41 ms, or ~710 Hz resonance





"Harmonic" graph shows mostly 11th, some 13th energy: 660 – 780 Hz range

Multiple Resonances

Each combination of C's and L's forms a resonance

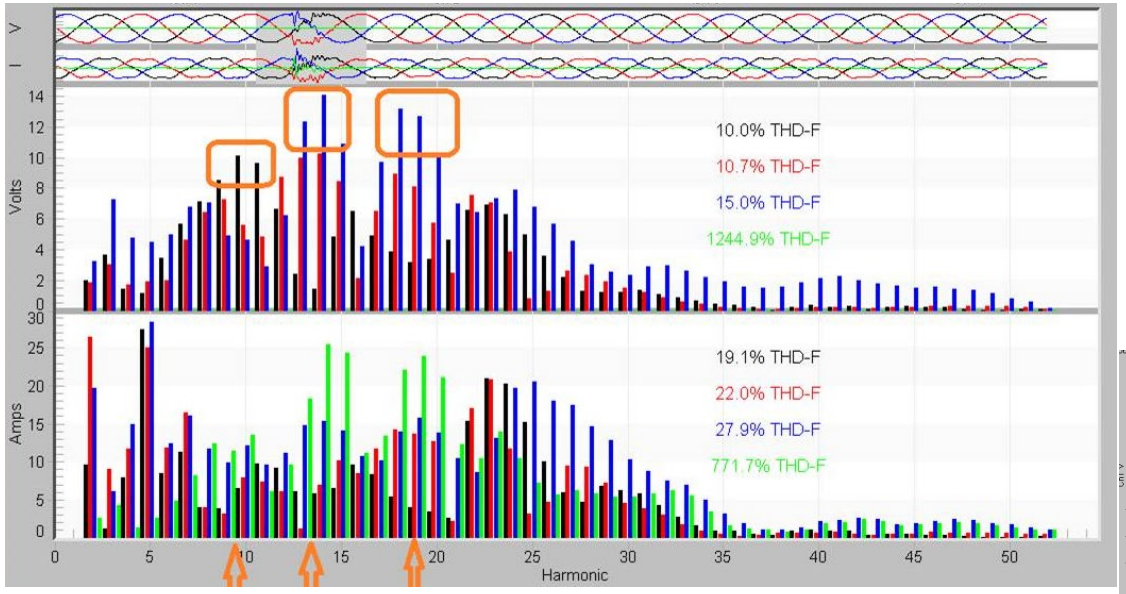
174 MVAR short circuit current at substation
Cap bank 1: 1200 KVAR
Cap bank 2 (1.5 miles away): 600 KVAR

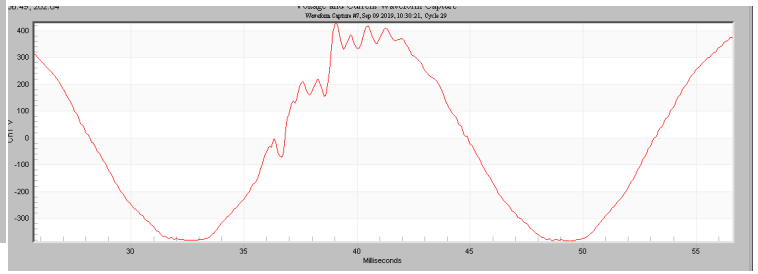
$$H = \sqrt{\frac{\mathrm{MVA_{SC}}}{\mathrm{MVAR_{CAP}}}}$$

$$H_1 = \sqrt{\frac{174}{1.2}} = 12 \ \ (722\mathrm{Hz})$$

$$H_2 = \sqrt{\frac{174}{0.6}} = 17 \ \ (1022\mathrm{Hz})$$

$$H_3 = \sqrt{\frac{174}{1.8}} = 9.8 \ \ (590\mathrm{Hz})$$





Measured resonances ~10th, 13th, 18th harmonics (600, 780, 1080 Hz)

Power Quality 102

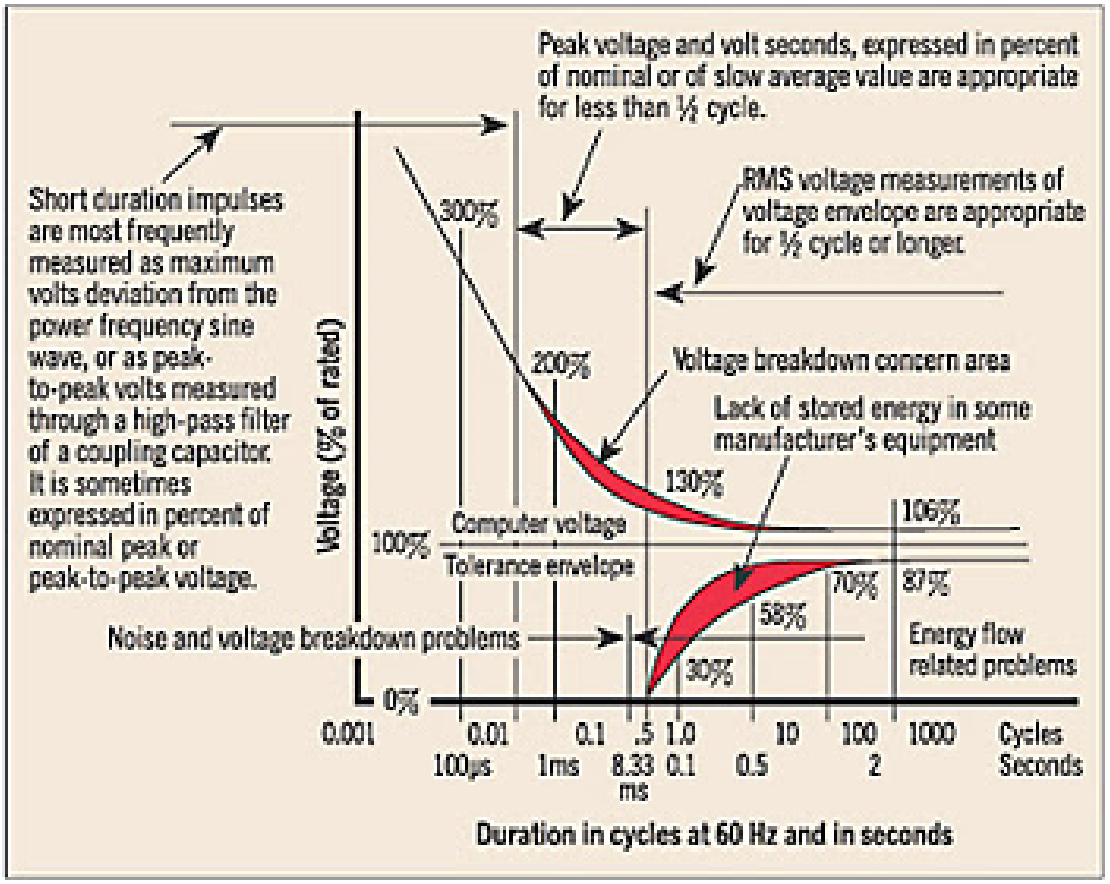
- Transients
- IEEE 519 Harmonics
- **CBEMA/ITIC**
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads and PQ

CBEMA Curve

Computer Business Equipment Manufacturers Association, ~1970s

Guideline for computer manufacturers – a power supply design guide, not a PQ standard

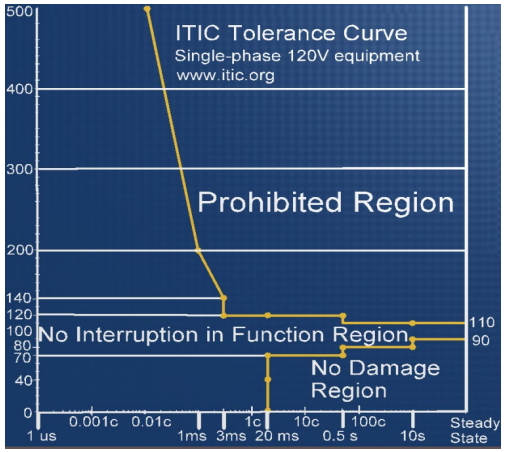
Continuous curve and lack of detail created problems for PQ monitor recordering

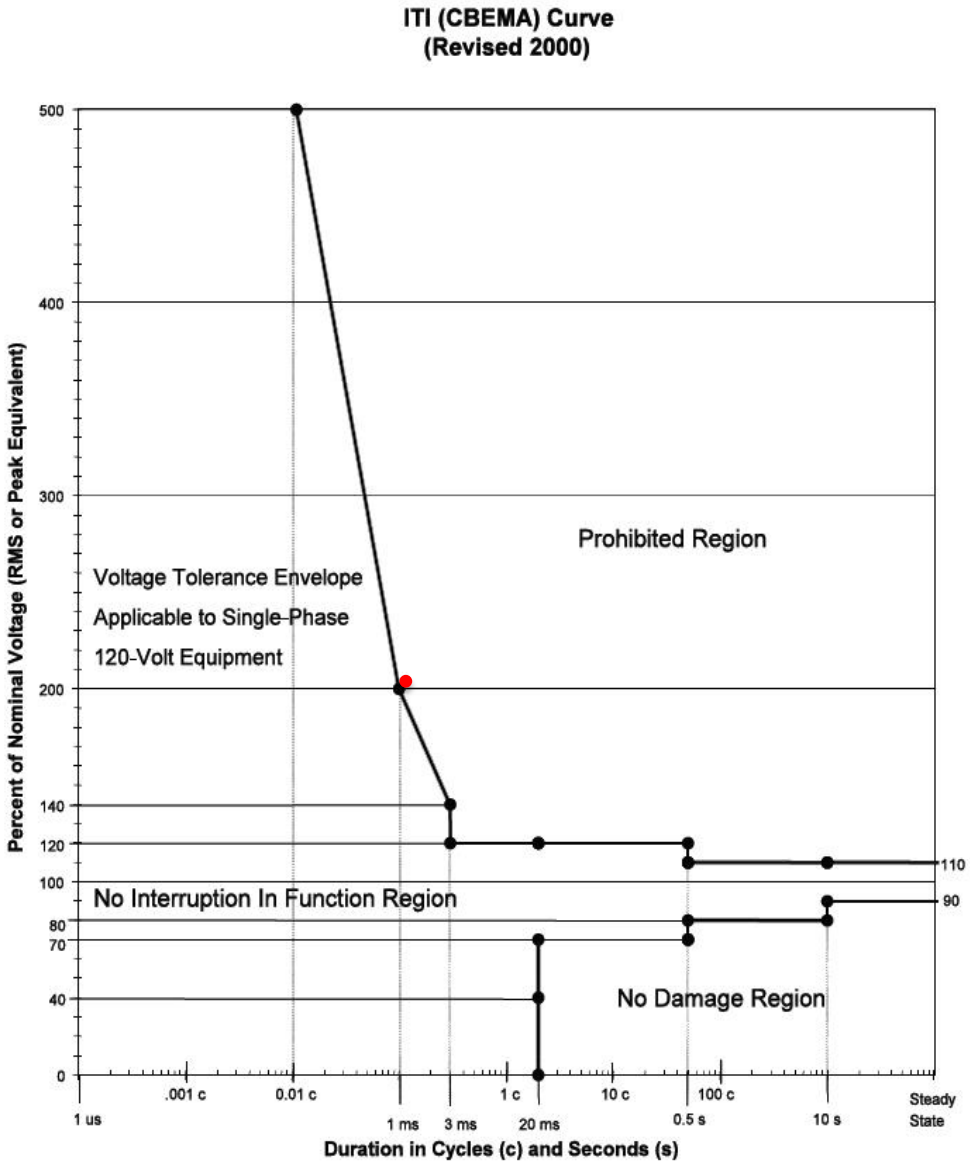


ITIC Curve

ITIC Curve

- Replaces CBEMA curve
- Applies to common 120V computer equipment
- Withstand capability – ride-through of loads to voltage variations
- Percent voltage vs duration of disturbance

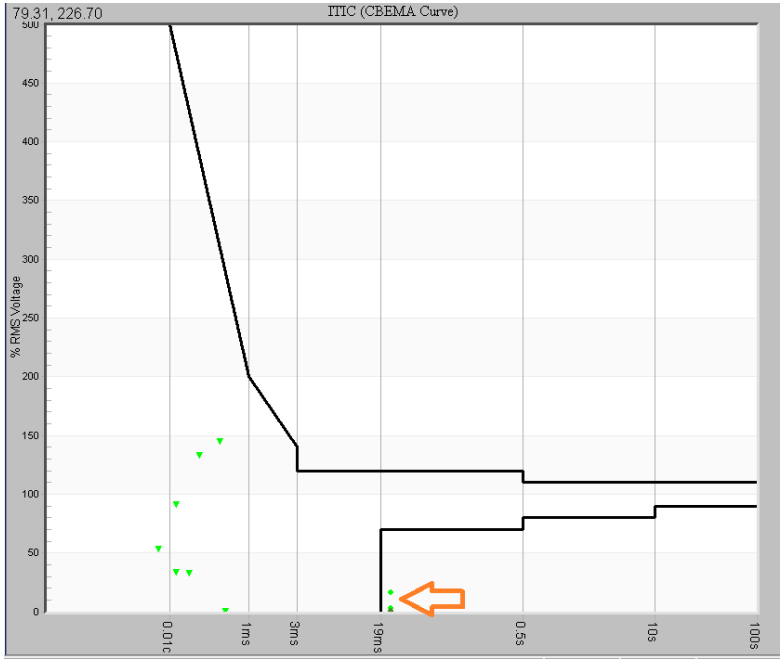


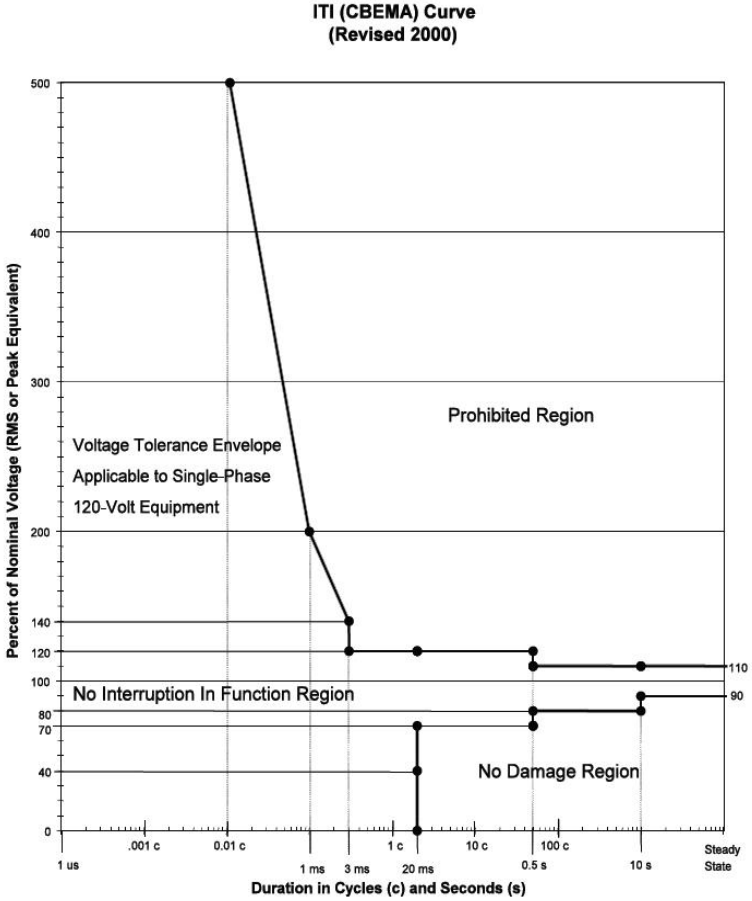


Incompatible Standard - ITIC

Reclosers cause brief, deep voltage sags, outside ITIC cure

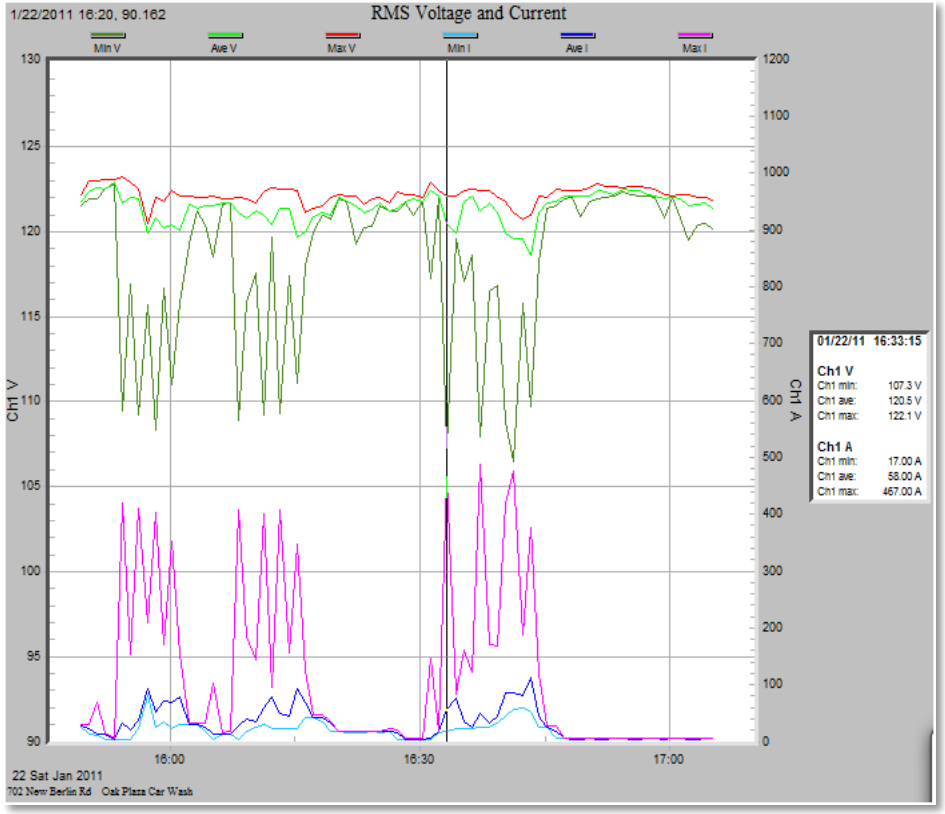
Cannot be met with normal utility infrastructure!

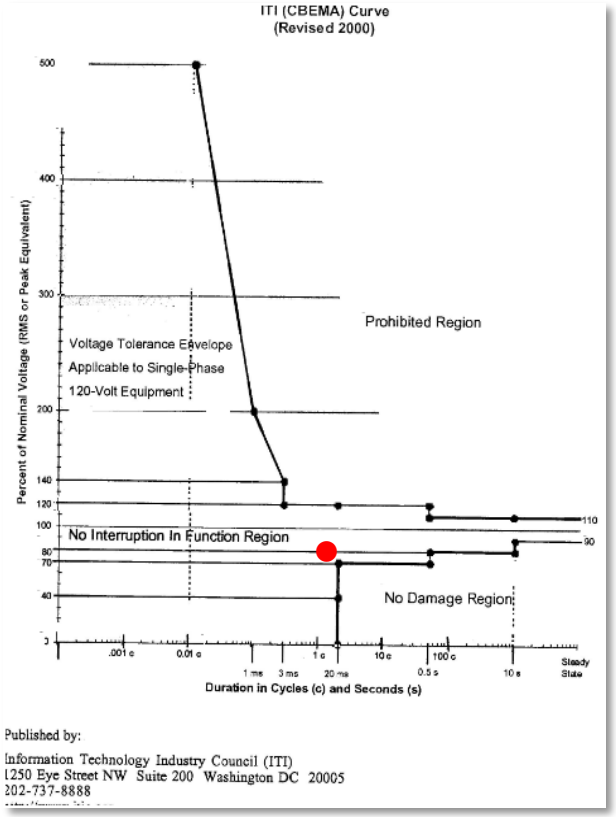




Interpreting Interval Graphs

Plotting a Disturbance on the ITIC curve





ITIC Curve – Point Location for 1 sec. duration = 89%, 1 sec duration.
% = 107.3/120.5 = 89%; Duration was 1 cycle, = 16.67ms

Power Quality 102

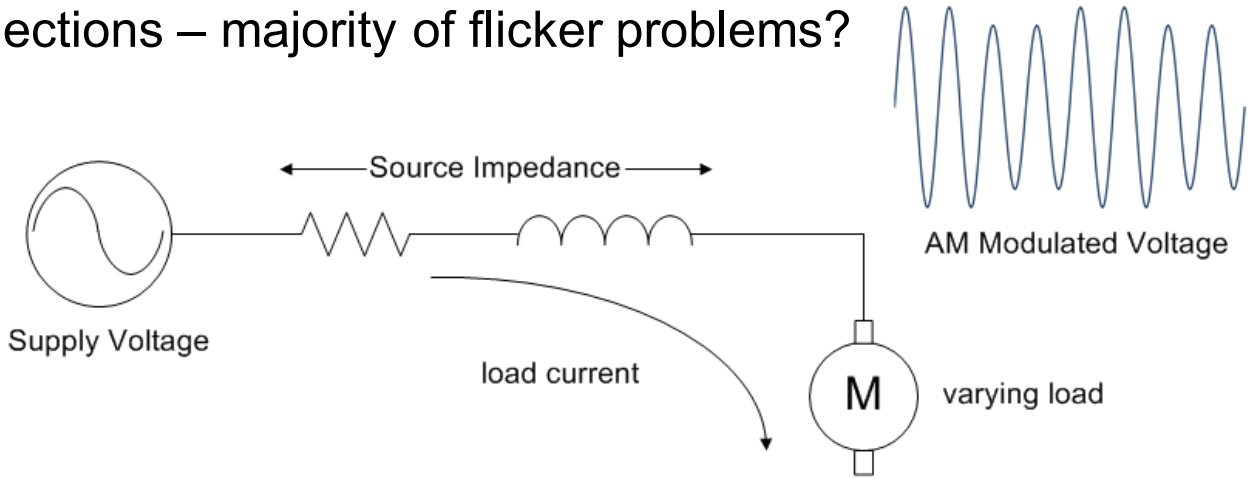
- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- **Flicker**
- Loose Neutral
- Variable Frequency Drives
- Modern loads and PQ

What is Flicker?

- Visible fluctuation in light intensity from changes in RMS voltage – more common for incandescent vs. fluorescent
- Human susceptibility to varying light intensity varies with
  - Magnitude of light intensity modulation
  - Frequency of occurrence (number of dips, time period)
- Humans more tolerant of larger light variations if less frequent, less tolerant of smaller variations if they occur more often
- Can cause headaches, complaints from all customers

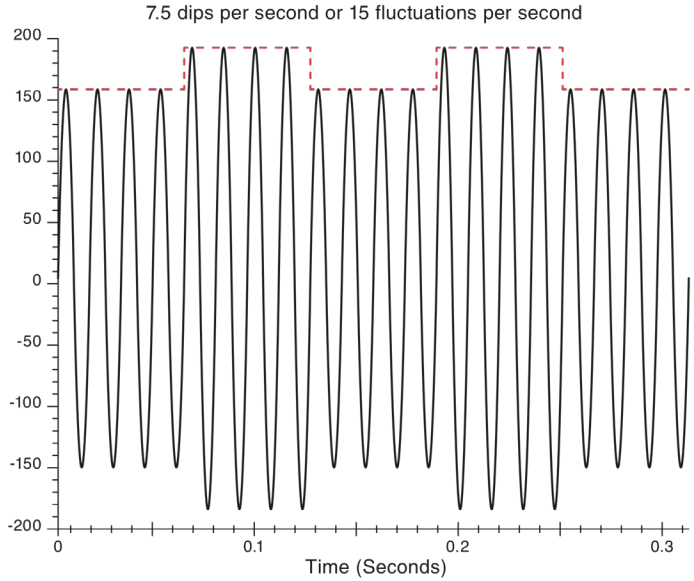
What Causes Light Flicker?

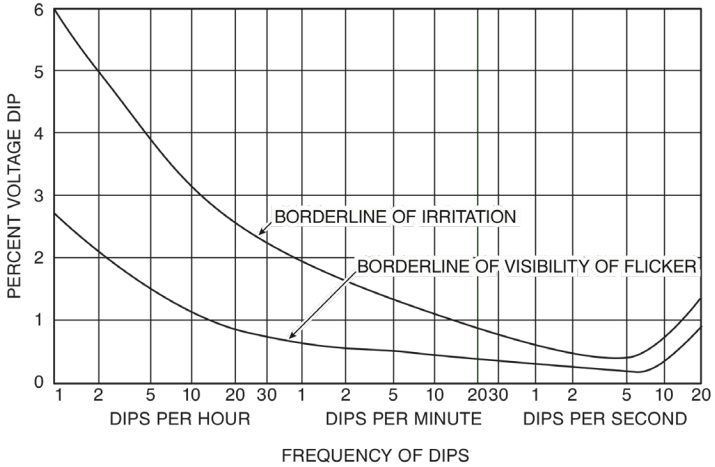
- Fast or periodic load changes produce a in voltage drop across system impedance - causes variation in voltage applied to lighting equipment
- Only small voltage changes cause problems – under 5%
- Large industrial loads – arc furnaces, welders, starting of large induction motors
- Residential – heat pumps, hair dryers, fans, tankless water heaters, ovens, small welders, air conditioners
- Loose connections – majority of flicker problems?



How is Flicker Evaluated?

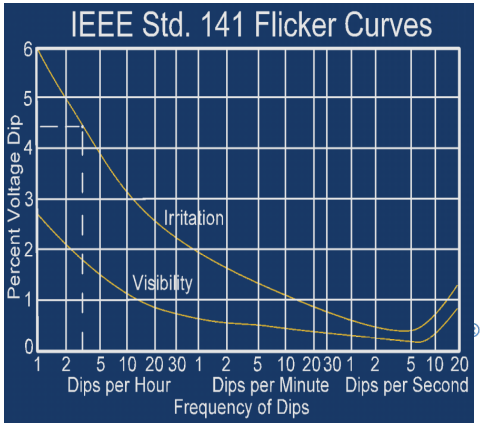
IEEE 141 Flicker Curve





FLICKER TOLERANCE CURVE FROM IEEE STD. 141-1993/IEEE STD 519-1992

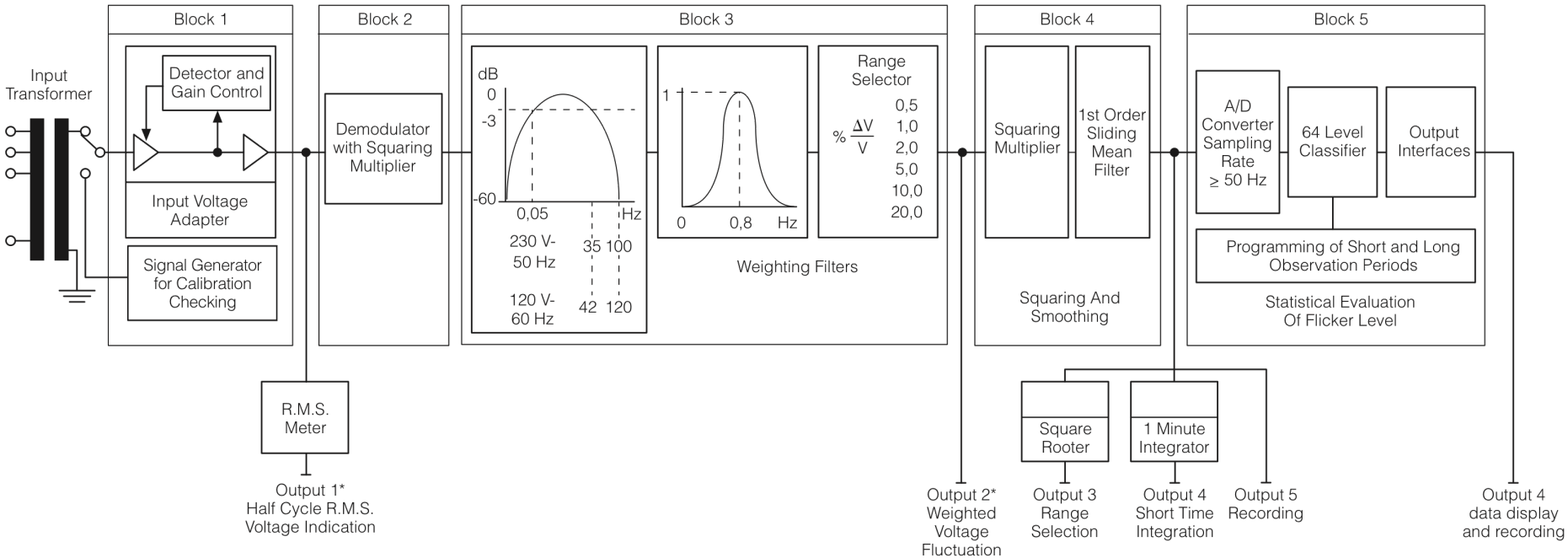
- Frequency based on number of voltage “dips”, not number of changes.
- 1925 – “GE Flicker Curve” developed from 1921 research into human response
- Tests used square-wave step changes in line voltage at a constant frequency
- % V dip = $\Delta V/V$
- Threshold of perceptibility
- Threshold of irritability



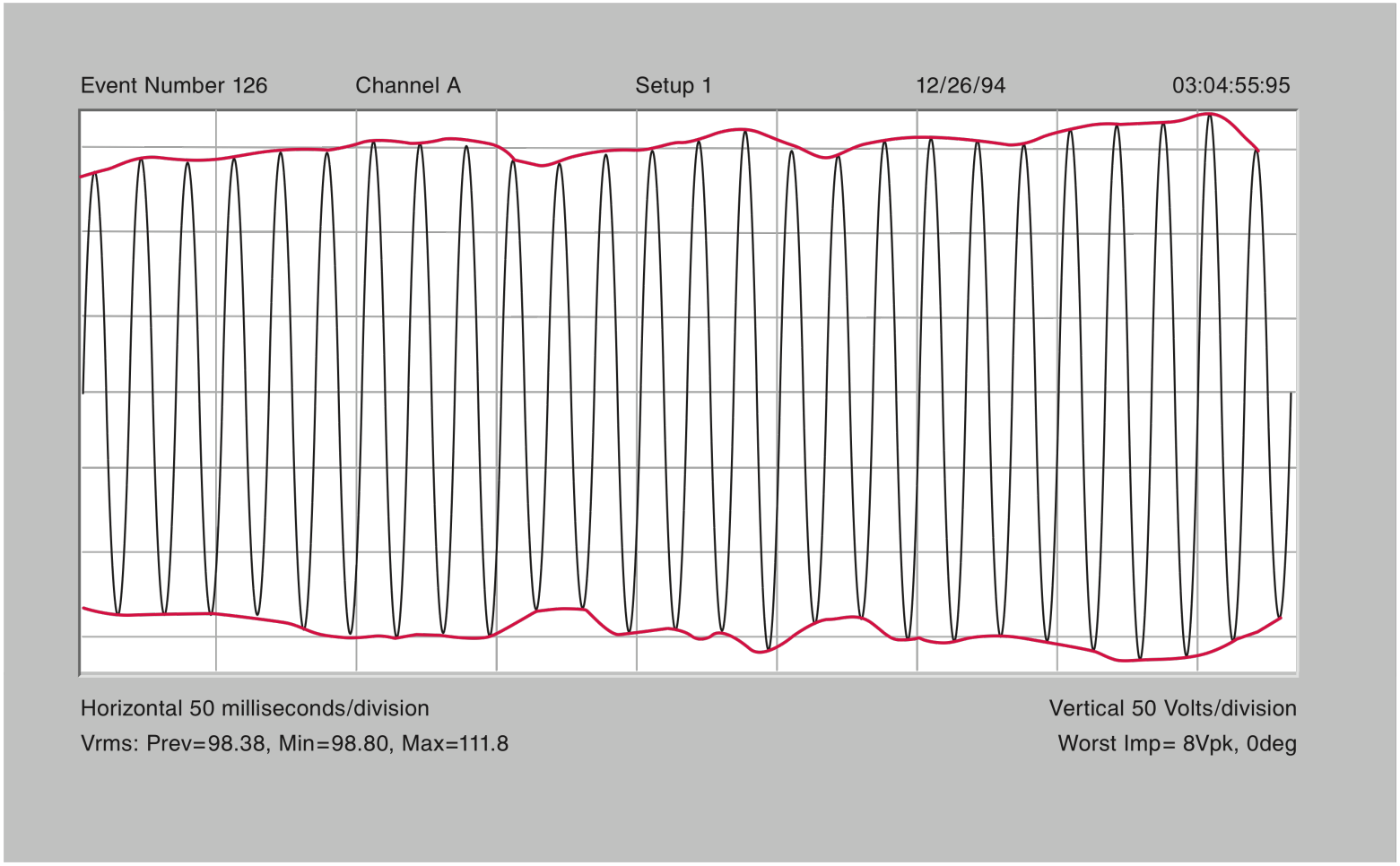
Flickermeter Block Diagram IEEE 1453-2004

Special amplitude modulation analyzer, based on human light-eye-brain response

Simulation of Lamp-eye-brain Response



Flicker Modulation – 60 Hz Waveform



IFL & Pst

IFL - Instantaneous Flicker Level Signal: Based on the IEEE 1453 standard. IFL quantifies voltage fluctuation at a given instant. Voltage sags will immediately cause a change in the IFL data. IFL calculations include the eye-brain sensitivity curve for different modulating frequencies, but not the statistical aspect of how often such fluctuations occur.

Pst - Perceptibility Short Term: A parameter used to measure the severity of flicker. It is calculated using the "time at level" values of the IFL over 10 minute periods in the statistical classifier.

Pst of 1.0 = threshold of irritability

Pst of 0.35 = threshold of visibility

Plt – Long Term Flicker Severity

- Useful for determining combined effect of several randomly operating loads (welders, motors)
- Also considers effects of flicker sources with long/variable duty cycles (arc furnaces)
- Typically evaluated over 12 Pst intervals – 12 x 10 min. = 2 hours

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{sti}^{3}}{N}}$$

Flicker Compatibility Levels

IEEE 1453 recommended flicker limits to avoid complaints

Compatibility Levels Low, Med. V, < 35 KV, >35 KV < 230 KV	Planning Levels Med. V, 1 KV - 35 KV	High V - EHV
Pst 1.0	.9	.8
Plt 0.8	.7	.6

IEEE 1453 Flicker Levels

	Compatibility LV-MV	Planning MV	Planning HV-EHV
Pst	1.0	0.9	0.8
Plt	0.8	0.7	0.6

$$P_{lt} = \sqrt[3]{\frac{\sum_{1}^{12} P_{st}^{3}}{12}}$$

Planning levels are 99% percentile over 1 week
Compatibility levels are 95% percentile
Pst = 10 minute interval Plt = 12 Pst intervals

Resolving Flicker Problems

1. Increase transformer size
2. Increase size of service drop conductors
3. Tighten/remake all connections and splices
4. Install soft starts on large motor loads
5. Check for open or loose neutral connections

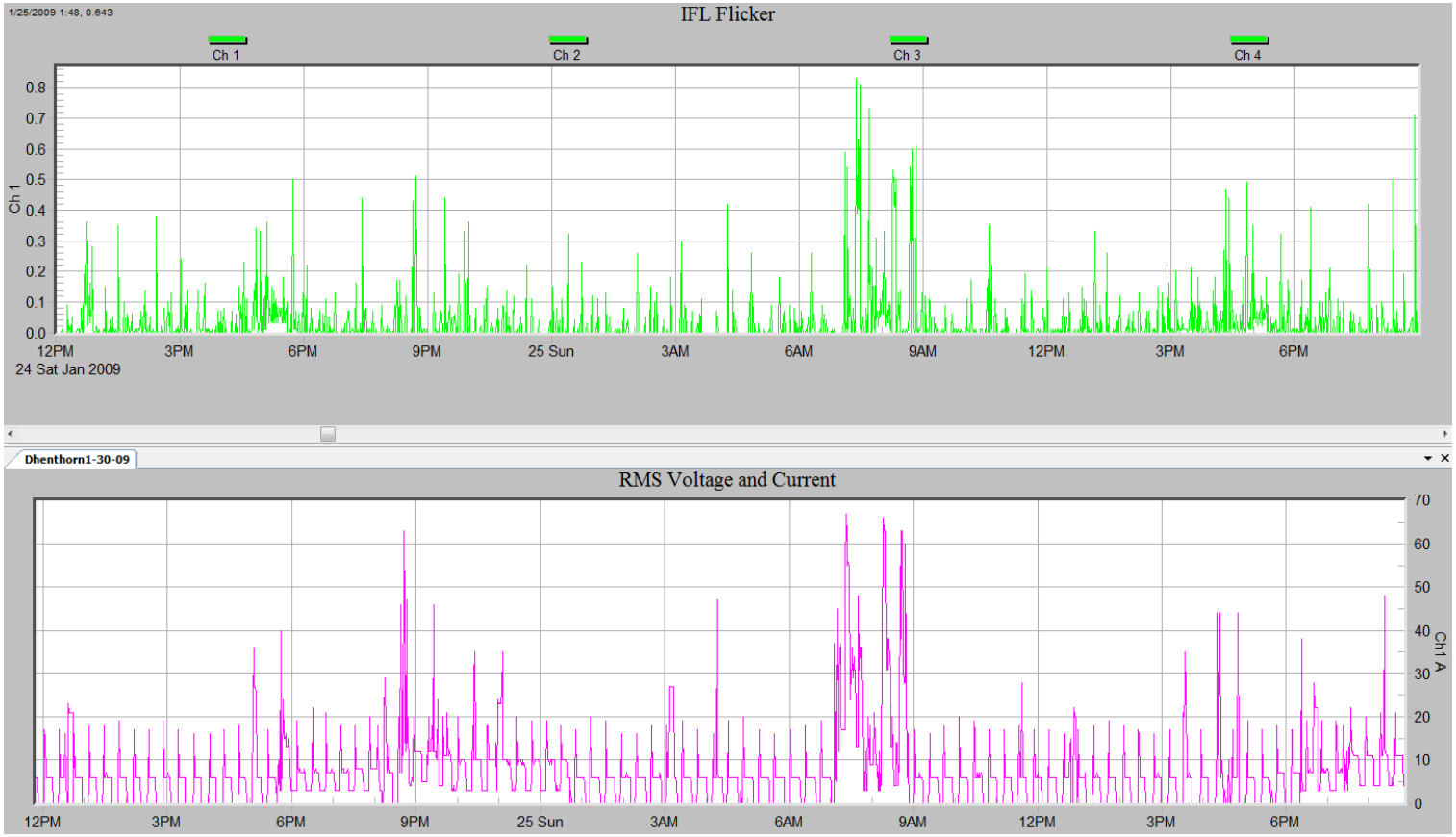
Advantages of 1453 Flicker Method

- IFL can be useful for locating source of flicker - shows fast time variations in voltage magnitude
- P_{st} used for determining flicker severity – is there a problem?
- P_{lt} - useful for determining combined effect of several randomly operating loads, and effects of flicker sources with long/variable duty cycles

Reasons to use older 141 Method

- Need to compare new readings with historical data recorded to IEEE Std. 141
- Utility had adopted “house flicker curve” – Std. 141 curve is adjustable, 1453 method is not
- Need to eliminate a single known flicker source – possible to customize the curve around a known flicker generator pattern
- Easier to estimate expected Std. 141 flicker levels by hand for a single large offender

IFL vs. Load Current - Stripchart Graph



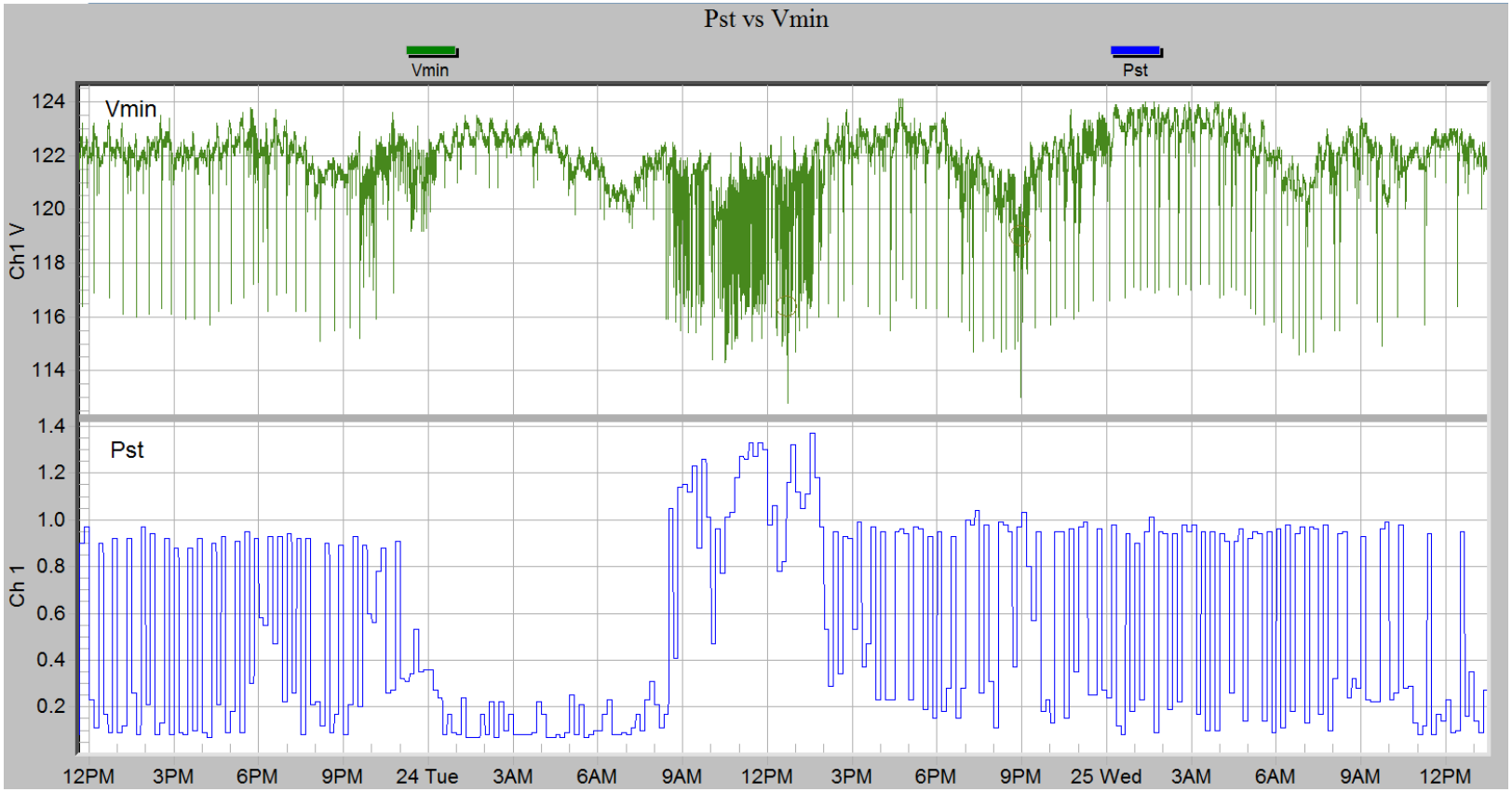
Captured by a PMI Eagle® 440

IFL useful for locating source of flicker

Pst used for determining flicker severity

Pst vs Voltage Fluctuations

Time Trend Plot



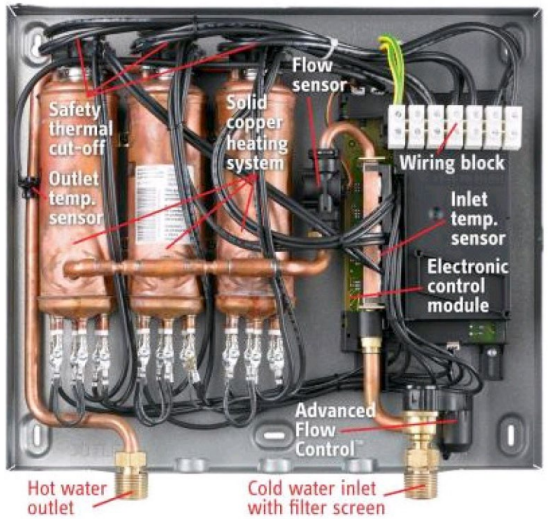
Captured by a PMI Revolution®

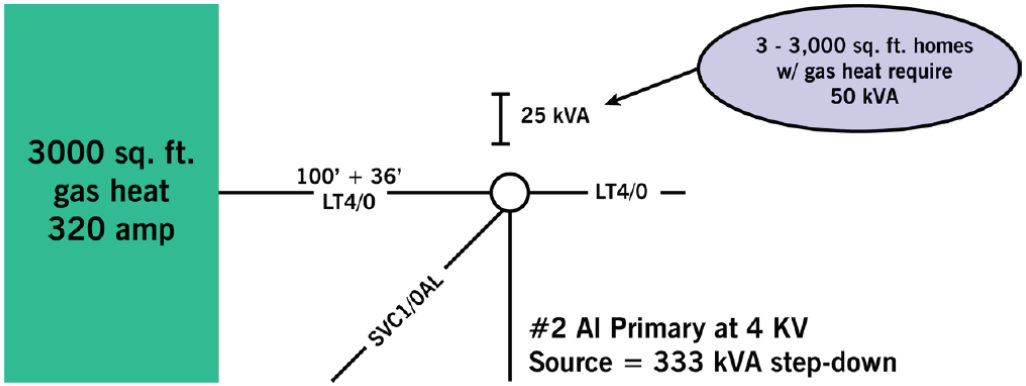
Vmin data points – single cycle worst case values – frequency of occurrence? Duration? Pst indicates human perception of flicker severity

Case Study 1: Tankless Electric Water Heater

Residential customer
25 kVA transformer

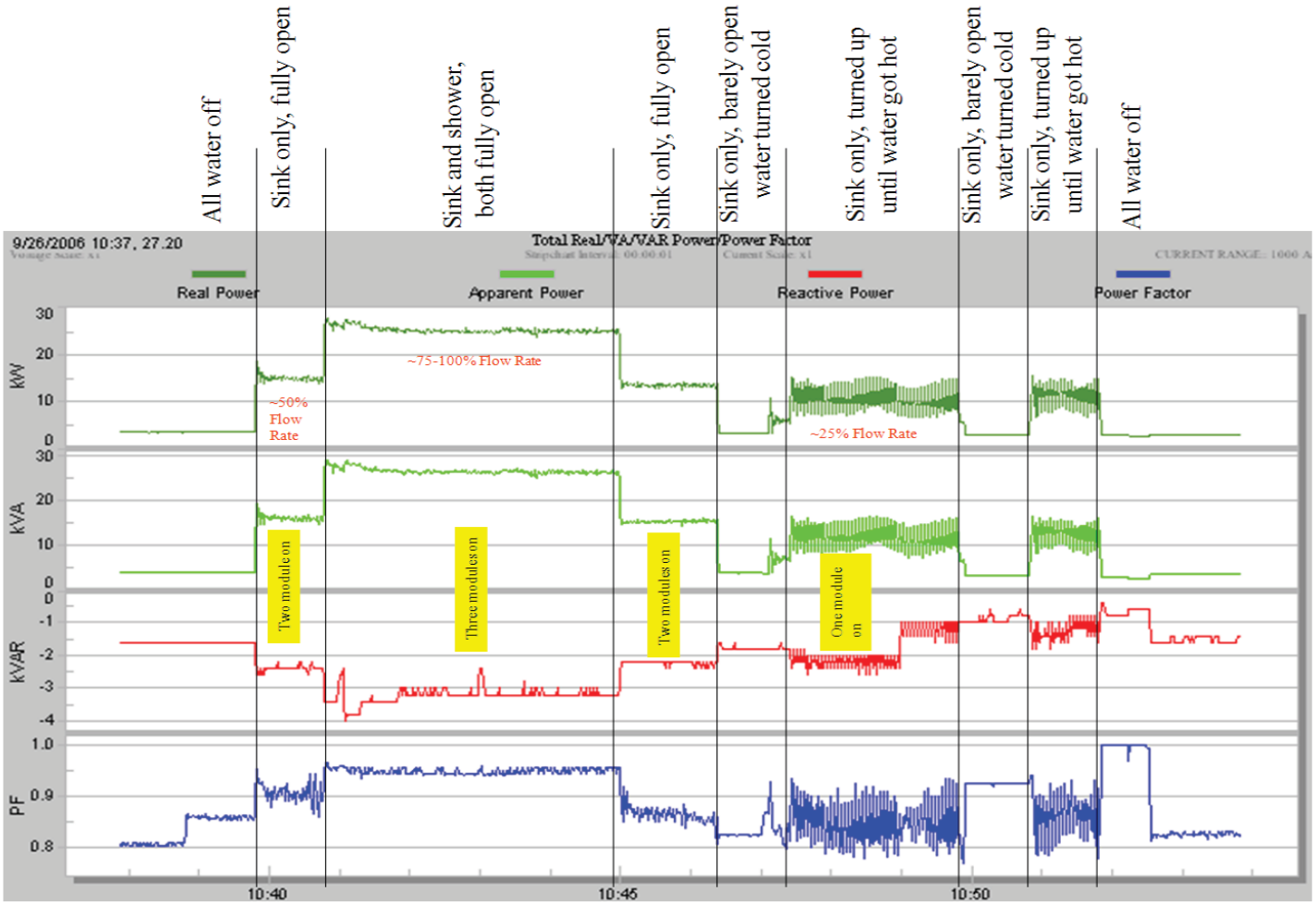
Customer installs 28 kW water heater:
EEMax EX280T2T





Case Study 1: Tankless Electric Water Heater

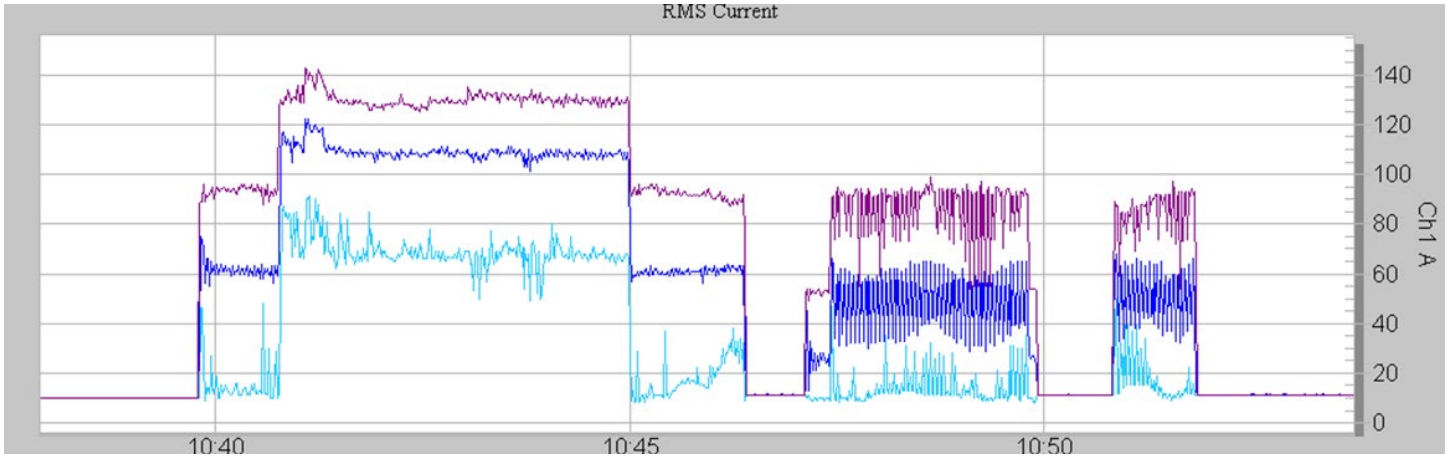
Water heater cycles elements for intermediate flow rates

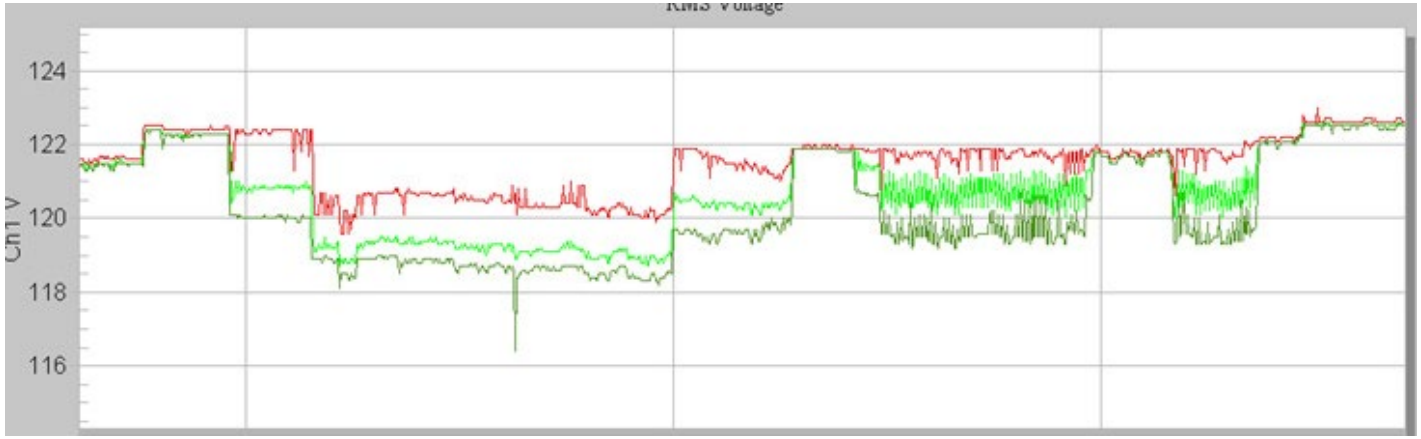


Case Study 1: Tankless Electric Water Heater

25 kVA xfmr replaced with 50 kVA to reduce flicker – reduces impedance, therefore reduces voltage drop

Continuous 60-80A current swings!





Case Study 2: Amish Heater

Appears to be simple space heater – ideal resistive load

Uses power semiconductors to cycle heating element at sub-second speeds

Produces huge amount of flicker

ADVERTISEMENT

Amish mantle and miracle invention help home heat bills hit rock bottom

Miracle heaters being given away free with orders for real Amish fireplace mantles to announce the invention that helps slash heat bills, but Amish craftsmen under strain of winter rush force household limit of 2

Save money: only uses about 8¢ electric an hour; so turn down your thermostat and never be cold again

By Mark Wood
Universal Media Syndicate

(UMS) Everyone hates high heat bills. But we're all sick and tired of simply turning down the thermostat and then being cold.

Well now, the popular HEAT SURGE* miracle heaters are actually being given away free to the general public for the next 48 hours starting at precisely 8:00 a.m. today.

The only thing readers have to do is call the National Distribution Hotline before the 48-hour deadline with their order for the hand-made Amish Fireplace Mantle. Everyone who does is instantly being awarded the miracle heater absolutely free.

This is all happening to announce the HEAT SURGE Roll-n-Glow* Fireplace which actually rolls from room-to-room so you can turn down your thermostat and take the heat

GENUINE AMISH MANTLES MADE IN THE USA: Everyone wants to save money on heat bills this winter, so entire Amish communities are working from the crack of dawn to finish. These fine real wood Amish made fireplace mantles are built to last forever. The oak mantle is a real steal at just two hundred ninety-eight dollars because all those who beat the order deadline by calling the National Hotline at 1-800-731-4796 to order the fireplace mantles are actually getting the imported hi-tech Fireless Flame HEAT SURGE miracle heaters for free.

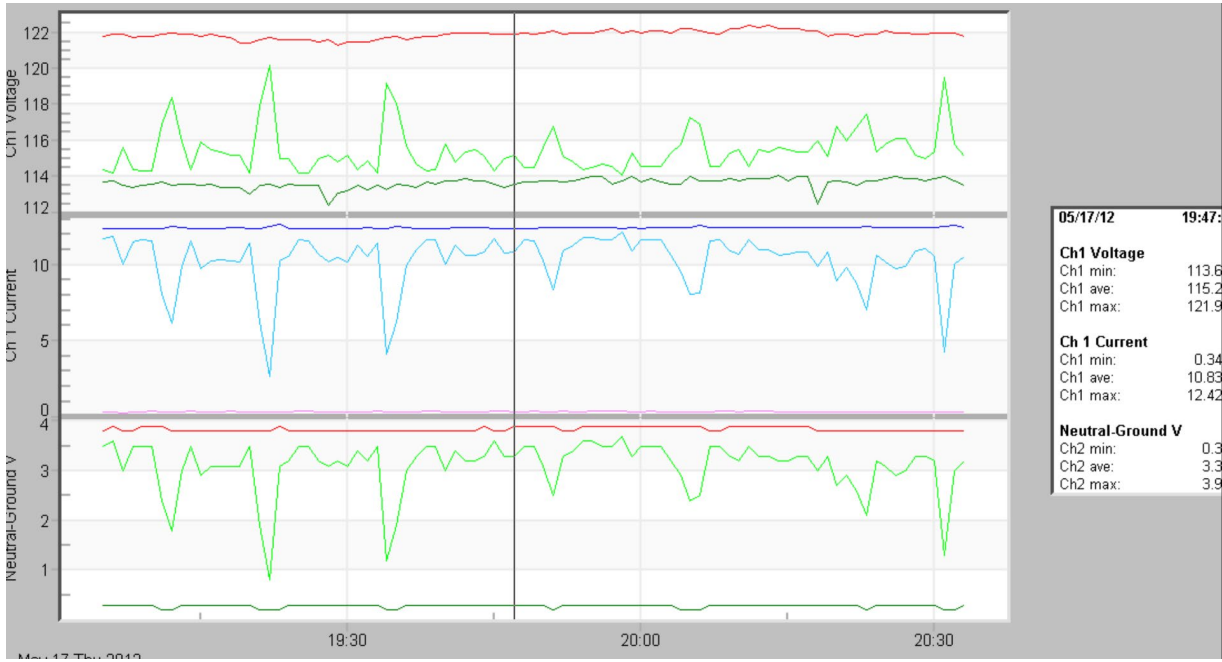
because they require no chimney. It amazes everybody because it has. Fireplaces are the latest home dec-

Amish Heater

Residential recording with plugin PQ monitor

Flicker well beyond threshold of irritability

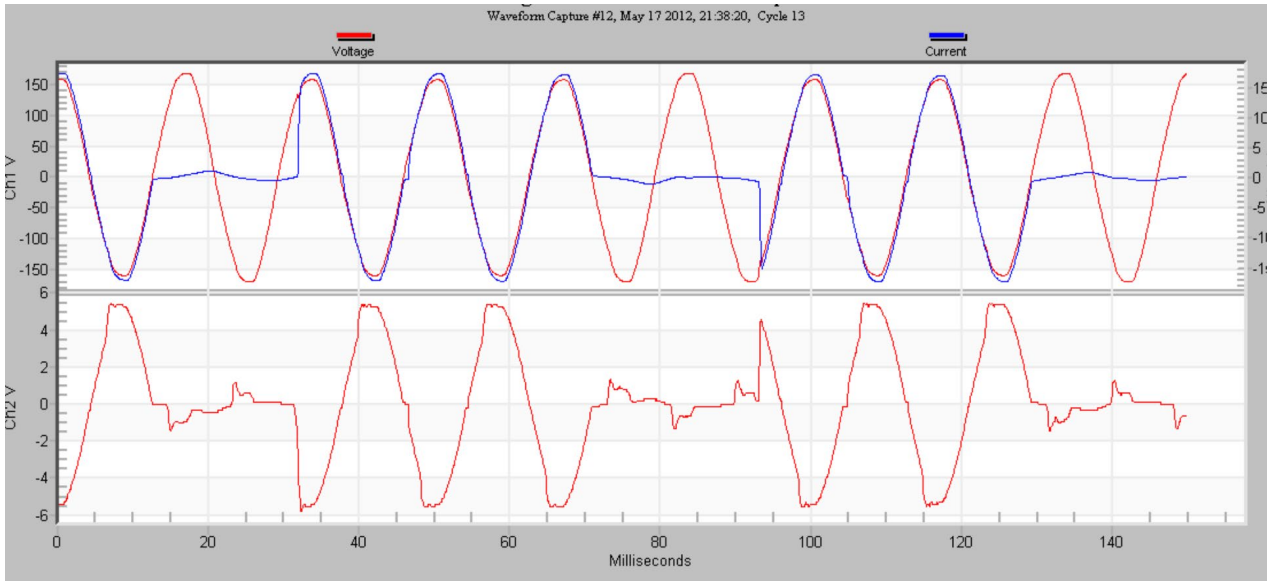
Date	Time	Tolerance	Time Span	Freq Limit	Events
05/17/2012	18:19:46	0.9%	10 seconds	5	10
05/17/2012	18:26:05	0.9%	10 seconds	5	6
05/17/2012	18:26:15	0.9%	10 seconds	5	17
05/17/2012	18:26:25	0.9%	10 seconds	5	11
05/17/2012	18:26:42	1.2%	1 minute	10	30
05/17/2012	18:31:33	0.9%	10 seconds	5	6
05/17/2012	18:31:36	1.2%	1 minute	10	11
05/17/2012	18:31:43	0.9%	10 seconds	5	20
05/17/2012	18:31:53	0.9%	10 seconds	5	20
05/17/2012	18:32:03	0.9%	10 seconds	5	18
05/17/2012	18:32:36	1.2%	1 minute	10	50
05/17/2012	18:34:17	0.9%	10 seconds	5	6
05/17/2012	18:34:20	1.2%	1 minute	10	12
05/17/2012	18:34:27	0.9%	10 seconds	5	20



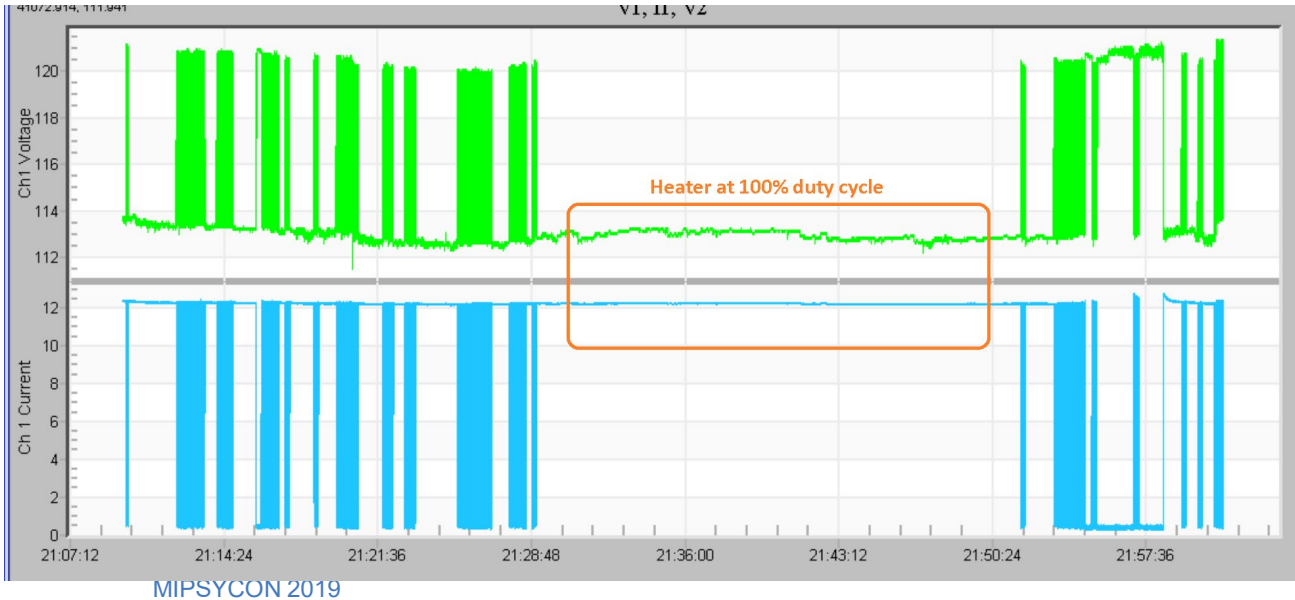
Continuous12A load swings
6V voltage fluctuations

Amish Heater

- 40ms on, 20ms off – 17Hz rep rate
- Pure resistive load
- Switching asynchronous with 60 Hz



Cycle stripchart reveals duty cycle changes based on heat demand



Power Quality 102

- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- **Loose Neutral**
- Impact Loading
- Variable Frequency Drives
- Modern loads and PQ

Loose Neutrals

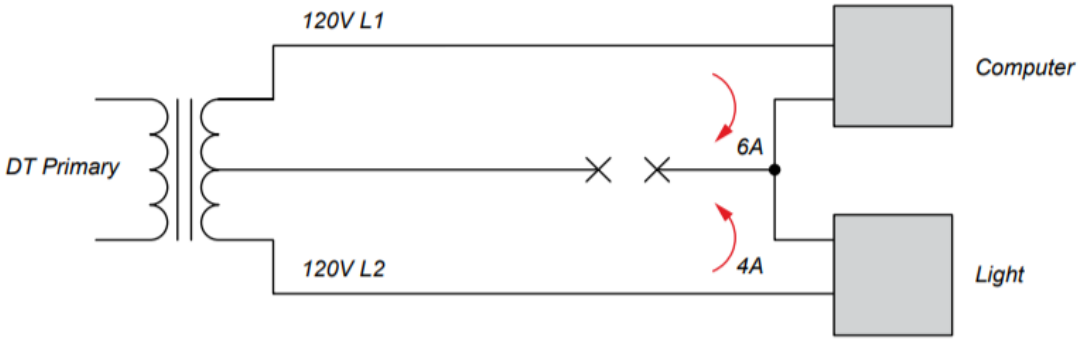
Very common residential problem
Can be very dangerous!

Open or high impedance neutral connection forms voltage divider with secondary loads

L1, L2 voltage sum to 240V, but can swing wildly depending on loads

Fluctuating light levels, especially increasing in brightness – can be confused with flicker

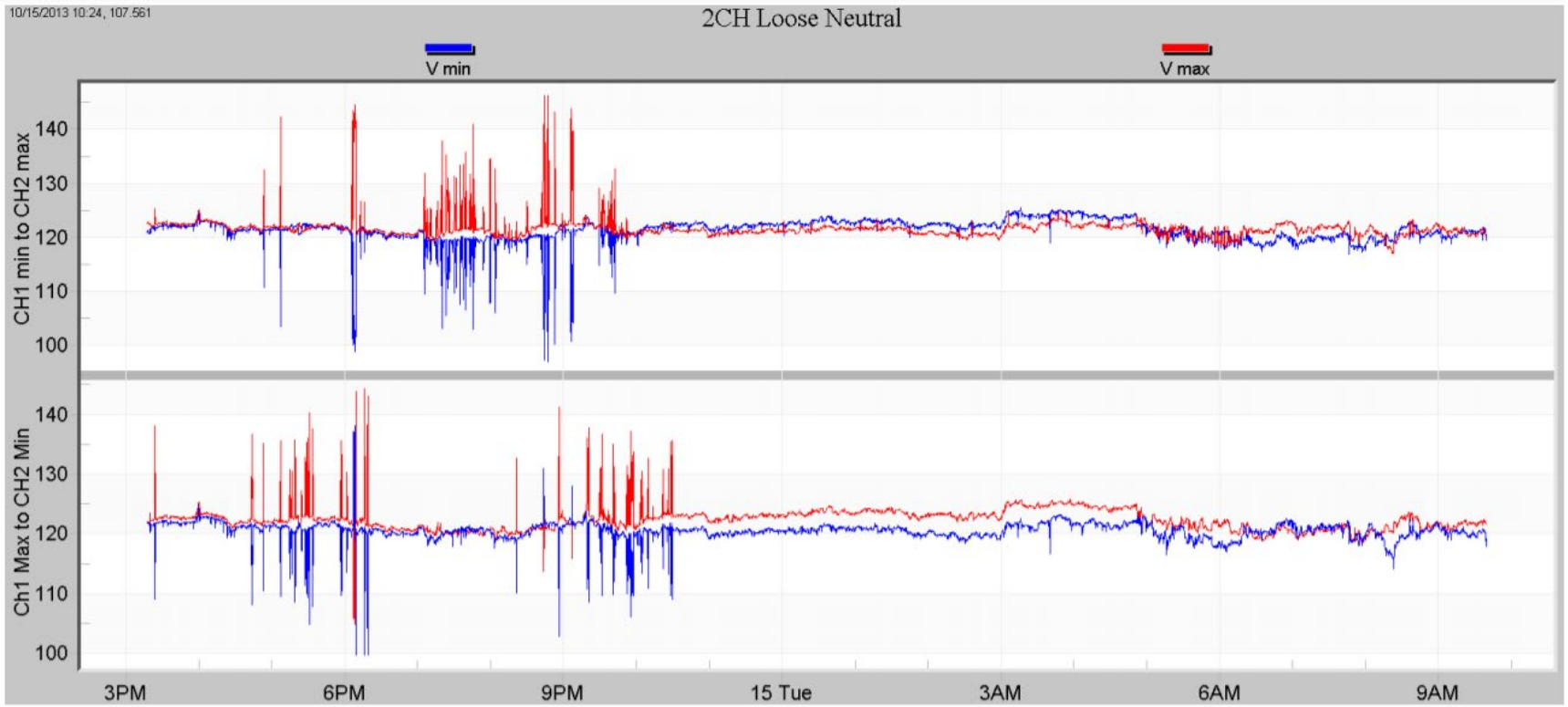
LED lights can hide symptoms



PQ monitor must be downstream of the neutral break to see symptoms

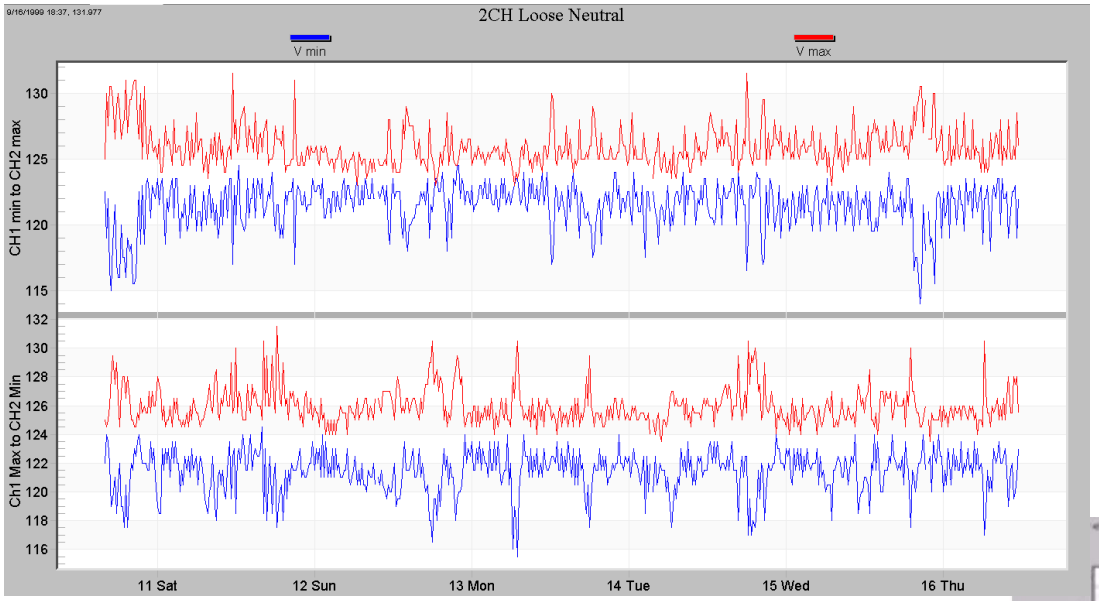
Loose Neutrals

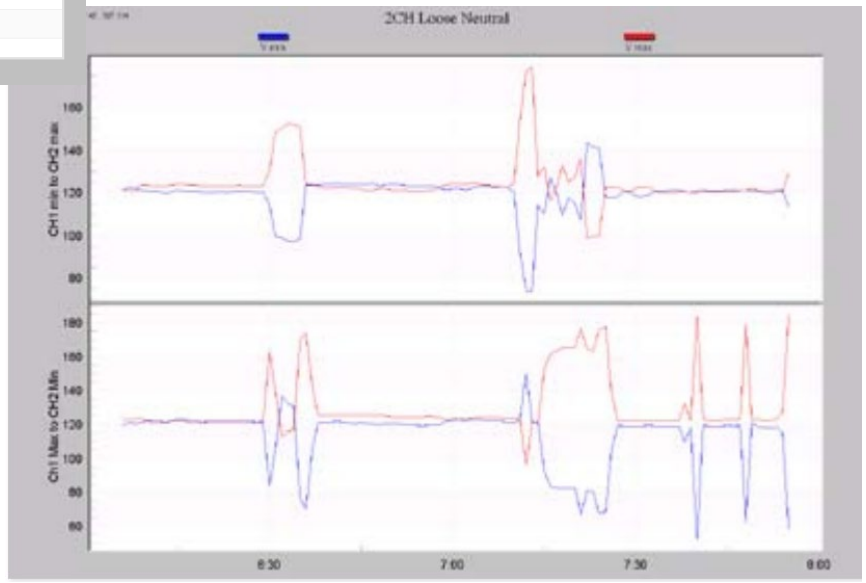
Look for matching high/low swings with opposite legs



Loose Neutrals

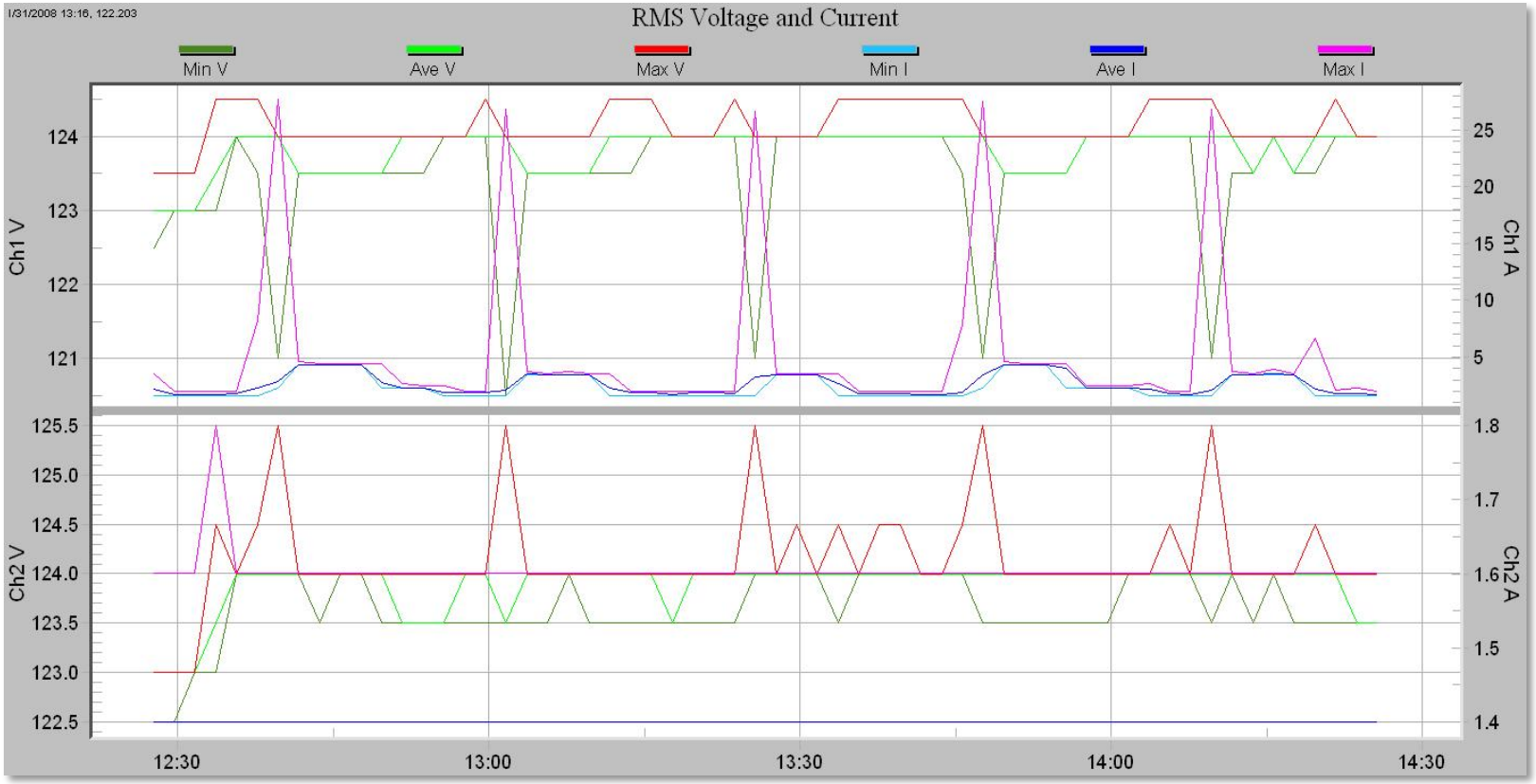
Look for matching high/low swings with opposite legs





Loose Neutrals

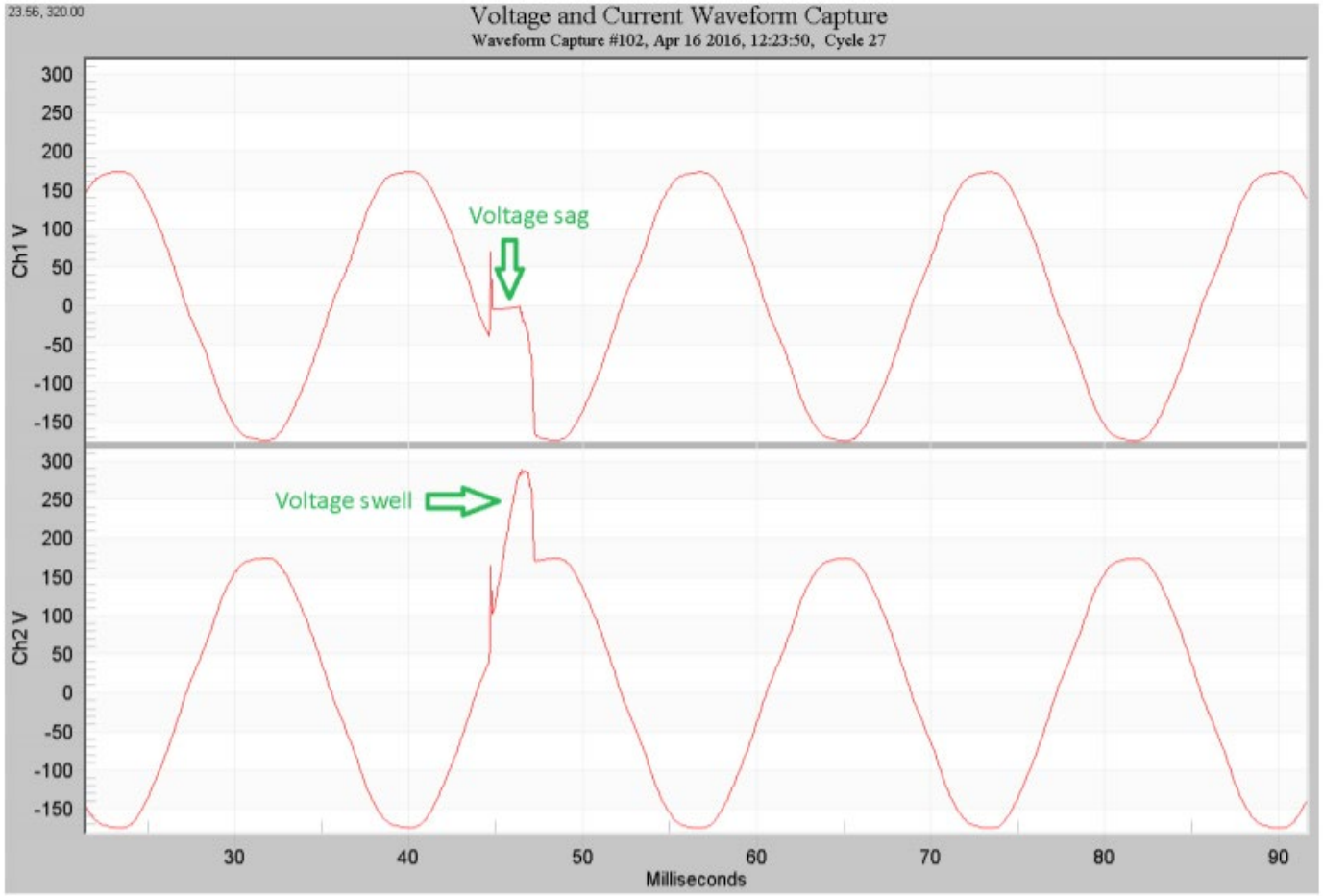
Motor start currents on CH1 (Vsags), causes Vswells on CH2



Captured by a PMI Revolution®

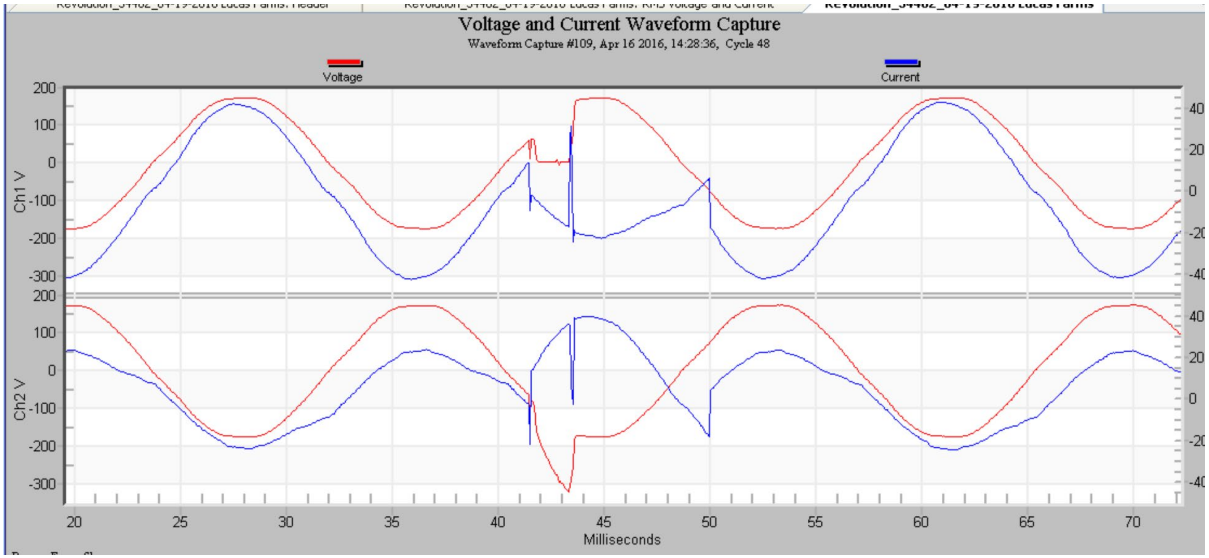
Loose Neutrals

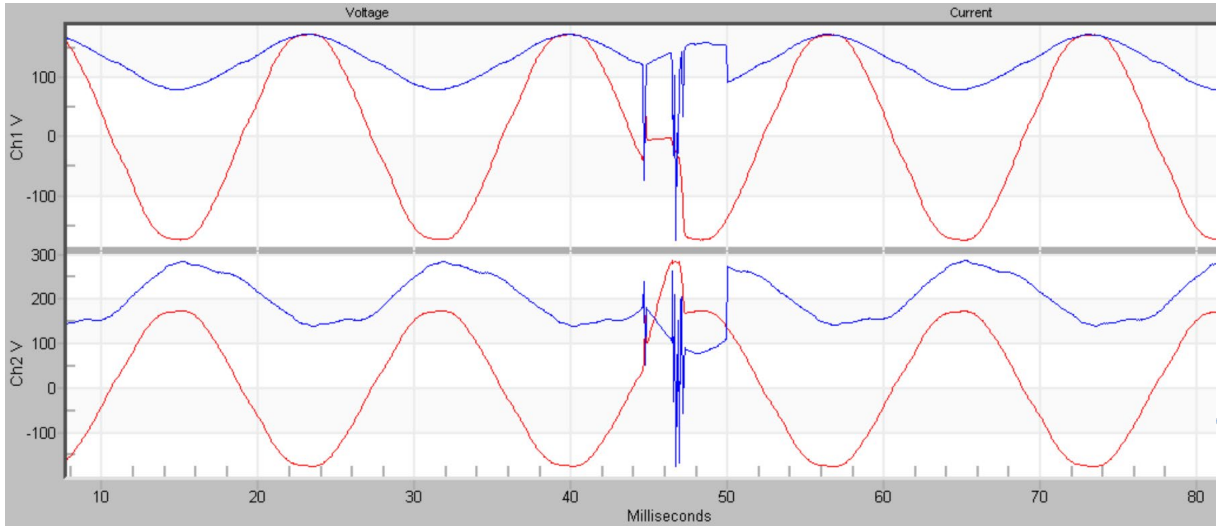
Waveform pattern is a bit different, since it's instantaneous, not RMS (no negative RMS values)



Loose Neutrals

Waveform pattern is a bit different, since it's instantaneous, not RMS (no negative RMS values)





Power Quality 102

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- Modern Loads and PQ

Impact Loading

Impact Loads: frequent very high current surges, usually greater than the nameplate rating of the transformer

- Usually caused from high motor inrush currents with frequent motor starts
- Appears to transformer as repeated near-short circuit condition

- High currents cause large mechanical stress on internal windings and core
- Repeated stress causes early failure
- More commonly seen on “unit transformers” dedicated to a single load, sized specifically for the steady state load current

Transformer may need to be de-rated with impact loads – loads with very high peak to average RMS current, and frequent peaks

Impact Loading

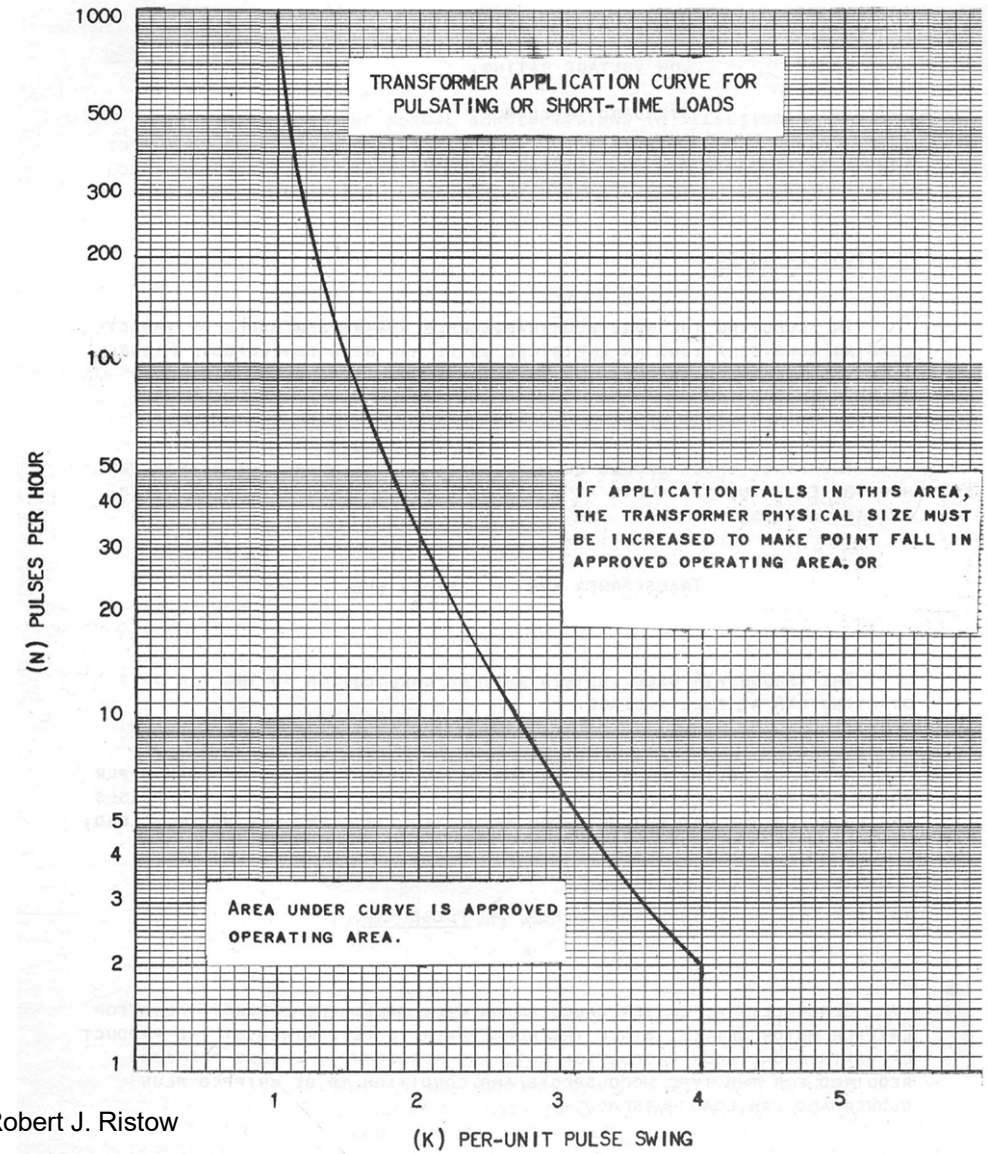
Transformer de-rating chart

- X-axis: per-unit "pulse swing"
- Y-axis: current pulses/hour

"pulse swing" $K = \frac{kVA_P}{kVA_T}$

kVA_P = inrush pulse
kVA_T = transformer KVA rating

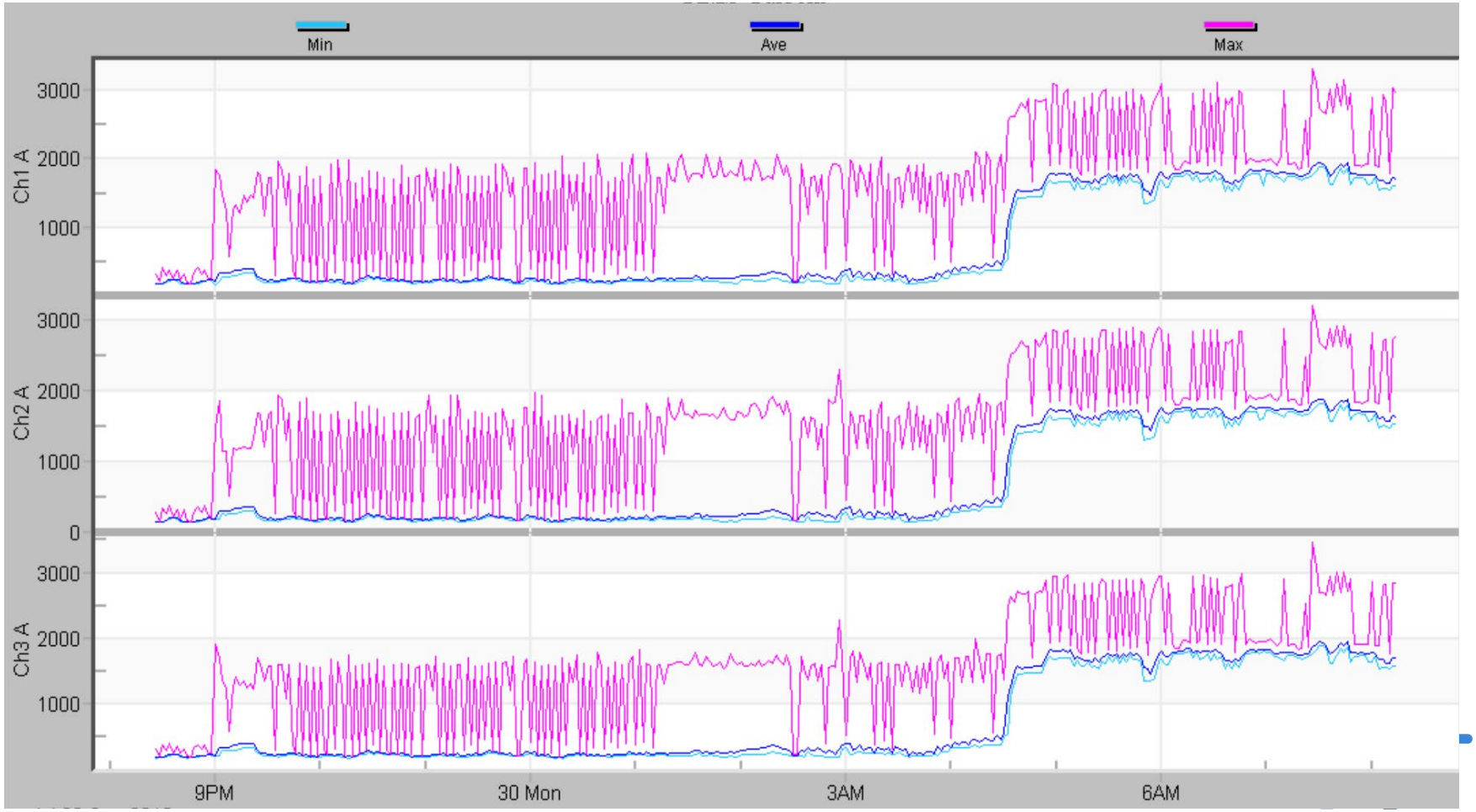
$$1hp \approx 1kVA$$



Problems of Impact Loading on Unit Transformers by Frank J. McCann and Robert J. Ristow

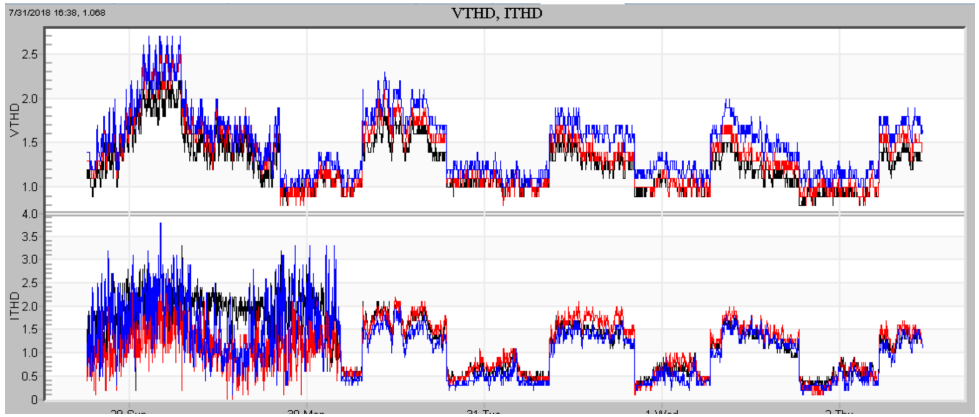
Case Study: Poultry Plant

Poultry Processing Plant
1 MVA transformer failed after 6 months. Peak 15 minute load ~1.1 MVA
2 minute stripchart interval, many 1500A current spikes

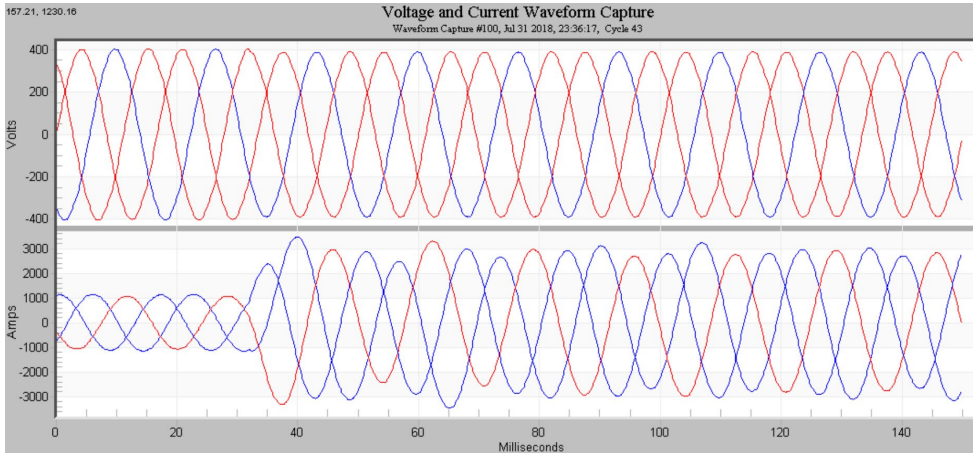


Poultry Plant

- Poultry plant used many directly connected AC motors
- Motors synchronized in a conveyor system
- Very frequent starts and stops
- No soft start or VFD drives



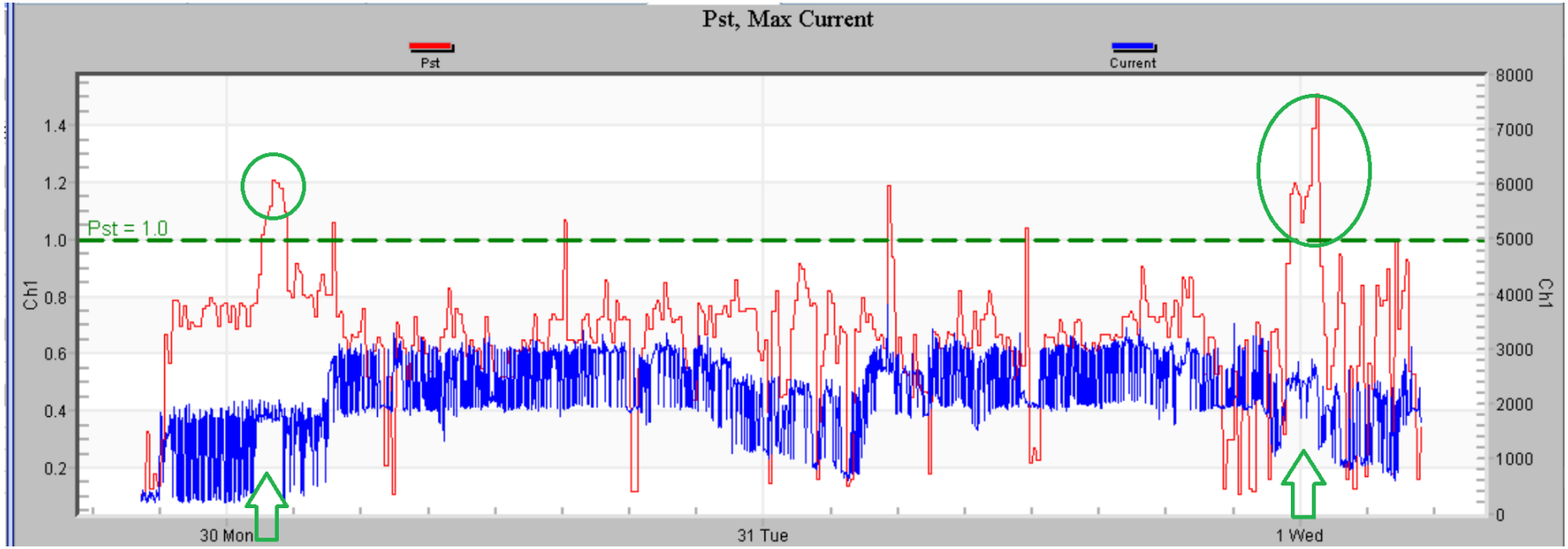
V, I THD both low



Normal looking V, I sine waves …

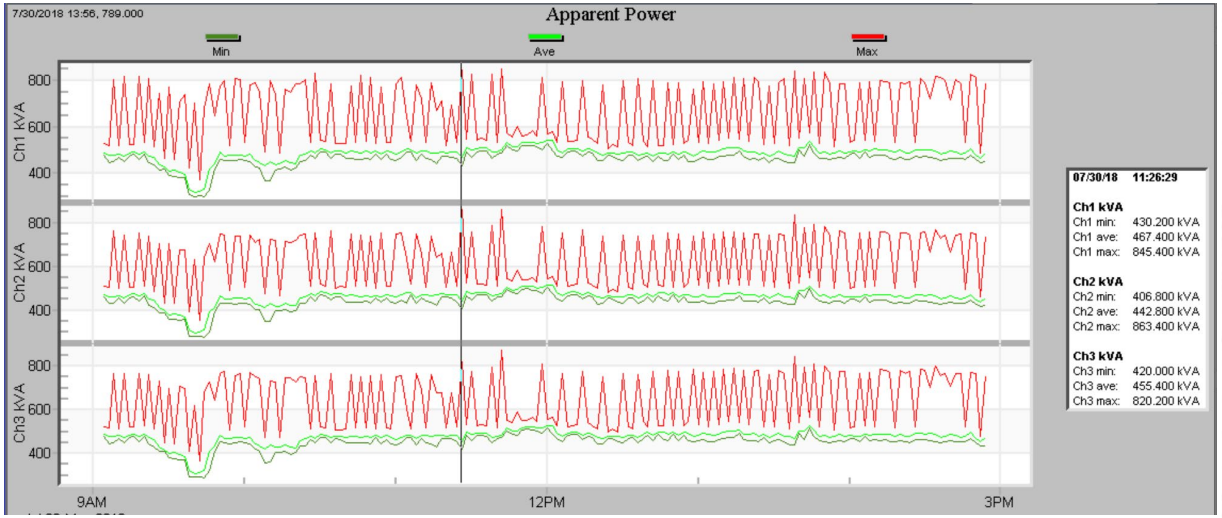
Poultry Plant

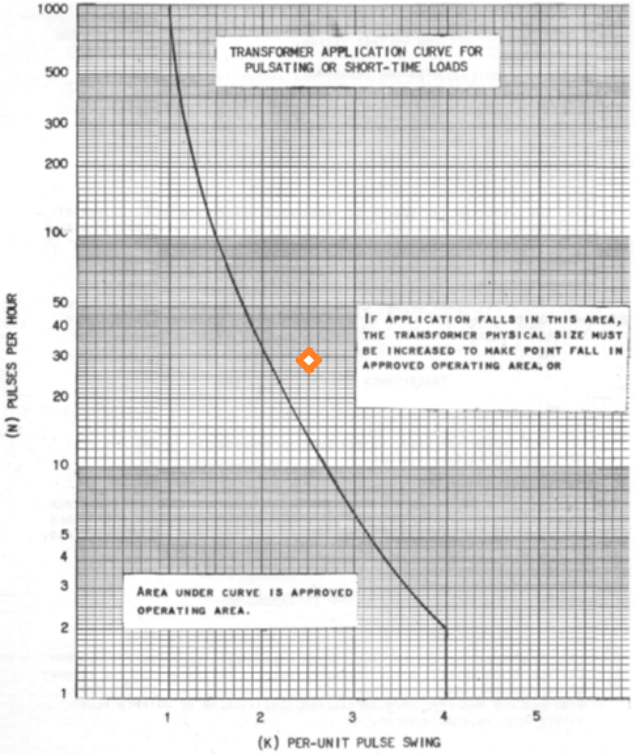
Flicker is high during periods where max current is spiking continuously (more than once per 2 minute interval)



Poultry Plant

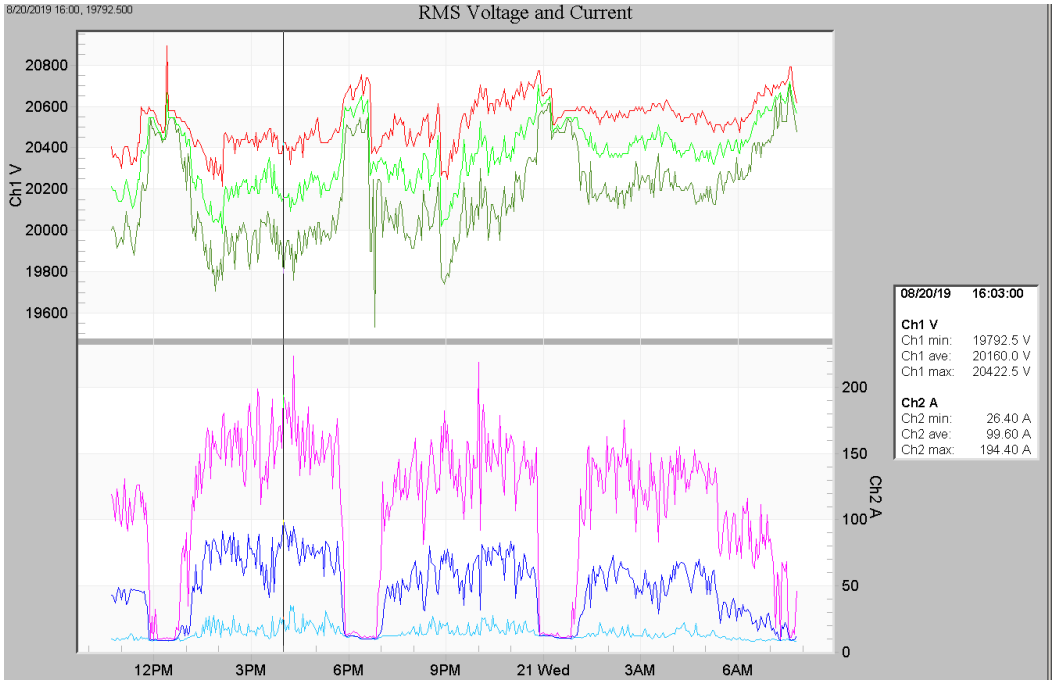
Repeated impact loads of 2.5 MVA (840 KVA / phase)
Pulse swing = 2.5 /1 = 2.5, rate of 30/hour
New 1.5 MVA transformer installed





Giant Cranes at Shipyard

- 34.5 kV primary metered customer
- 12 cranes moving 50 ton containers, start approx. every 90 seconds
- 150-200A inrush every 7 seconds = ~7MVA inrush pulse



3.2% voltage swings every few seconds

Customer needs to triple the number of cranes!

Expansion needs to account for impact derating

Power Quality 102

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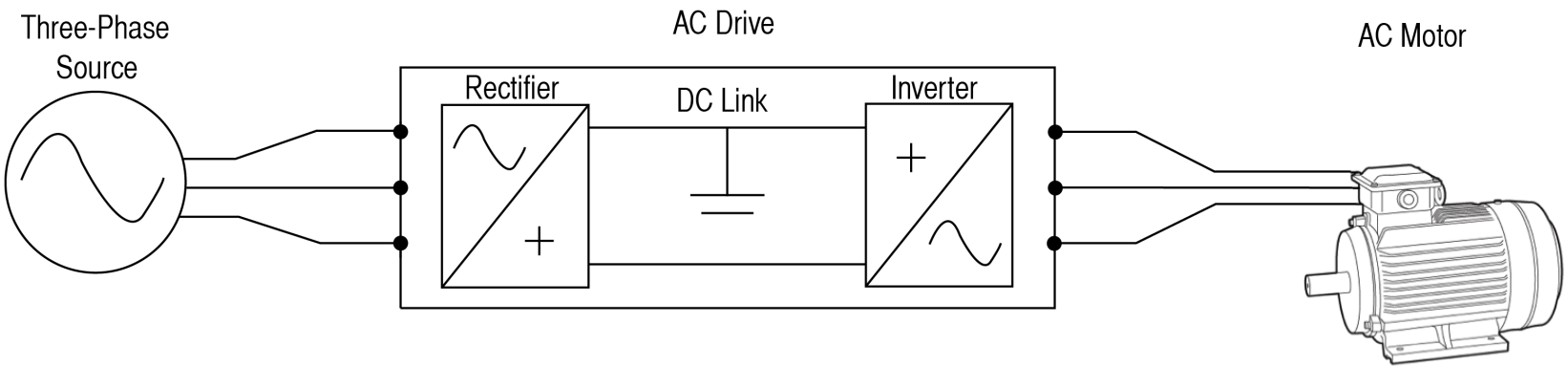
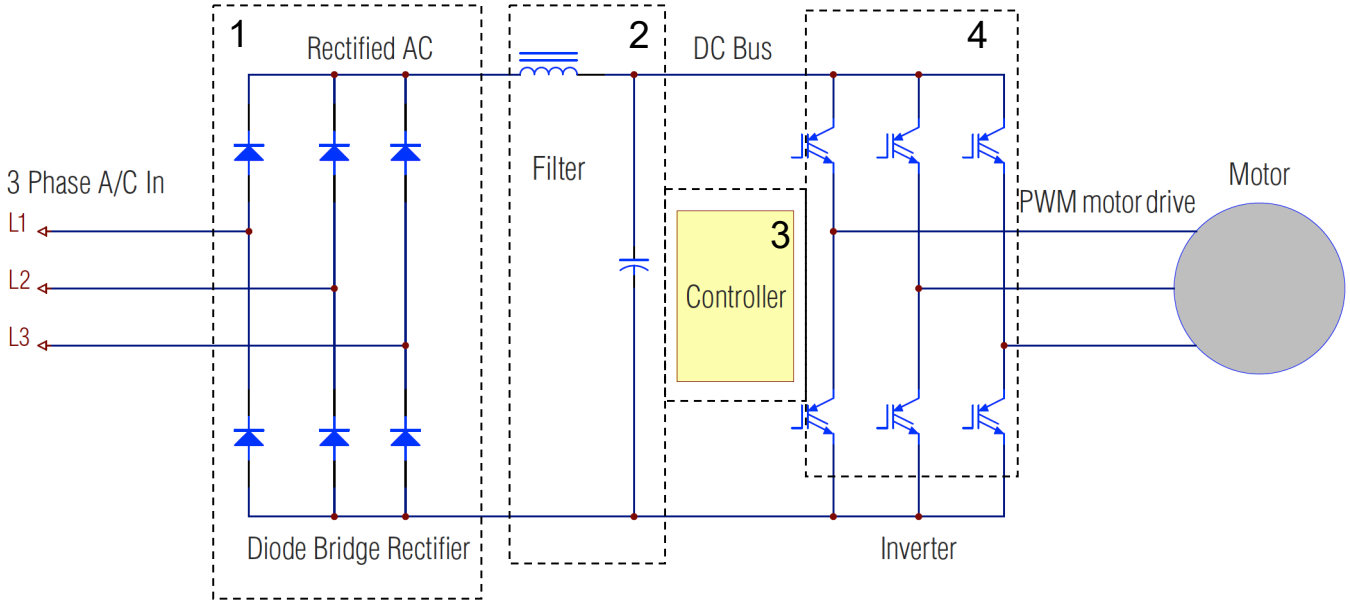
What is a Variable Frequency Drive?

Variable Frequency Drive

- Electronic equipment used to control motor speed, voltage and torque
- Composed of diodes, transistors, thyristors, MOSFETs, IGBTs,capacitors etc.



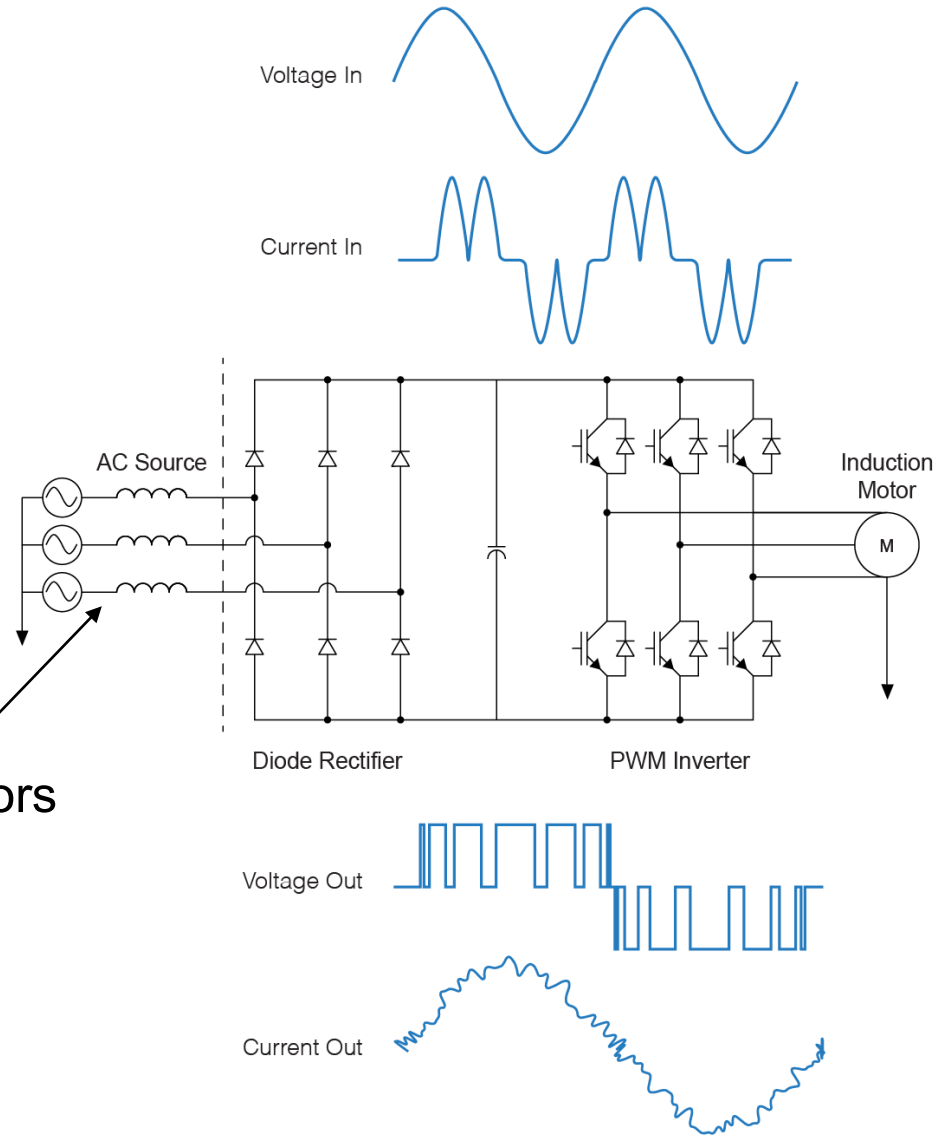
Main Sections of an AC Drive



1. Rectifier: typically uses diodes to change AC to DC
2. DC Link: includes a choke and capacitor to filter out ripple; ensures the desired voltage or current is supplied to the inverter; monitored for protection from surges
3. Controls: inputs are operator settings including start, stop, motor speed upper and lower limits and system feedback; controls switching of input and output devices, monitors and reports malfunctions, shuts down VFD if needed
4. Inverter: typically uses thyristors or transistors to change DC to a variable frequency AC to control motor speed and torque

PWM Drive Characteristics

- VFD DC Link voltage is constant
- Pulse amplitude is constant over entire frequency range
- Lower resultant current is created by more and narrower pulses
- Higher resultant current is created by fewer and wider pulses
- Motor inductance smooths voltage pulses into smooth current flow

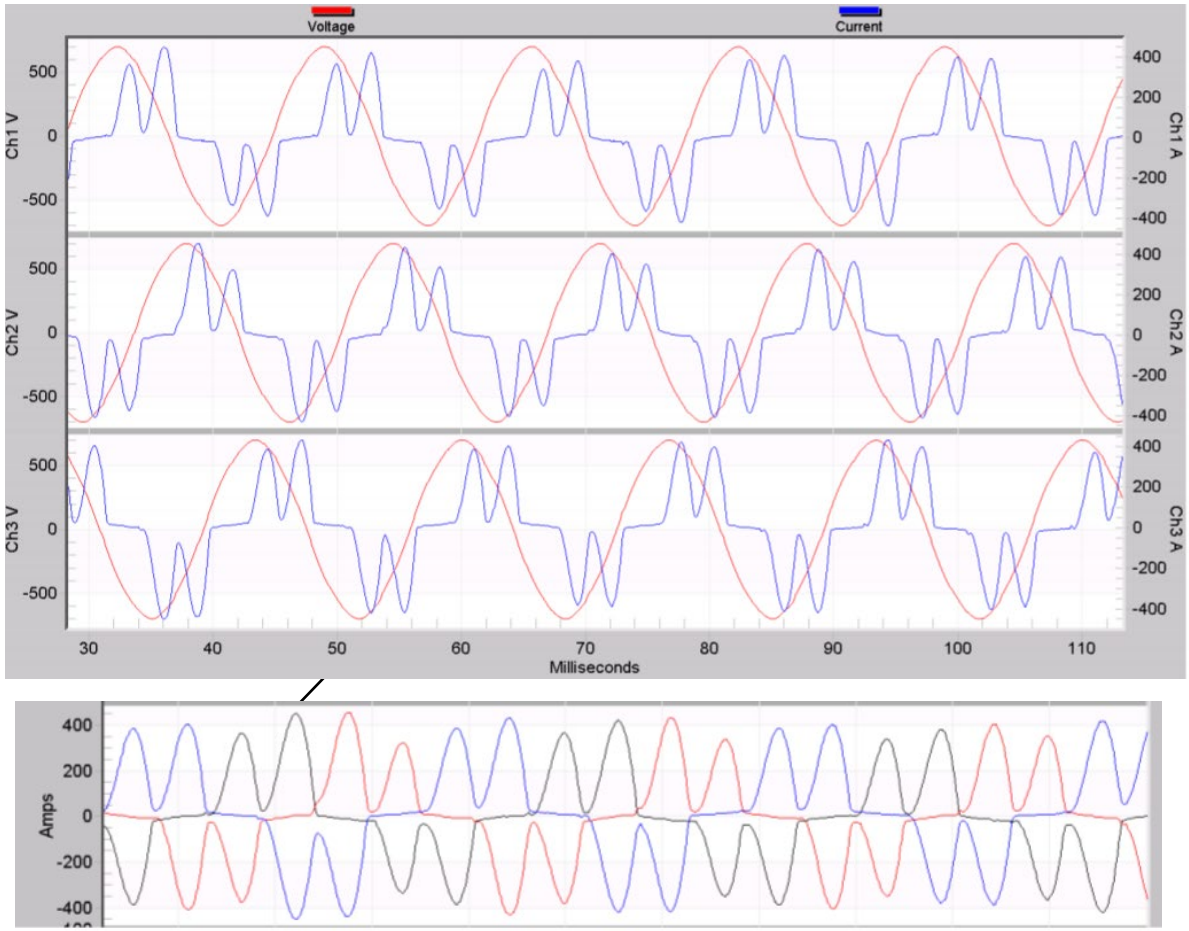


Optional line reactors

6 pulse VFD

6 current pulses per cycle,
2 in each phase-phase pair

Simplest configuration, but highest harmonic content



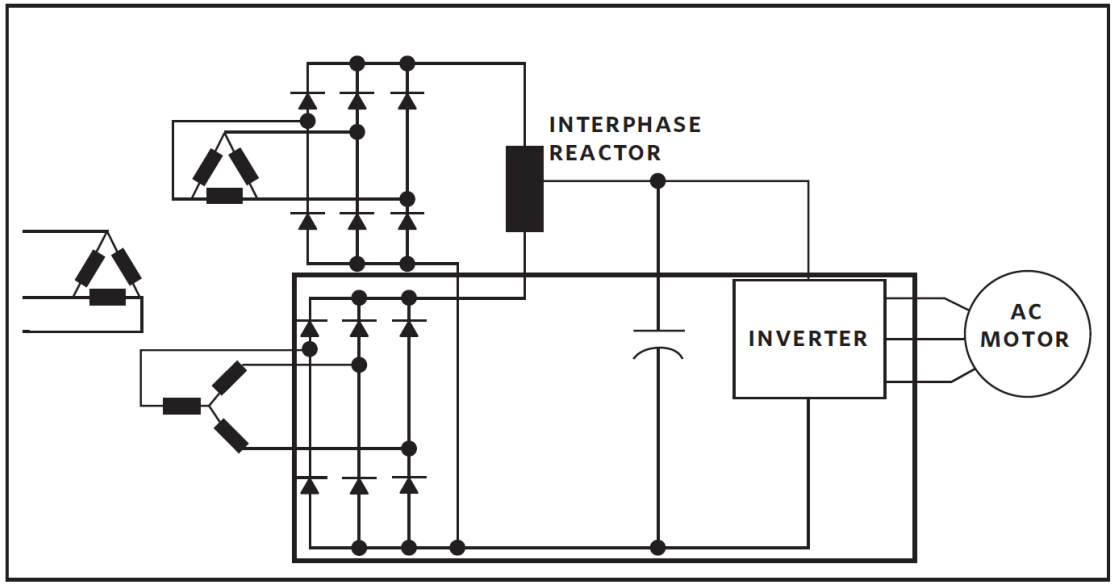
12 pulse VFD

1 primary transformer, 2 secondaries (wye and delta)
2 6-pulse rectifiers

Transformer phase shift results in 12 pulses

Lower harmonics than 6 pulse, but much larger

Can be extended to 18 pulse



Armstrong, whitepaper on 6 pulse vs. 12 and 18 pulse harmonics effect reduction

Benefits of Using a VFD

- Can transform single phase input to 3-phase motor drive
- Lowers Motor Starting Current
- Isolates the system from motor switching transients
- Reduces Thermal and Mechanical Stresses on Motors and Belts During Starts
- Improves Power Factor
- Reduces KVA
- Lowers Cost Compared to a DC Motor
- Regeneration Possibilities
- Permits unlimited number of starts per hour
- Extends Equipment Life and Reduces Maintenance

Problems Produced by VFDs

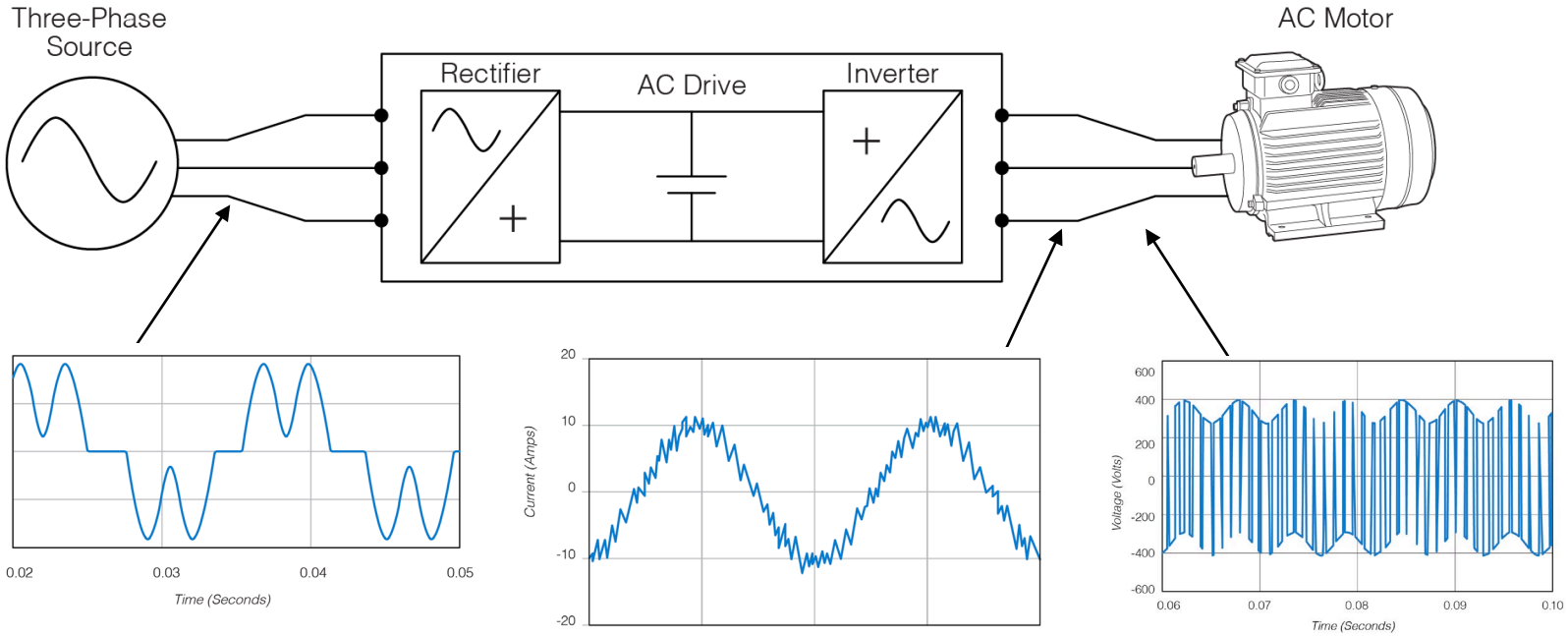
- VFDs are often a significant source of excessive harmonic distortion.
- Harmonic distortion can result in misoperation of utility and customer relays and controls, capacitor failures and increased power system losses.
- Harmonics originate from both the supply input and motor sides of the drive
- Notching and Transients resulting from switching and commutation in power electronics can cause VFD component failures.

Other Problems Related to Use of VFDs

- Nuisance tripping caused by sags, transients, and momentary interruptions can cause protection circuits to shut down VFDs and production lines.
- Audible noise caused by high frequencies used in inverters can be annoying to employees.
- Overvoltages produced by long lead length between the VFD and motor can cause excessive Peak Inverse Voltages causing damage to semiconductor devices.
- Unbalance in 3 Phase Supply- can cause excessive current in one or more phases damaging VFD components.

PQ Problem Produced by VFDs: Harmonics

- Harmonics are created in both the converter and inverter sections of a VFD



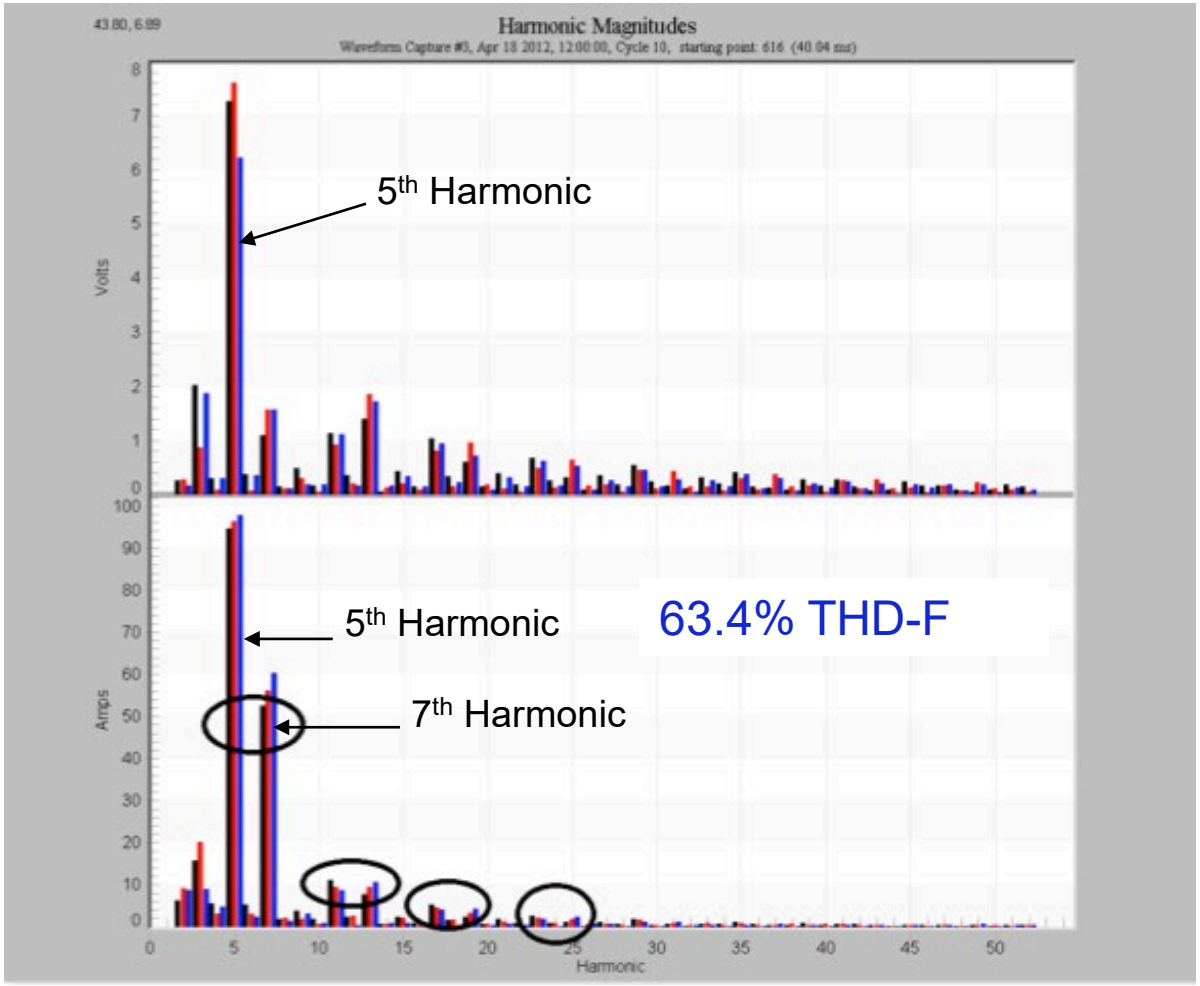
Distorted input current waveform causes distorted voltage drop across source impedance

Output motor current waveform

Output voltage applied to motor

PQ Problems Produced by VFDs: Harmonics

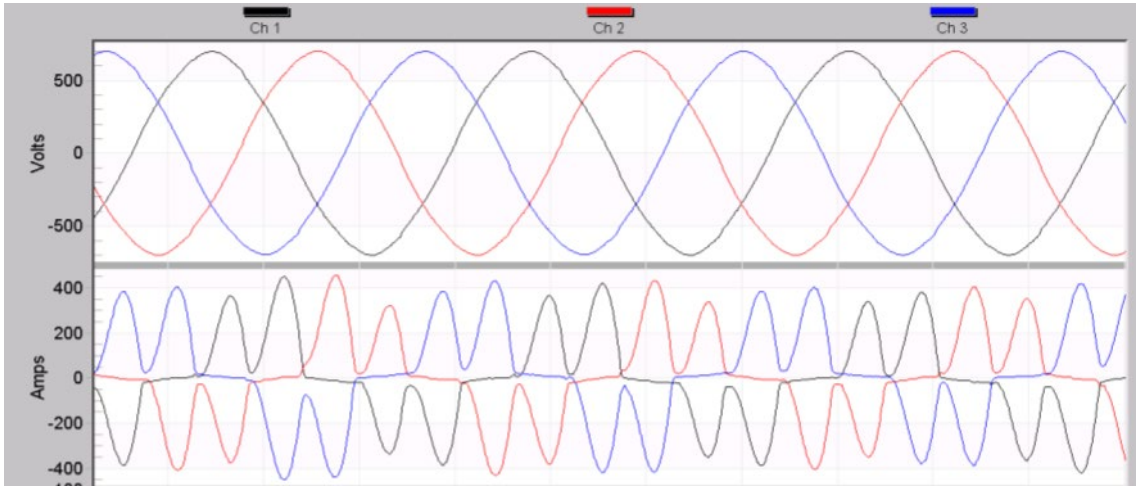
A VFD is a very nonlinear load. A spectrum of the input voltage and current is shown in the figure below. THD in the current is 63%, in the voltage is 1.7



VFD PQ Sensitivities

Voltage Unbalance

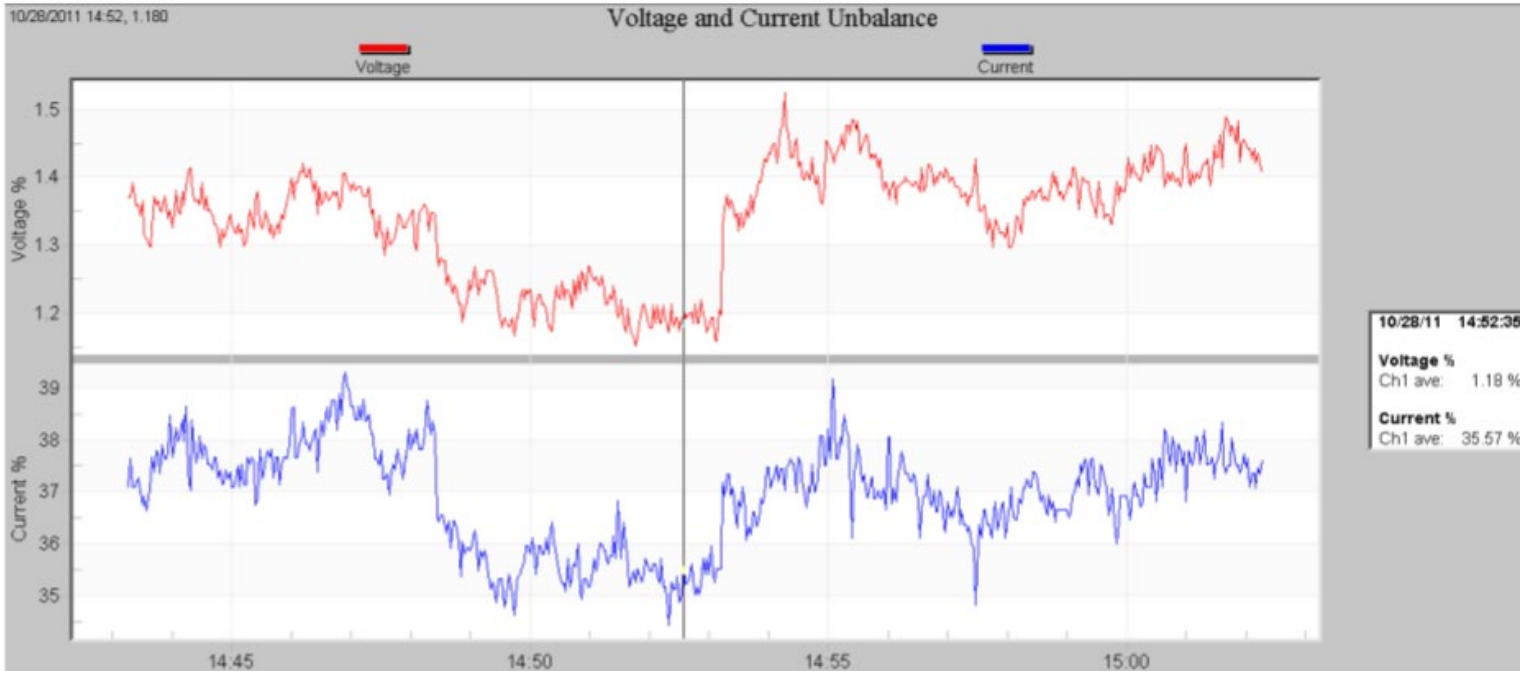
- Causes unequal currents through 3-phase rectifiers
- Increased heating can lead to “thermal runaway”, causing the rectifier to fail



Voltage Unbalance

Unbalance ratio – Current unbalance / Voltage unbalance

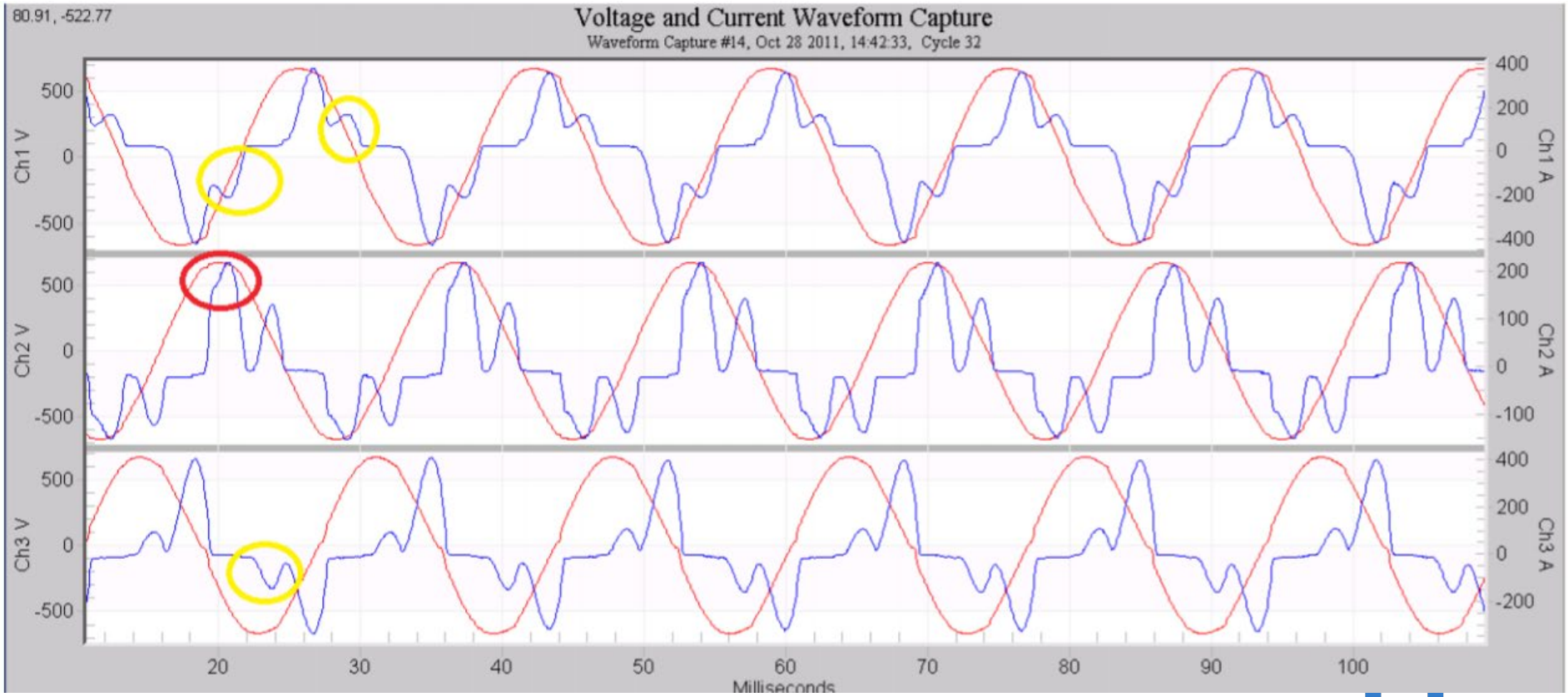
- Typical VFD ratio is 10-20
- Ratio is over 30 below (1.18% voltage, 35% current) – indicates possibly failing VFD bridge input



Voltage Unbalance

Unbalance ratio – Current unbalance / Voltage unbalance

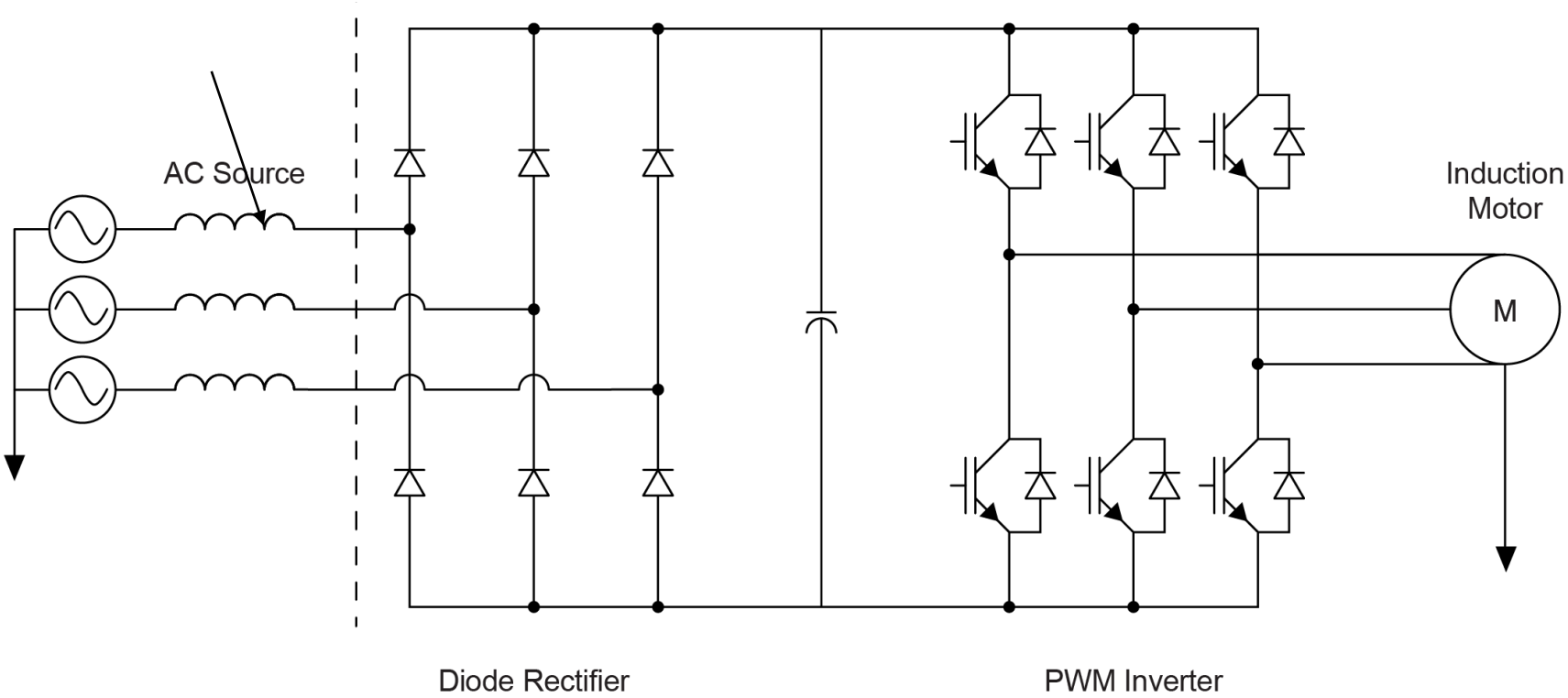
- Waveform analysis – high and runt current pulses – failing VFD rectifier



Solutions for Harmonic Problems

Resolving Harmonic Problems

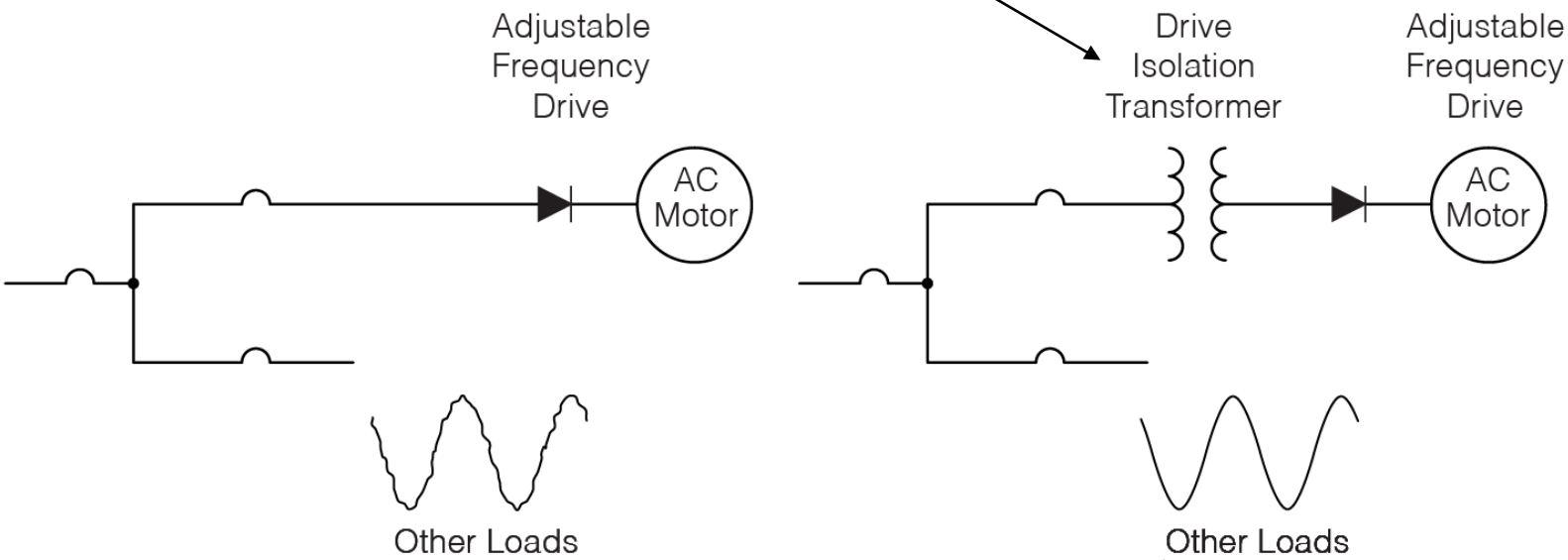
Install Line Reactors



Solutions for Other Problems

Resolving Harmonic Problems

Install Drive Isolation Transformer

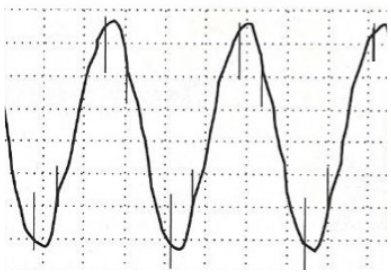


Drive isolation transformers reduce harmonic distortion effect of VFDs

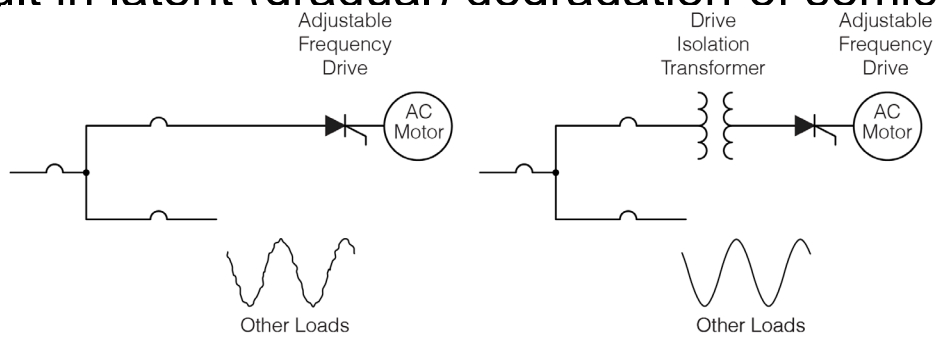
Solutions for Other Problems

Resolving Transient/Notching Problems

- Solid state switching devices cannot switch instantaneously
- This causes commutation overlap where two diodes conduct briefly at the same time.
- Commutation causes transients and can excite system resonances.
- Transients can result in latent (gradual) degradation of semiconductors and conductor insu



Voltage waveform displaying notching

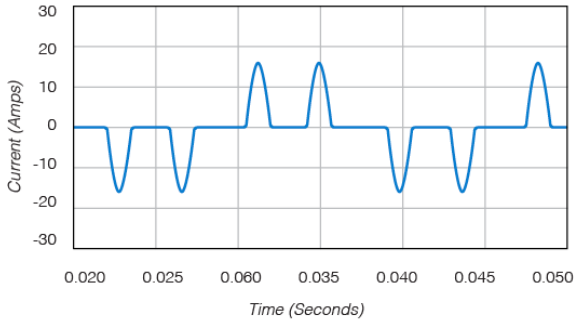


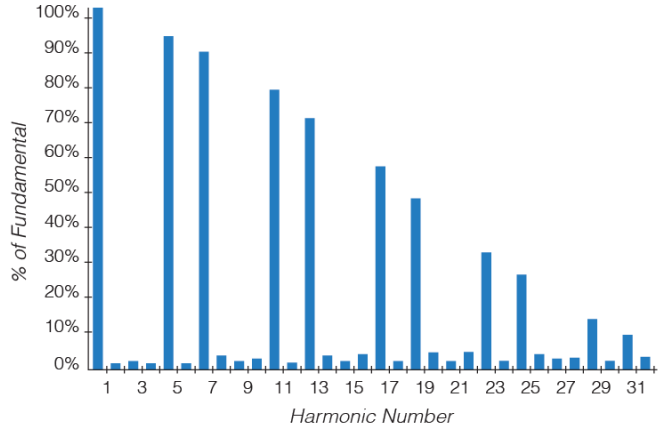
Use of drive isolation transformers to mitigate source voltage notching

Other VFD Characteristics:

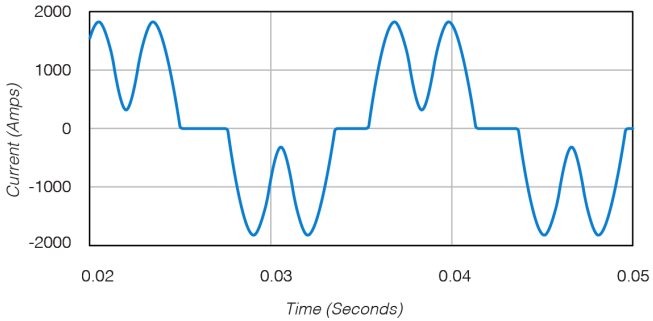
Input Current Waveform and Harmonic Spectrum Comparisons

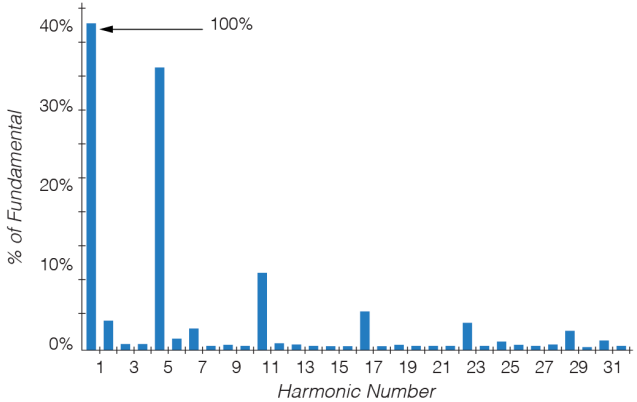
Voltage Source Inverter has Capacitor in DC Link





Current Source Inverter has Choke in DC Link





Formulas for characteristic harmonics where n = 1, 2, 3 … $6n \pm 1$ $6n - 1$

Current Source Inverter has fewer and lower level of harmonics.

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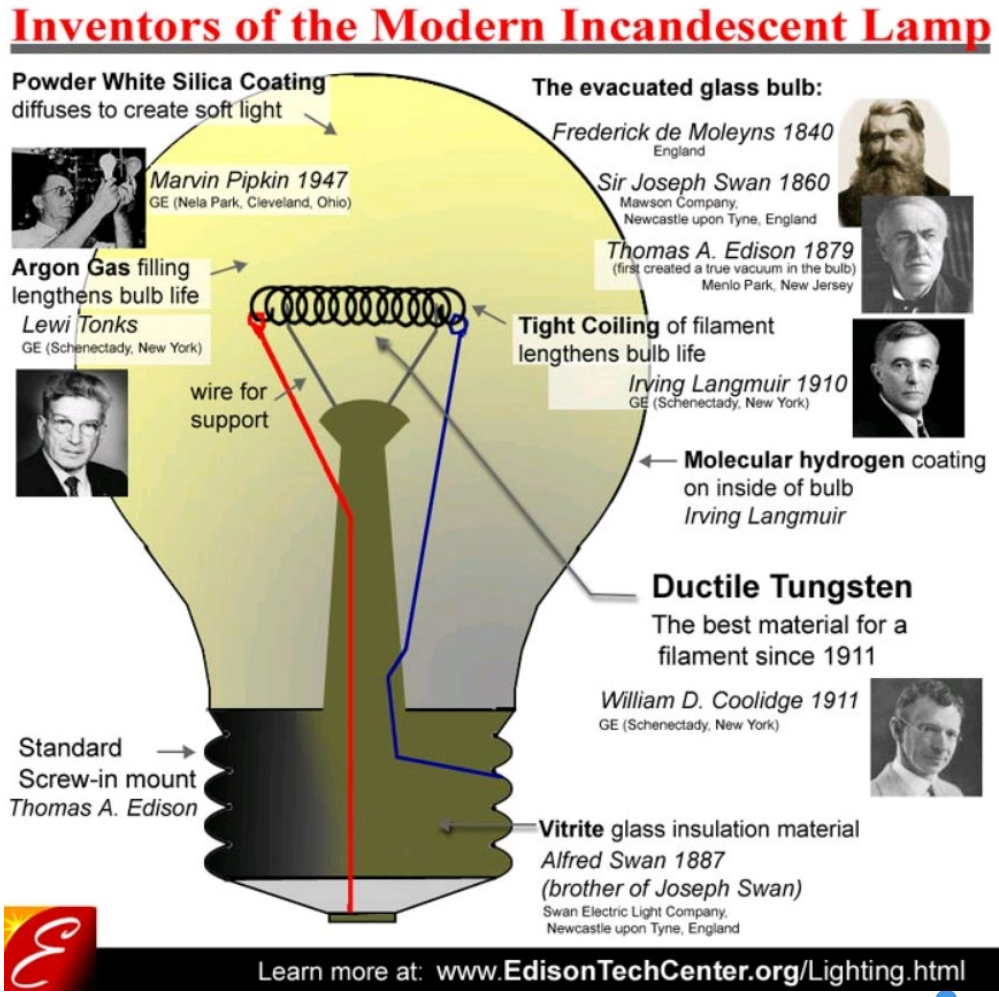
Incandescent Bulb - Design

Modern design stabilized in the 1950s

Very simple electrical design

Physics of operation simple and repeatable



Incandescent Bulb – Consumer Perspective

State of the art – colored bulbs in the 1950s

“Advanced” = 3 way bulb with multiple filaments

Dimming requires external hardware

Improvements focused on cost reductions, lifetime

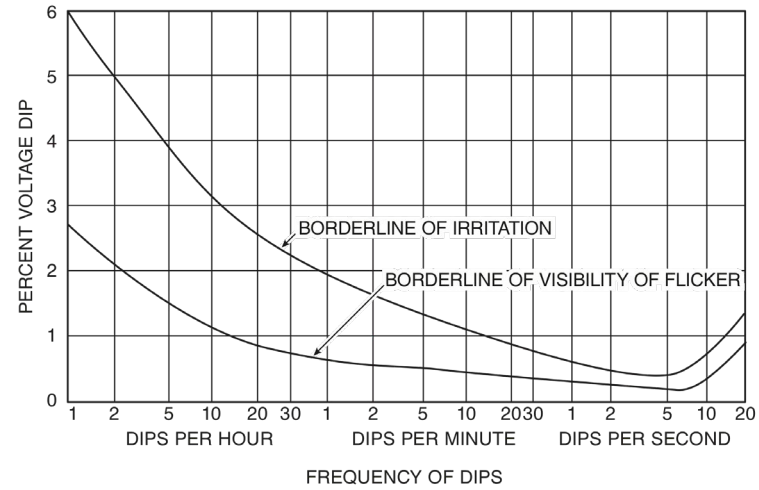
1958
$1.16 = $10.26 today

Incandescent Bulb – Utility Perspective

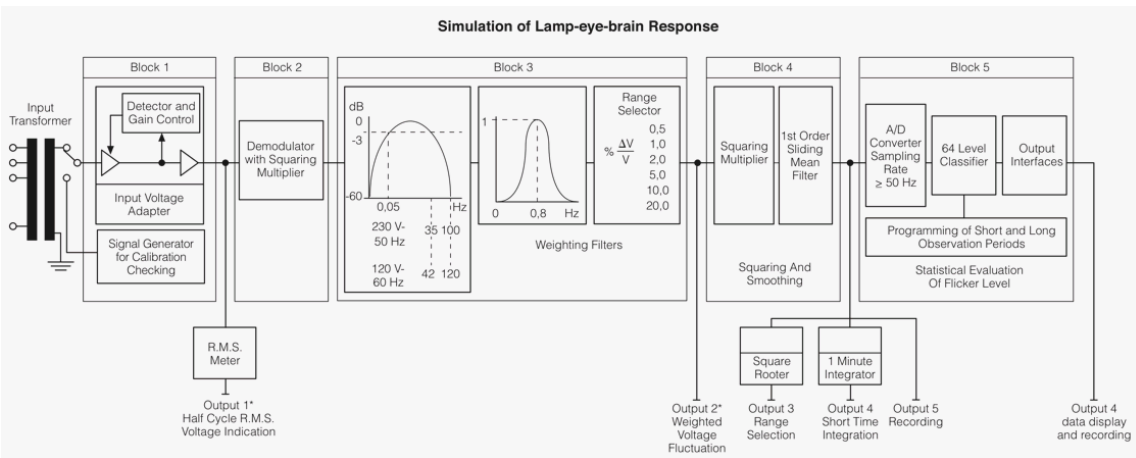
Pure resistive load – ideal for utilities

2002: incandescent = 98.1% of all residential lighting
13% of total energy usage

Light Flicker from RMS voltage variations well known, predictable, and repeatable -> well developed IEEE standards for PQ



FLICKER TOLERANCE CURVE FROM IEEE STD. 141-1993/IEEE STD 519-1992



http://www.johnsonconsults.com/presentations/Residential%20Lighting%20in%20the%20US-July%20182004%20DMEA.pdf

Modern LED “Bulb” – Design

Complex electrical design w/ multiple subsystems
Multiple power supplies
Incoming AC voltage rectified and re-regulated – not used directly
Nonlinear logic, microprocessor operation, complex state
Advanced features such as WiFi, audio in/out
Connected to other equipment

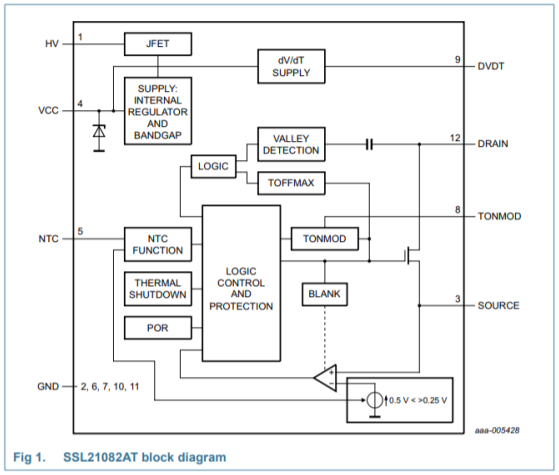
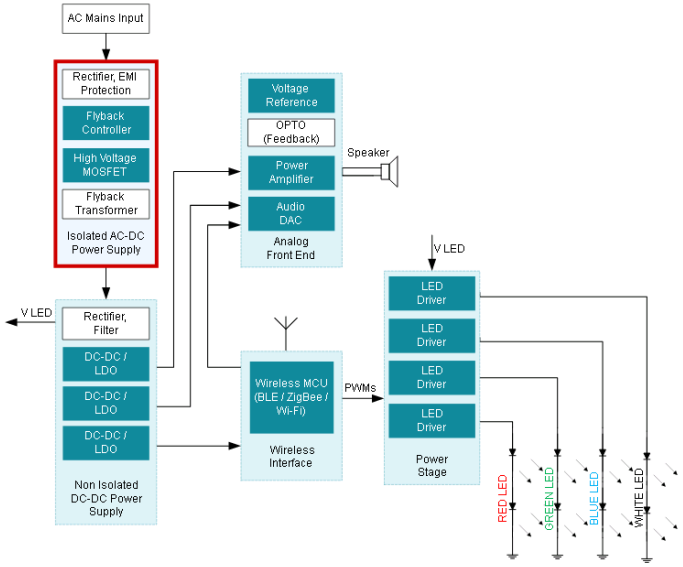


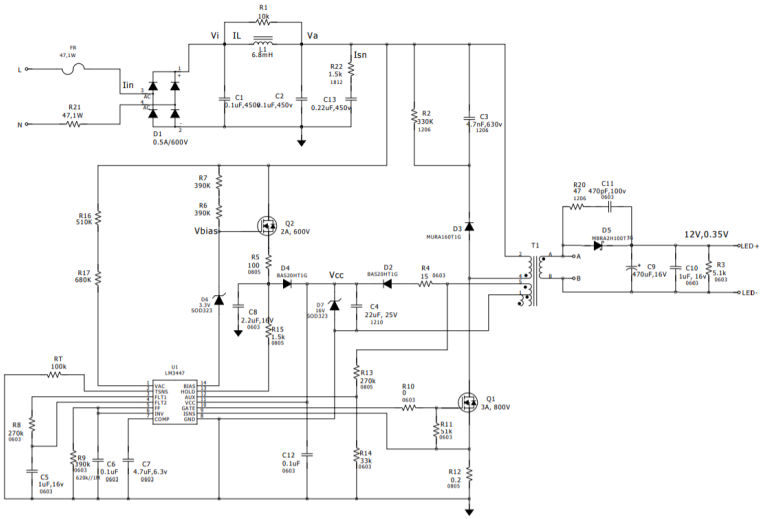
Fig 1. SSL21082AT block diagram

Simple Dimmable LED driver
http://www.ti.com/lit/df/slura44/slura44.pdf



eufy Lumos Smart Bulb By Anker- White & Color, Tunable White, Multiple Colors, 9W, Works With Amazon Alexa & Google Assistant, No Hub Required, Wi-Fi, 60W Equivalent, Dimmable LED Light Bulb, A19, E26
by eufy
65 customer reviews
32 answered questions
Note: This item is only available from third-party sellers (see all offers).
Available from these sellers.
WORKS WITH ALEXA
Control this product with your voice through select Alexa devices.

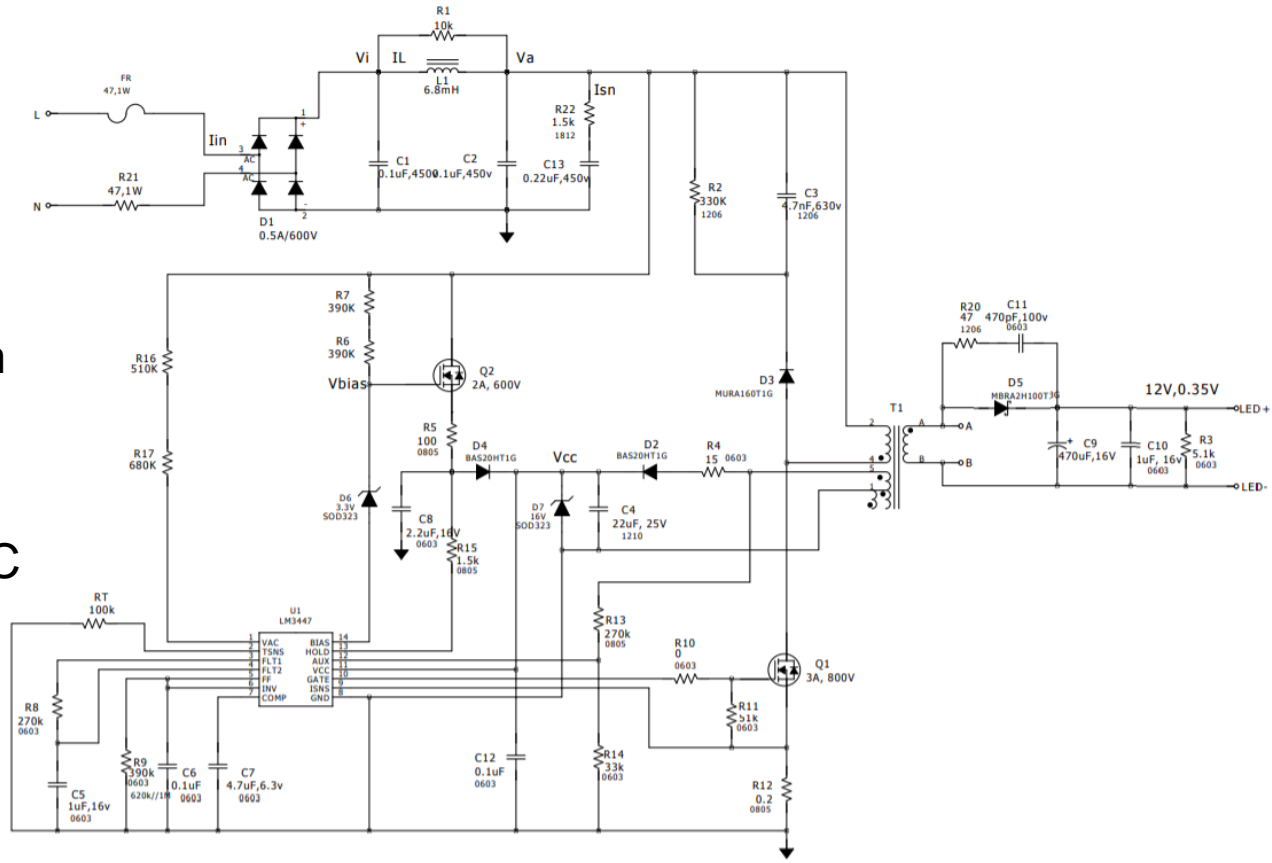
WiFi bulb – 802.11 b/g/n
32 bit ARM, 1MB Flash
14 dBm at 2.4 GHz
150 Mbit/sec – enough throughput for a mid-sized town in the 1950s
Adds ~$3 to production cost



http://www.ti.com/solution/lighting_bulb_replacement

Modern LED “Bulb” – Design

- Immediate AC->DC rectification
- DC hold-up time depends on high quality capacitor selection
- Dimmer sensing relies on analog waveform detection of SCR dimmer pattern
- Component selection determines sensitivity to AC power quality, esp. over time – could be good, or poor



http://www.ti.com/solution/lighting_bulb_replacement

LED “Bulb” – Consumer Perspective

- Advanced features – any color, any brightness, timers, remote control
- Long life – will become obsolete before it fails
- Low power – so low, power can be ignored
- Part of a larger networked system – smart home, phone
- Complex state – different modes, timers, etc.
- Same equivalent cost as 1950’s colored bulb

Sunnest 120 Colors LED Light Bulb, Dimmable E26 LED Light Bulb, 10W RGBW Color Changing Light Bulb with Remote Control, Decorative Lights, Mood Light Bulb, Great for Home Decor, Stage, Party and More

by SUNNEST

383 customer reviews | 64 answered questions

Amazon's Choice for "color led light bulbs"

Price: $11.99 ✓prime

Your cost could be $1.99. Eligible customers get a $10 bonus when reloading $100.

Color: Rgb+w

$15.99 ✓prime | $11.99 ✓prime

So advanced, it’s assumed it will outperform incandescent bulbs in every way

Hue lights

These smart and energy-efficient LED lights come in a wide variety of shapes, sizes, and models to suit your space.

Hue Bridge

The heart of your Philips Hue system, the Bridge acts as a smart hub, connecting your devices to your smart lights. You can add up to 50 Philips Hue lights and accessories to one Bridge.

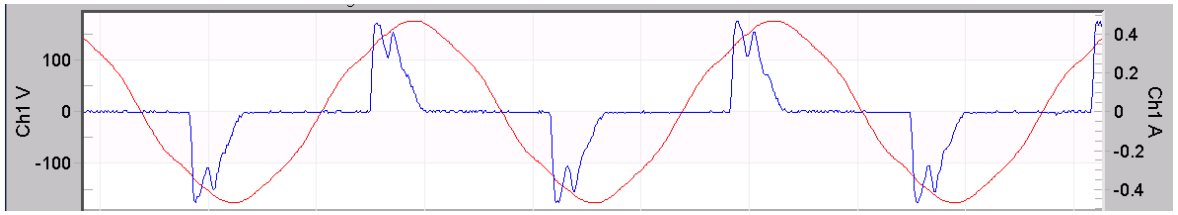
Hue app

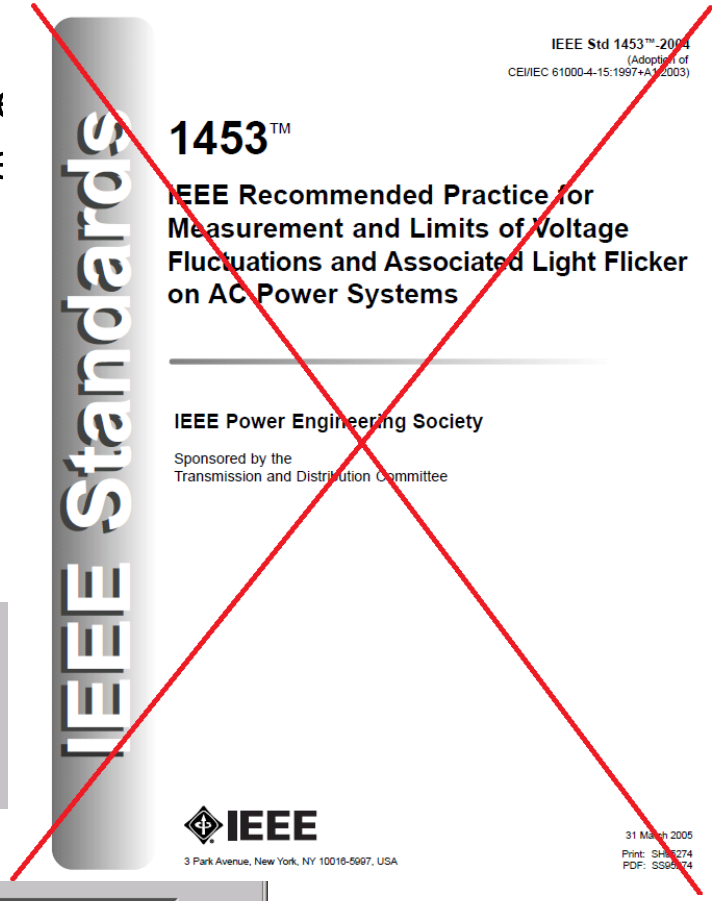
Control your smart lights quickly and conveniently with the Philips Hue app.

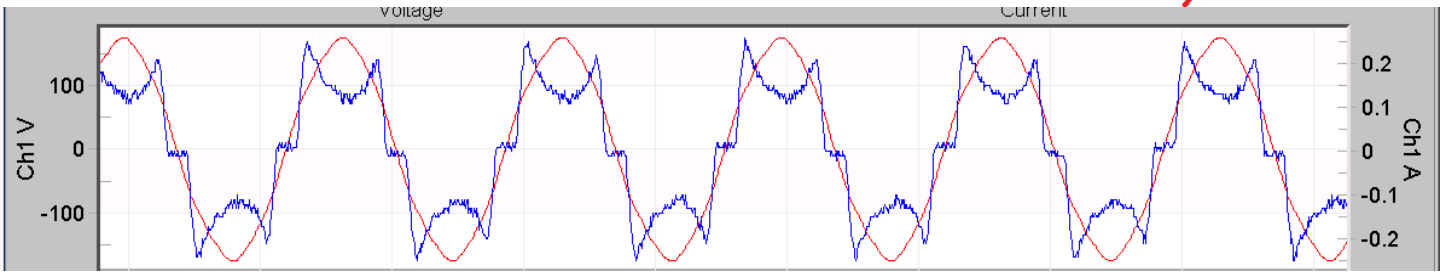
LED “Bulb” – Utility Perspective

- High current distortion
- Momentary “blinks” may reset complex light state
- Unpredictable relationship between RMS voltage and LED light output
- LED controller sensitive to power line carrier AM systems, AC feeder events from upstream

Modern load characteristic – load behavior is only indirectly related to AC voltage – difficult to characterize or predict







Modern Power Load Example – Variable Frequency Drive

Conversion of AC to DC breaks direct link between utility AC and load – motor never sees utility voltage

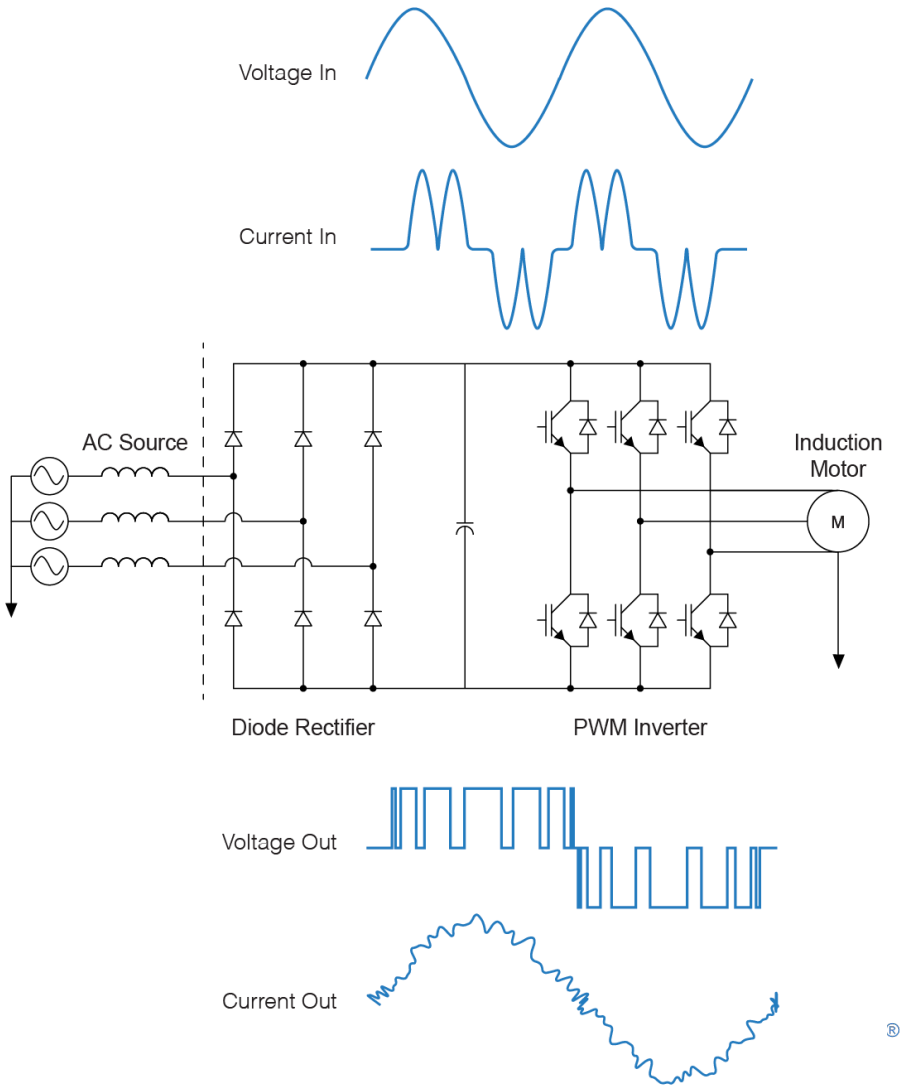
VFD Controller is in charge, determining motor operation and judging incoming PQ

VFD benefits:

- No motor-inrush current – eliminates voltage sags
- High efficiency
- Very fine-grained control of motor operation

VFD problems:

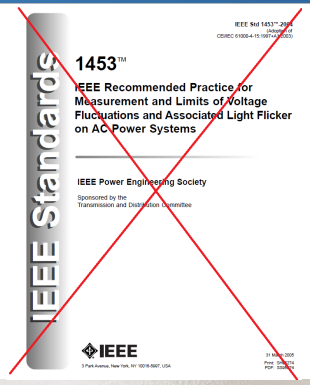
- High current harmonic distortion
- Voltage notching, transients from overlapped switching
- Complex VFD threshold programming – can be overly sensitive to AC power



Modern Load Characteristics

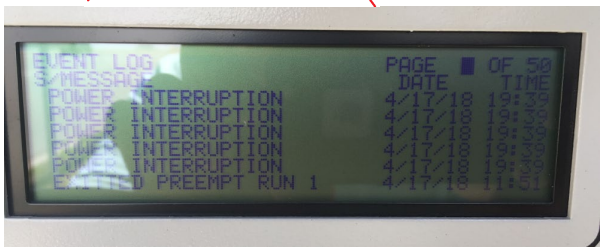
Disconnect between utility voltage and load performance

- Actual load doesn't directly utility incoming AC voltage to do work
- Load driven by synthesized AC/DC from controller
- Relationship between utility voltage and load performance much blurrier



Increased/different sensitivity to upstream PQ events

- Smart load microcontroller the judge of PQ problems, not the load
- PQ sensitivity driven by load internal power supply design, not the actual load itself
- Extra layer of PQ sensitivity – controller thresholds

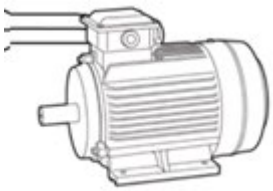


Higher proportion of harmonic loads

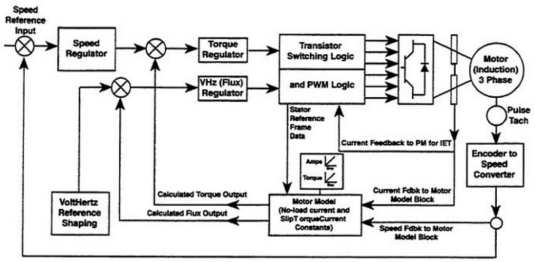
- switching power supplies are inherently nonlinear, drawing harmonic current
- plummeting cost of high power supplies turning even simple resistive loads into switched loads

Increased load complexity

- Complex power supply
- Complex controller
- Complex load state



VS



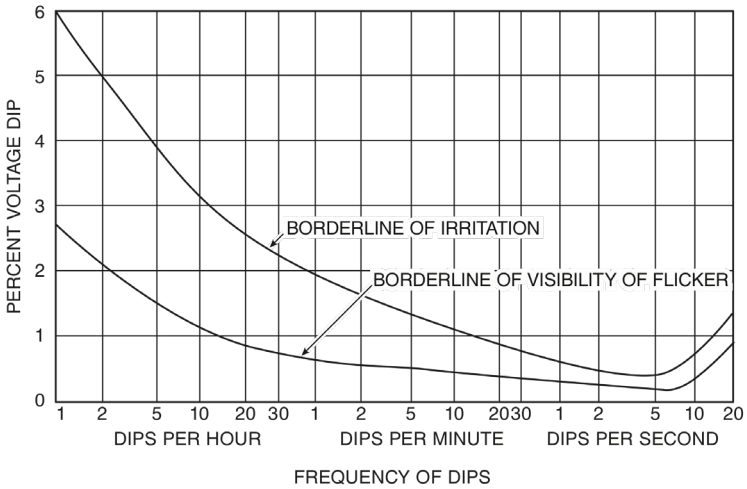
Utility Challenges – PQ Standards

Traditional PQ standards out of date, not as useful for predicting equipment compatibility

Example: modern lights

Incandescent:

- Light flicker well determined based on physics of glowing filament
- IEEE 141 and 1453 provide voltage variation limits based on perceptible light flicker



FLICKER TOLERANCE CURVE FROM IEEE STD. 141-1993/IEEE STD 519-1992

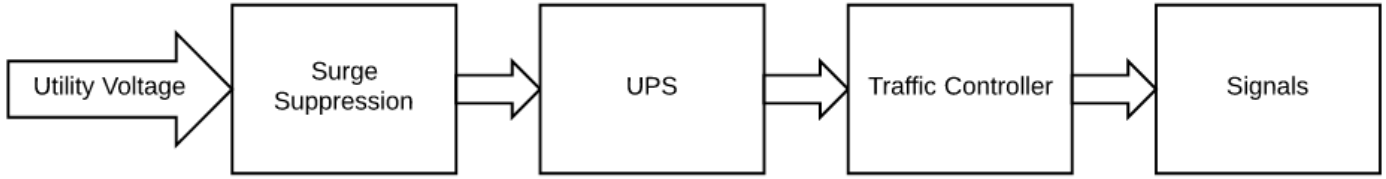
LED:

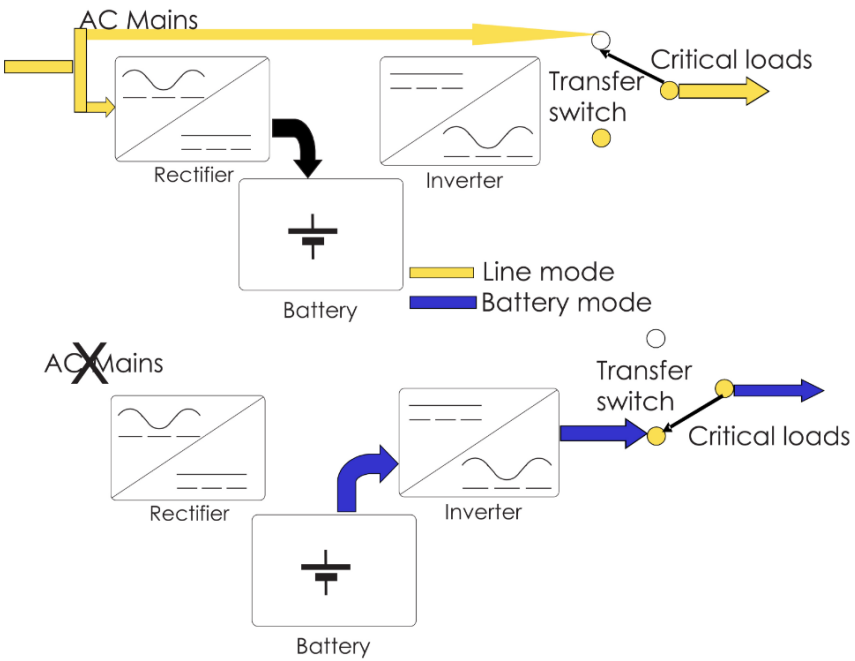
- Light output based on internal power supply output, not utility voltage
- operation in presence of voltage sags depends on power supply design – internal energy storage, etc.
- No standardized LED driver response to AC voltage changes
- LED bulb response often nonlinear

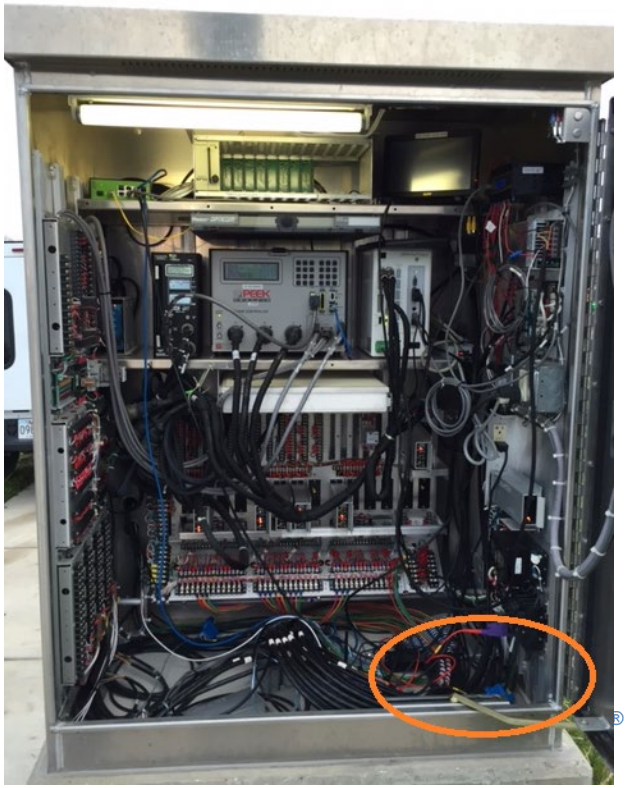
Voltage sag causes LED bulb to reset from purple to white – is that light flicker?

Utility Challenges – Increased Sensitivity

Example: UPS-based traffic signal controller



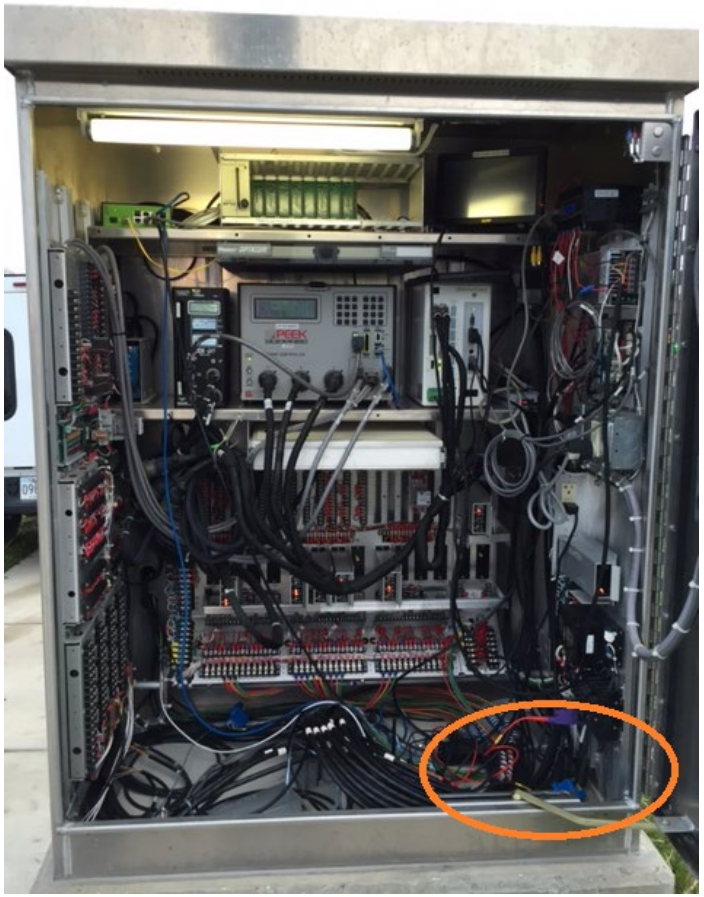


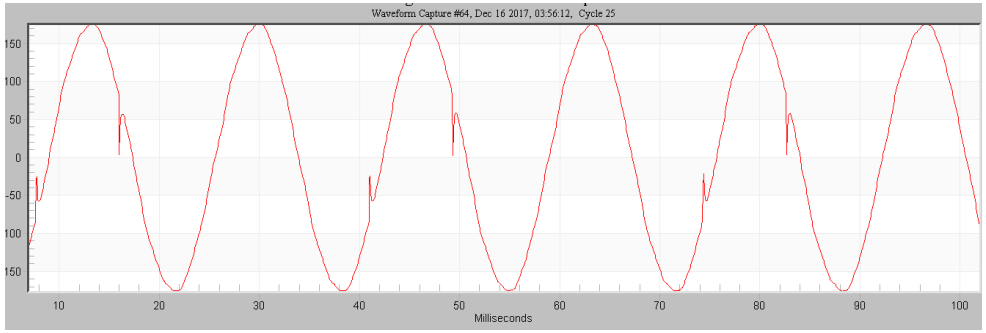


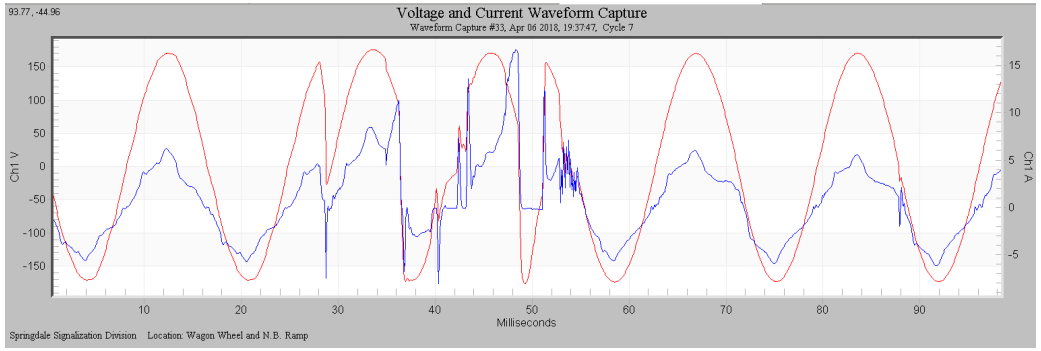
Utility Challenges – Increased Sensitivity

Nonlinear or “smart” operation can magnify PQ events

UPS-based traffic signal controller
Benign powerline carrier meter-read signal causes traffic signal UPS to operate







Utility Case Study – Residential LED light “flicker”

Electric Coop in Missouri
LED lights “flickering”
Still no resolution
Specific LED bulb may be obsolete before problem solved

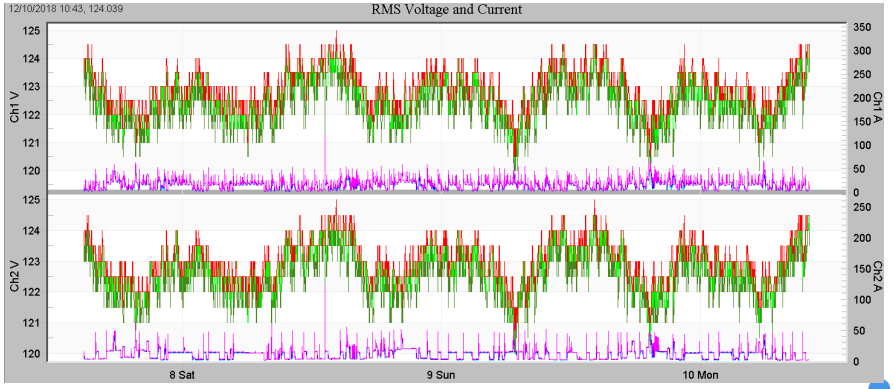
video-1544823235.mp4

A member on our system is having problems with flickering LED lights on one circuit in their home though our monitor does not show any issues. They have indicated that the problem is only on one leg in the home. We switch our leads in the meter can and after switching the leads and checking all upstream connections the problem still persists. I've attached some of our monitor data and a video of one of the flickering lights along with the PMI version below. Any input would be helpful.

When we first changed the leads in the meter can the owner told us the same lights were still flickering, but we have not heard anything since then. As far as we know it is still the same. The voltage readings that have shown up in the event report were all able to be traced back to an outage or temporary fault on the feeder. Most of the days look fine and the voltage levels stay within the acceptable range of 114-126 V. Even within this range the LEDs will flicker.

There are a few dimmable LED fixtures that are flickering, but not all of the fixtures having this problem are dimmable. They have all LEDs in their home but not all of the LEDs are having this issue. We took over some of our own LED bulbs and they did the same thing. We do not have a PMI monitor on the location at this time, but Joe is sending us a demo wall plugin recorder to see if we can identify the problem that way.

We've checked the neutral and connections, all upline devices and connections as well as replaced the transformer.



Power Quality 102

- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads and PQ
- **Further Reading**

Power Quality Standards
Partial List

ANSI C84.1-1995: American Nations Standard for Electric Power Systems and Equipment: Voltage Rating (60 Hertz): Nominal Voltages, Ranges and % Unbalance in 3 Phase Systems

IEEE 519:2014 IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

IEEE 1453D2 (1453.1): Recommended Practice for Measurement and Limits Of Voltage Fluctuations and Associated Light Flicker on AC Power Systems

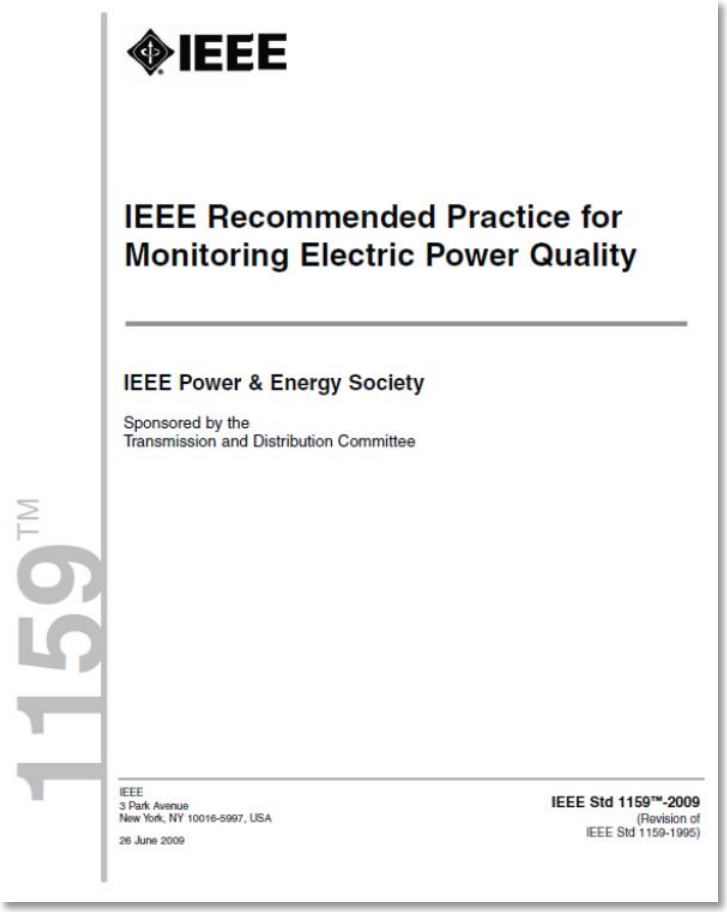
IEEE 1159, 2009: Recommended Practice for Measuring Electric Power Quality

IEEE C62.41: Recommended Practice on Surge Voltages in Low Voltage AC Power Circuits

PQ Standards- PQ Monitoring

IEEE 1159 *Recommended Practice for Monitoring Electric Power Quality*

- Provides guidelines for power quality monitoring
- Standard definitions for short term and long term power quality disturbances, distortions
- Provides common language for identifying and describing power quality events
- PQ monitoring objectives: effects on equipment settings
- Types of monitoring: predictive, diagnostic
- Disturbance effects on customer equipment
- Recommended practices, techniques
- Selecting monitoring location


IEEE

IEEE Recommended Practice for Monitoring Electric Power Quality

IEEE Power & Energy Society

Sponsored by the
Transmission and Distribution Committee

1159™

IEEE
3 Park Avenue
New York, NY 10016-5997, USA

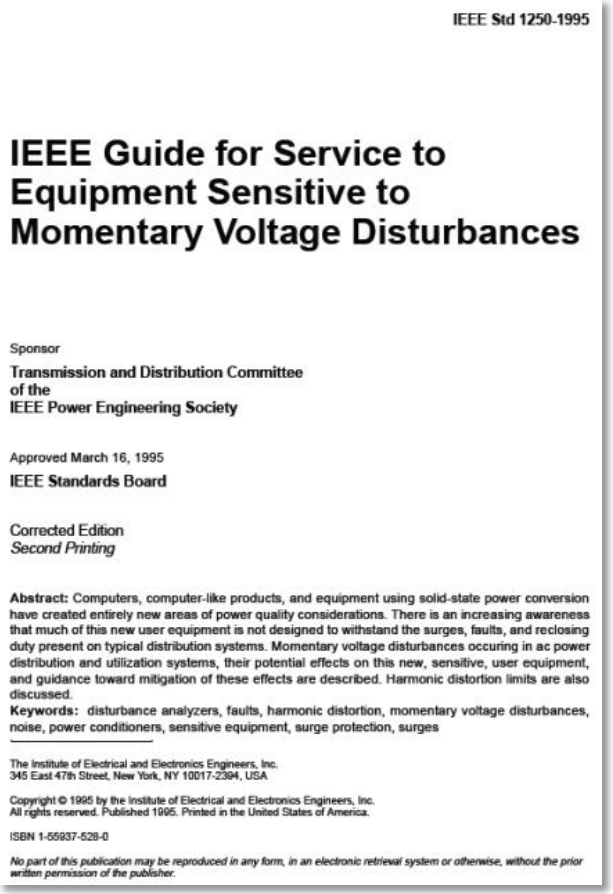
26 June 2009

IEEE Std 1159™-2009
(Revision of
IEEE Std 1159-1995)

PQ Standards – Voltage Quality

IEEE 1250: *Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances*

- Describes momentary voltage disturbances, distortions, and causes in AC power distribution systems
- Effects on sensitive equipment
- Describes types of sensitive loads, ride-through capability
- Tolerance of computers to voltage magnitude, duration variations – CBEMA/ITIC curves
- Solutions to problems caused by voltage disturbances



IEEE Std 1250-1995

IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances

Sponsor

Transmission and Distribution Committee of the IEEE Power Engineering Society

Approved March 16, 1995

IEEE Standards Board

Corrected Edition
Second Printing

Abstract: Computers, computer-like products, and equipment using solid-state power conversion have created entirely new areas of power quality considerations. There is an increasing awareness that much of this new user equipment is not designed to withstand the surges, faults, and reclosing duty present on typical distribution systems. Momentary voltage disturbances occuring in ac power distribution and utilization systems, their potential effects on this new, sensitive, user equipment, and guidance toward mitigation of these effects are described. Harmonic distortion limits are also discussed.

Keywords: disturbance analyzers, faults, harmonic distortion, momentary voltage disturbances, noise, power conditioners, sensitive equipment, surge protection, surges

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

ISBN 1-55937-528-0

Further Reading

- IEEE 519:1992 – good background
- IEEE Std C57.110-1986 – IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Current
- IEEE Std. 1159-2009 – IEEE Recommended Practice for Monitoring Electric Power Quality
- IEC 61000-4-7 – General Guide on Harmonics and Interharmonics Measurement
- IEC 61000-4-30 – Power Quality Measurement Methods
- IEEE Std. 1453 – IEEE Flickermeter Specification

- PMI whitepapers: https://library.powermonitors.com/

IEEE Standards

1159: Monitoring PQ
519: Harmonics
1453: Voltage Flicker
1459: Power Formulas
1250: Improving PQ
1695: Stray, Contact Voltage
Emerald Book: grounding
www.ieee.org

Thank you for attending!