Surge Protection 101 and Harmonics

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2021

Agenda

- SPD Design Goals & Characteristics
- Surge Activites Defined
- History of NEC Surge Requirements 2008-11
- Overview of 2014 NEC SPD Code Change
- Studies and Data Behind 2017 Code Changes
- Overview of 2017 NEC SPD Code Additions
- Review of Proposed/Rejected 2017 SPD Code Change Recommendations
- SPD NEC 2020 Addition
- Best Practices in Applying SPD’s/Discussion of Important Standards
- Harmonic Correction – Issues and Solutions

What is Power Quality?

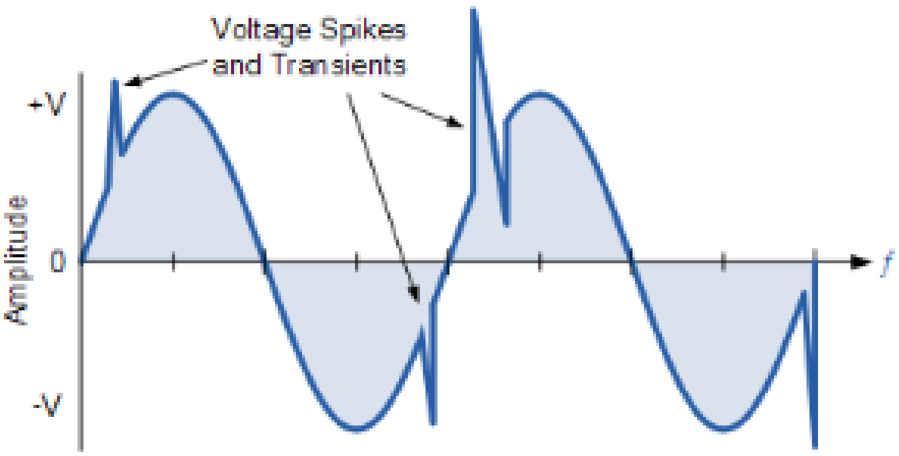
- "The concept of powering and grounding **sensitive** electronic equipment in a manner that is suitable to the operation of that equipment."[1]
- "The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment (and compatible with the premise wiring system and other connected equipment)"[2]
- The definition of Power Quality cannot be limited to the characteristics of the supply power. The definition must also include the requirements of the load and neighboring loads.

[1] **IEEE 1100-1992**

[2] **IEEE 1100-1999**

Voltage Transients

Definition: a high rising voltage condition on one or more phases lasting 2 milliseconds or less



Characteristics:

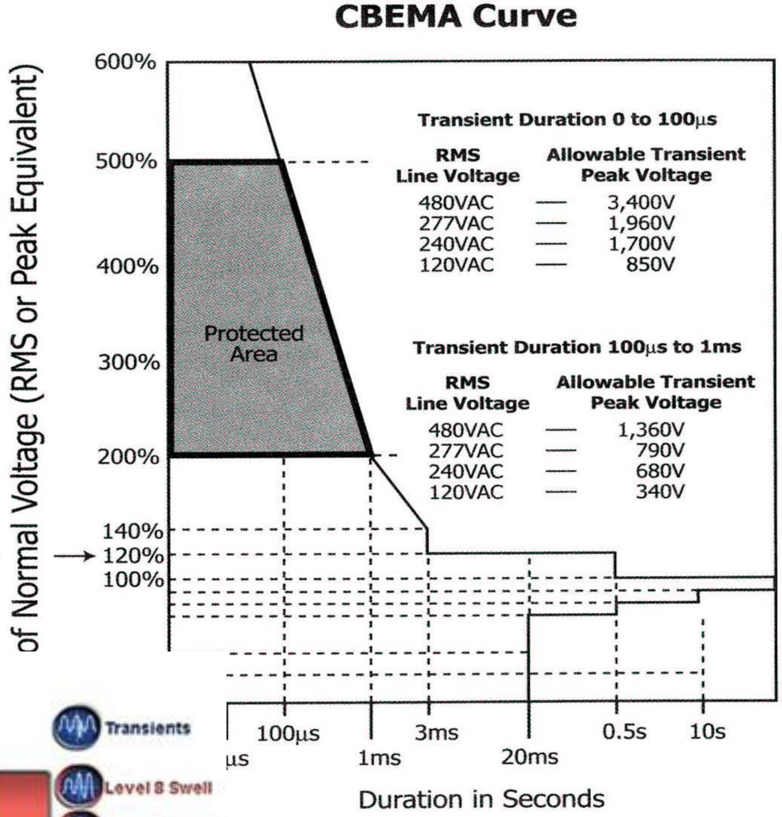
- Duration - 50ns to 2ms
- Rise time - 10ns to 100µs
- Frequency - 20Hz to 20MHz (ringing transients)
- Voltage - up to 20kV

Surge Protection Relating To CBEMA or ITEC Curve

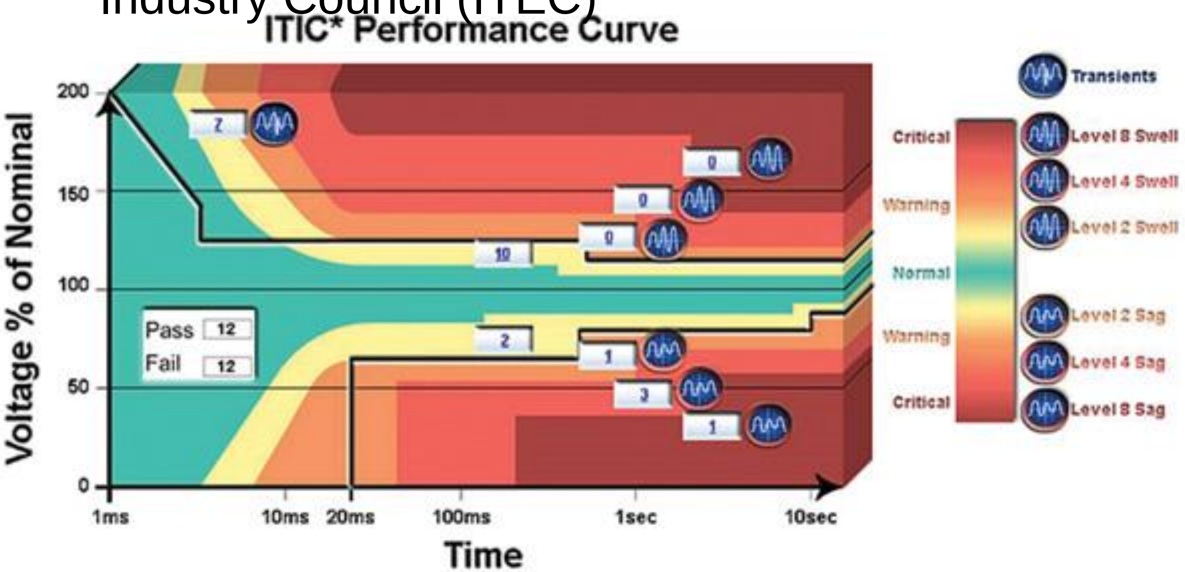
Computer Business Equipment Manufacturers Association (CBEMA – From Mid 1990's)

200% to 500% (100µs to 1ms) defines the maximum permissible suppressed transient voltage levels for reliable computer operation.

Protection starts here



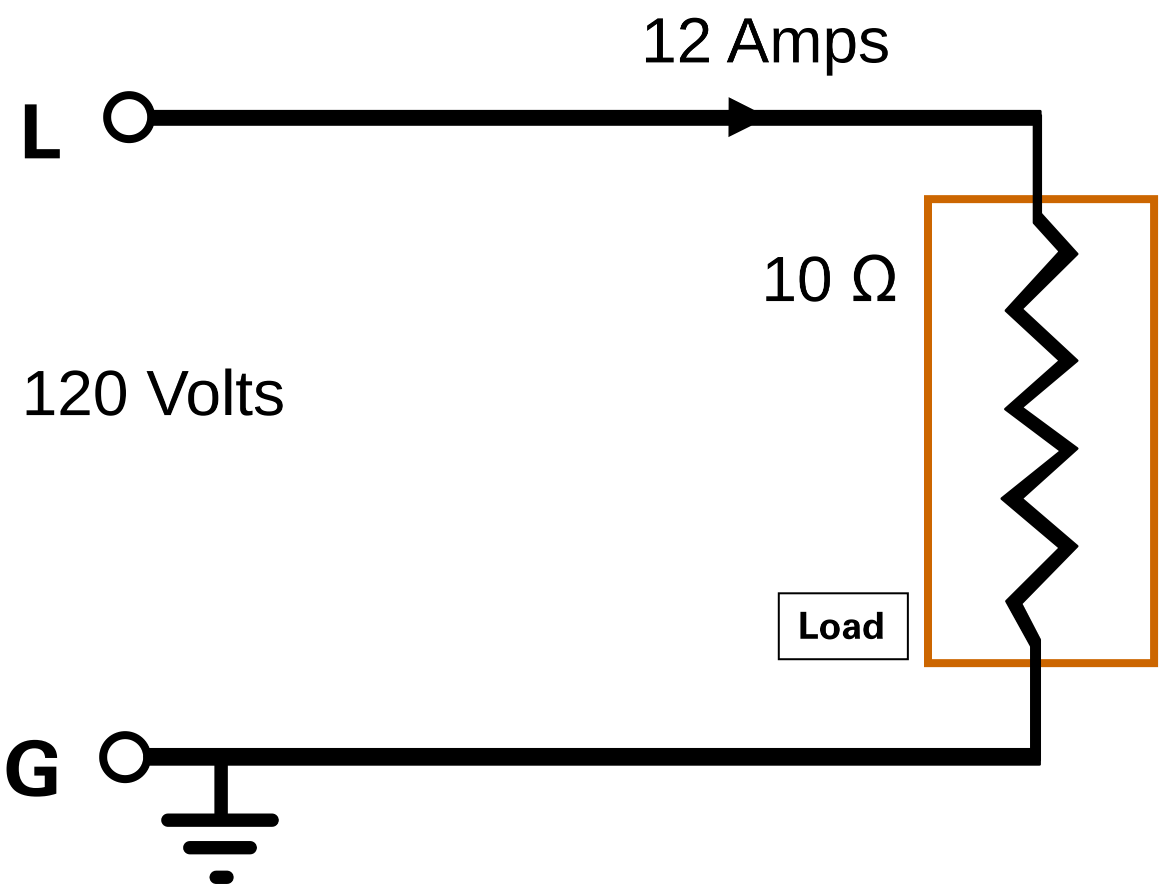
Information Technology Industry Council (ITEC)



SPDs Act As “Pressure Relief Valves”

- The ideal SPD shunts harmful surge current to **ground** under a surge condition and appears as a high impedance under normal operating conditions
- The SPD is a self sacrificing device – bearing the brunt of harmful surge currents

Normal Operation - No Protection



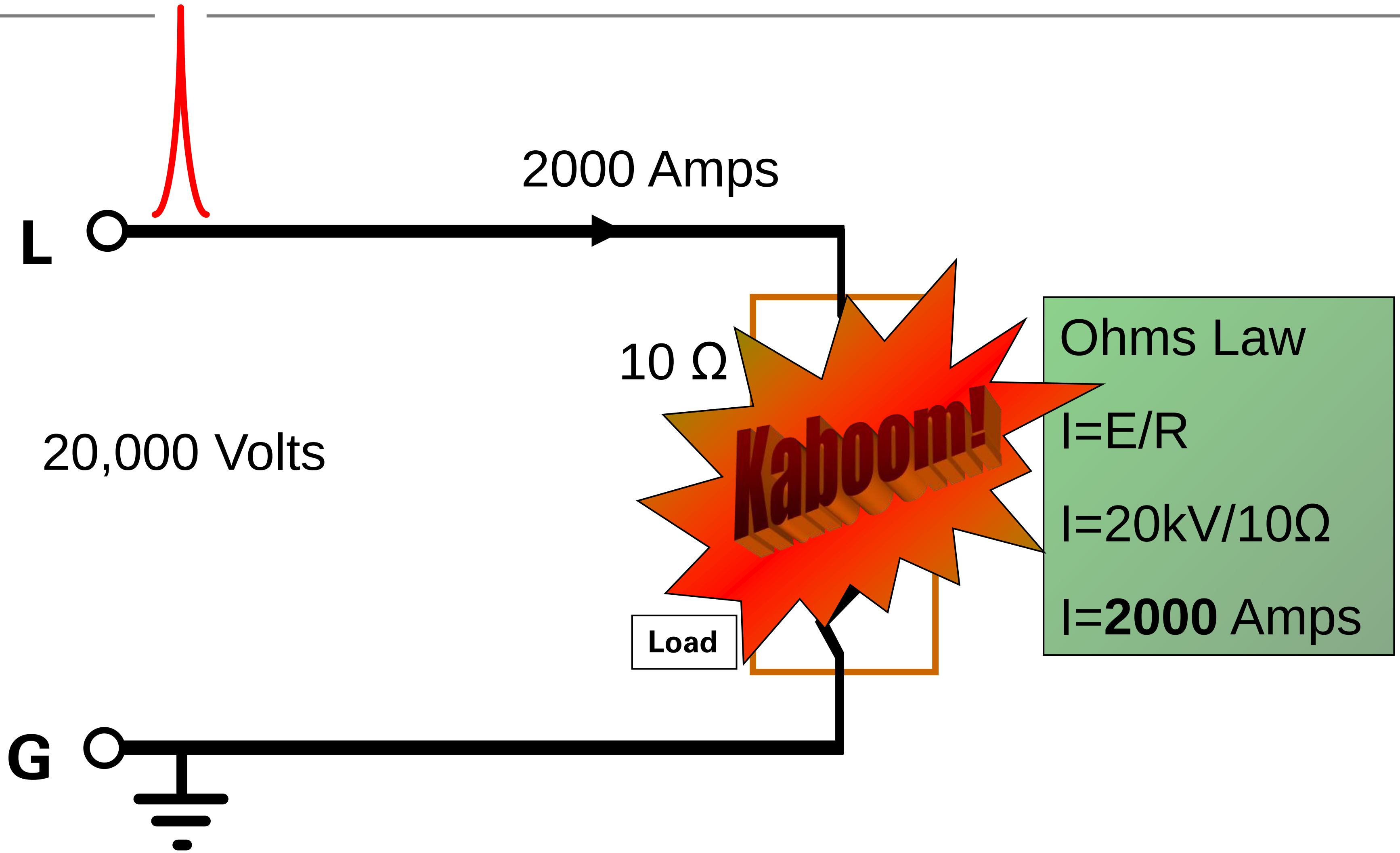
Ohms Law

I=E/R

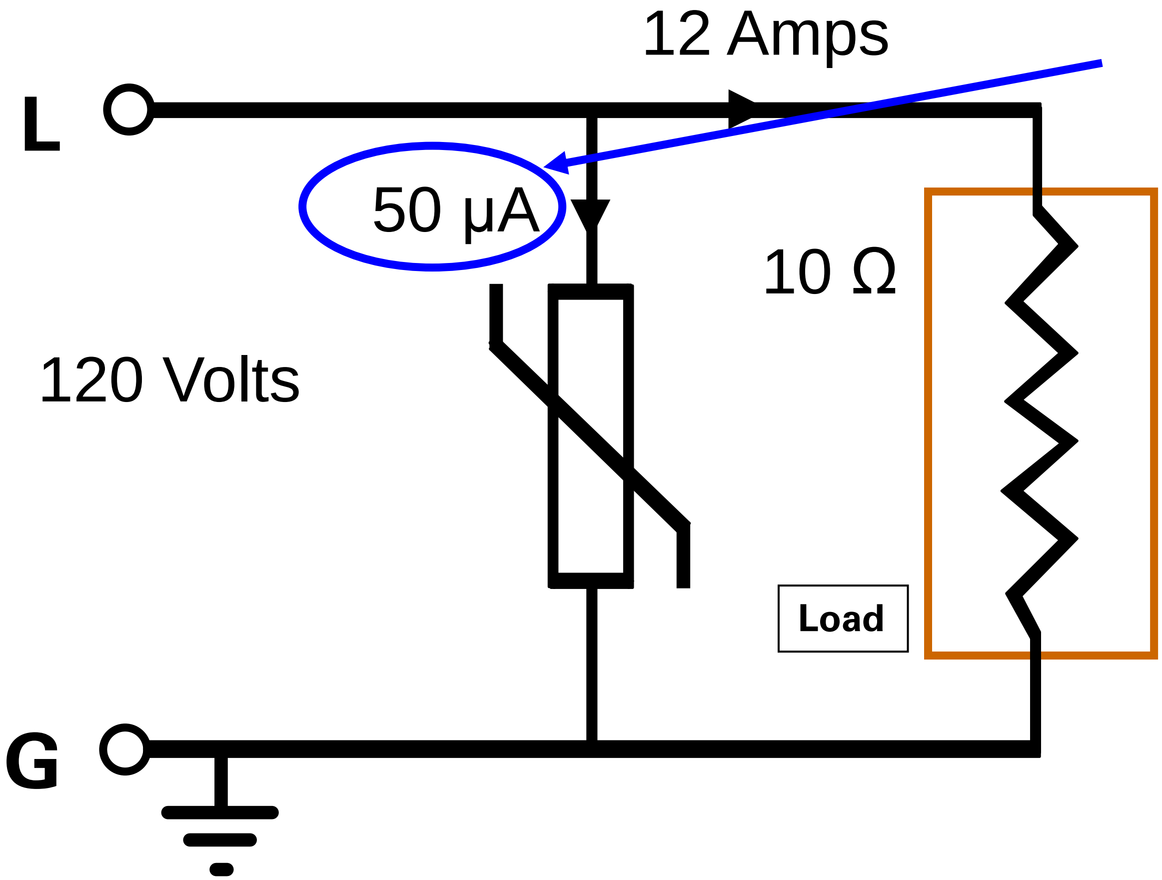
I=120V/10Ω

I=**12** Amps

Surge - No Protection



Normal Operation - Protection



Leakage current has very negligible effect on circuit

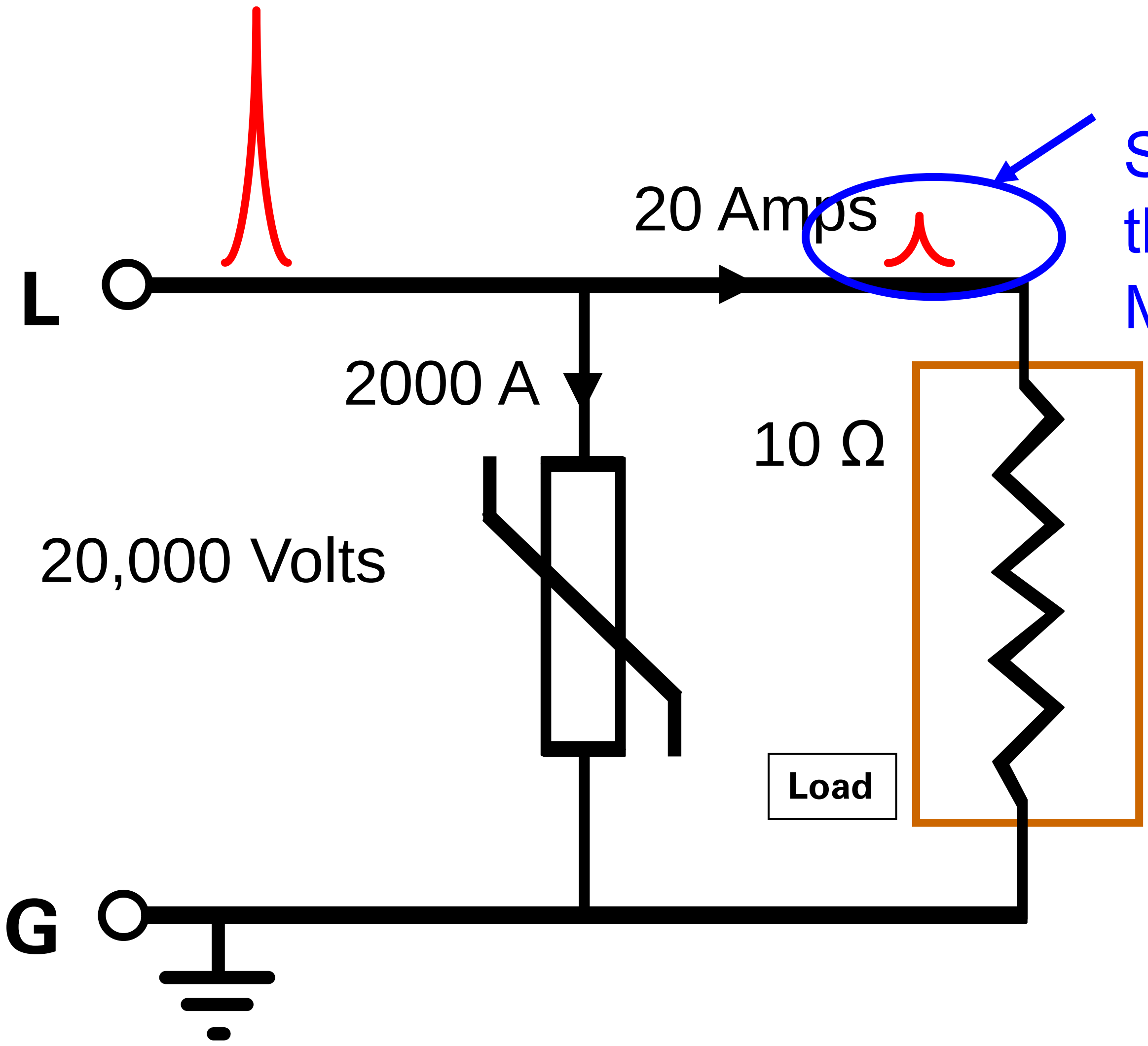
Ohms Law

I=E/R

I=120V/10Ω

I=**12** Amps

Surge - With Protection



Some residual “let-through” voltage. Manageable by load

Ohms Law

I=E/R

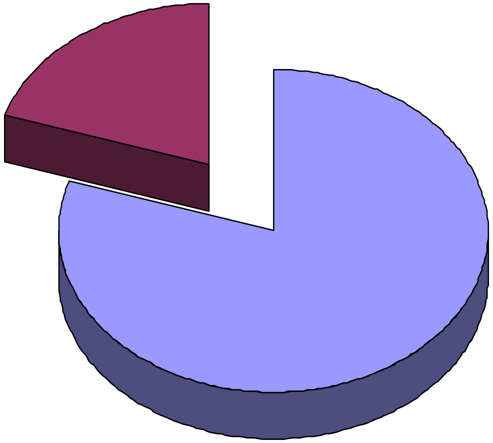
I=200V/10Ω

I=**20** Amps

Question!

What is the Primary Surge event Culprit??

Where Do Voltage Transients Come From?



80% Internal

- Load switching
- Short circuits
- Capacitor switching
- Imaging equipment
- VS Drives
- Arc welders
- Light dimmers

20% External

- Lightning
- Capacitor switching
- Short circuits

Symptoms of Voltage Transients

According to the Surge Protection Institute of NEMA, the

Symptoms of Surge Damage are:

- Computer lock-ups
- Unexplainable data corruption
- Equipment shutdown
- Flickering lights
- Premature failure of electronic ballasts or printed circuit boards

There is no such thing as a transient free facility. Many people do not realize that their company's productivity and profitability is being significantly impacted by the effects of transients*. The problems described above result in billions of dollars of lost profits to U.S. businesses every year.*

http://www.nemasurge.org/surge-damage/

Symptoms of Voltage Transients

The Surge Protection Institute of NEMA groups Surge Damage into three categories:

Disruptive effects:

- These effects are usually encountered when a transient enters the equipment by inductive coupling (aka magnetic flux). The energy source for this inductive coupling can act on the data output lines that integrate an electronic installation. The electronic components then try to process the transient as a valid logic command. The result is system lock-up, malfunction, erroneous output, lost or corrupted files, and a variety of other undesirable effects.

Dissipative effects:

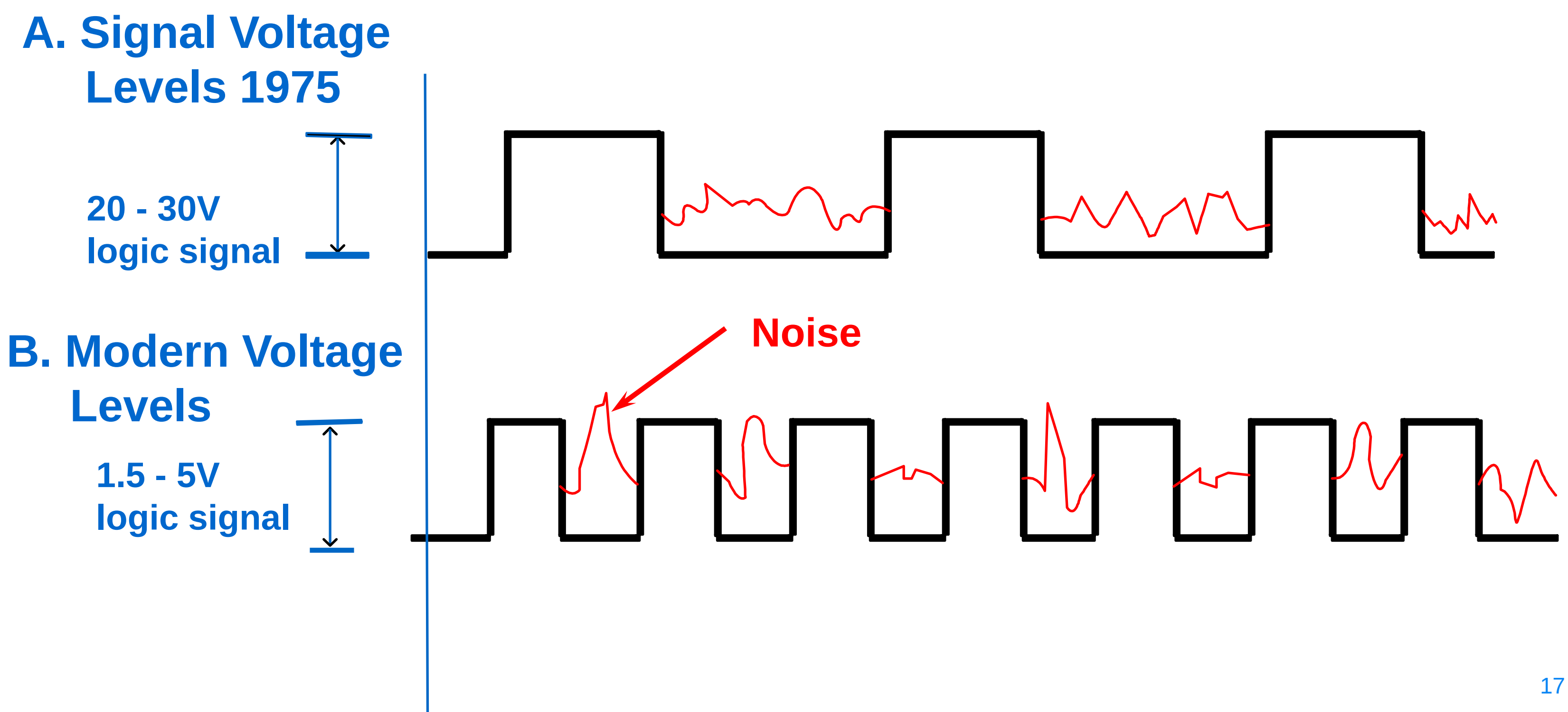
- These effects are associated with repeated stresses to IC components. The materials used to fabricate IC's can only withstand a certain number of repeated energy level surges. After long-term degradation, the device fails to operate properly. The failure is due to the cumulative build-up of transient-created stresses which result in arc-overs, shorts, open circuits, or semiconductor junction failures within the IC.

Destructive effects:

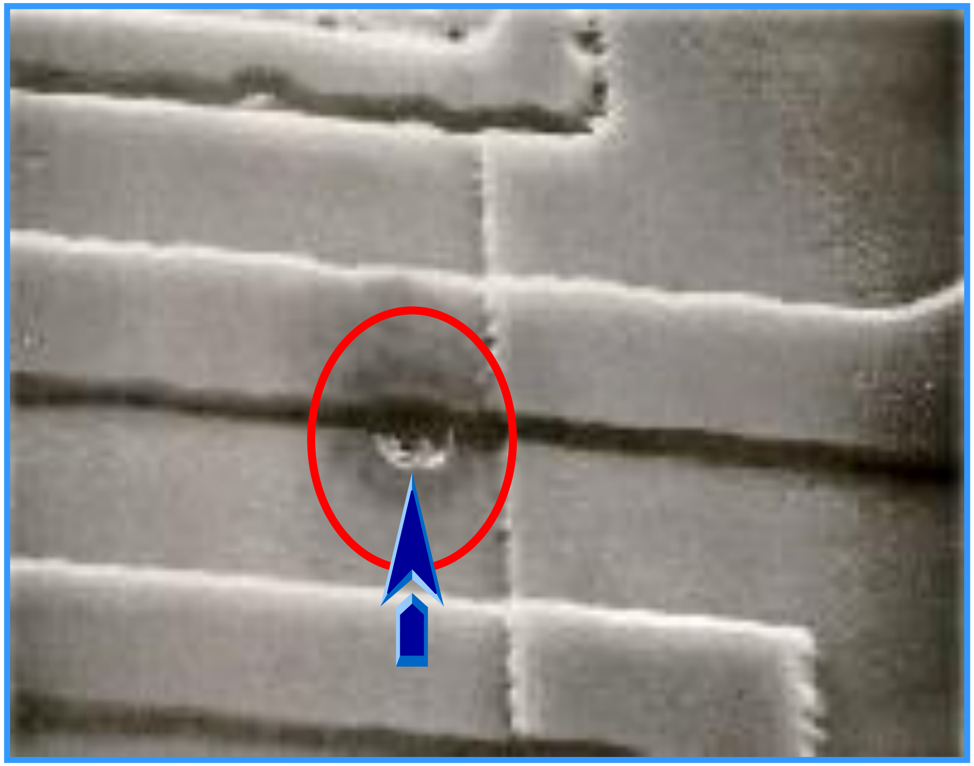
- These effects include all conditions where transients with high levels of energy cause equipment to fail instantaneously. Very often, there is actual physical damage apparent, like burnt PC boards or melting of electronic components.

Disruptive Damage

Surge disturbances can create physical damage and even affect logic signals in electronic equipment. Noise disturbances can be interpreted as legitimate ON/OFF signals, resulting in operating errors, process interruption and equipment downtime.

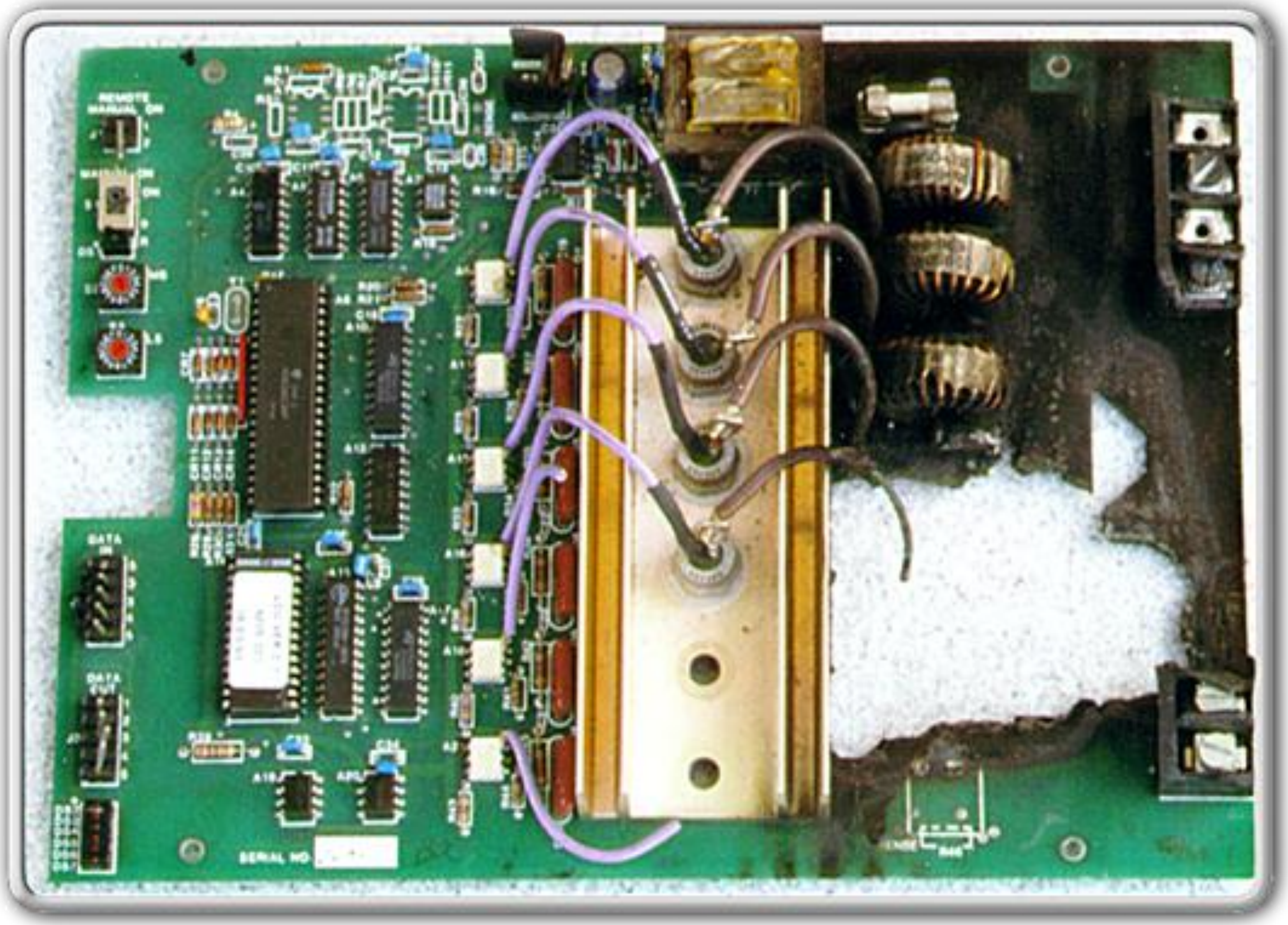


Dissipative Damage



- Damage to trace on electronic printed circuit board. Known as "Electronic Rust"
- This type of "Cumulative" damage will lead to failure

Destructive Damage



Catastrophic damage to equipment can occur as a result of a high energy transient voltage event

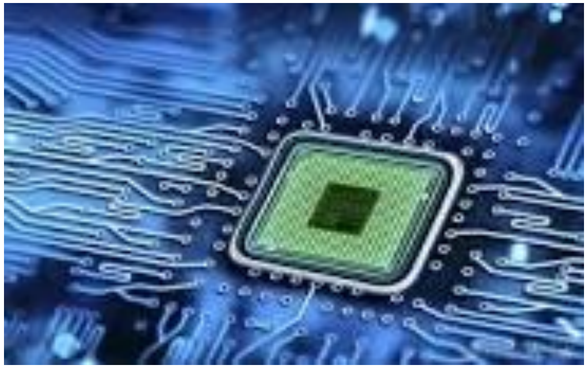
Clean Power is a Necessity

Microprocessors are everywhere!

- Technology revolution has driven microprocessors in all equipment and processes
- Microprocessors are getting smaller, faster, and more SENSITIVE

Lightning and other natural phenomena is major cost to productivity.

- According the Lightning Safety Institute, lightning strikes in the US cost over <u>$5 Billion</u> per year in insurance claim losses.
- The $5 billion does not typically include costs of down time and other damage that does not meet claim requirement



Customers must invest $$ in surge protection or expect down time and equipment losses

examples

Regulations and Applications

- NEC Past and Recent Code Adoptions
- Application of SPD’s in NEC world
- Data Supporting Adoption
- Looking to the Future of NEC
- Applying Best practices

2008 NEC Code Requirement – 708.20 Critical Operation Power Systems (COPS)

In 2008 the NEC began requiring surge protection. The first article added was 708.20 regarding Critical Operation Power Systems (COPS). NEC states at the beginning of Article 708 that Critical Operation Power Systems is those systems so classed by municipal, state, federal, or other codes by any governmental agency having jurisdiction or by facility engineering documentation establishing the necessity for such a system. These systems include but are not limited to power systems, HVAC, fire alarm, security, communications and signaling for designated critical operations areas

2011 NEC Code Requirement – 694.7 (d) Wind Applications

In 2011 the NEC began requiring surge protection for wind generation by adding Article 694.7 (d). This section was slightly updated in 2017 to add the word “wind” and now reads “ A surge protective device shall be installed between a wind electric system and any loads served by the premises electrical system”

IEEE 1100-1999: The definition of Power Quality cannot be limited to the characteristics of the supply power. ***The definition must also include the requirements of the load and neighboring loads.***

2014 NEC Code Requirement – 700.8 Emergency Panels

- Article 700.8 was added covering Emergency Systems. The NEC defines emergency systems in section 700.1
- Reasoning for change - 2014 NFPA Study found 34.7% of Smoke Detectors, 33% of emergency lighting and 18.7% CO2 Detectors were found to be damaged due to surge activity

The purpose of an emergency system is to protect human life by providing the essential power and illumination [700.1] for egress and the operation of equipment such as ventilation, elevators, fire pumps, and communication systems.

NEC 2014 and Progression to NEC 2017

- Why not more additions in 2014 beyond 700.8?
  - More data collection is needed to assess losses related to electrical surges in facilities, and to address the potential impact electrical surge protection devices would have in mitigating these losses.
- Solution – More Independents Studies to Quantify the issues
  - Fire Protection Research Foundation Study began in 2014, in part sponsored by the NFPA
  - Panel consisted of NFPA Engineers, Insurance Company Representatives, NECA Representatives, and the U.S. Consumer Product Safety Commission (CPSC)

FPRF Findings

- Study Involved over (100) Participant Locations.
- Summary of Findings
  - (48%) Of participants noted that their facility had experienced unexplained Process Interruptions, Catastrophic failure or damage of electrical or electronic equipment due to a lightning event or voltage surge.
  - Premature failure of electrical or electronic equipment were frequently reported in (41%) of events.
  - More than a third (38%) noted the occurrence of lockup of computers or industrial process systems

FPRF Findings - Continued

- For most respondents (61%), it cost less than $10,000 to repair the damage resulting from voltage surges, but a sizable number (16%) reported damage costing in excess of $150,000 to fix.
- Nearly 95% of those who reported having experienced a surge event resulting in equipment damage indicated that they subsequently purchased surge protection. Virtually all of those who did so, purchased immediately or within three months of the event and most noted significant reduction in failures and disruptions.
- Over 65% reported downtimes associated with voltage surges of 6 hours or more

FPRF Findings - Continued

Respondents reported damage or loss of function of the following types of life safety equipment because of voltage surges:

- Smoke detector (34.7%)
- CO2 detector (18.7%).
- Fire alarm system (41.3%).
- Security system (49.3%).
- Ground fault circuit interrupters (22.7%).
- Emergency lighting (32.0%)
- Emergency generators or backup power (33.3%).
- Fire pumps (12.0%).
- Elevators or escalators (24.0%).
- Safety interlocking systems on machines (26.7%)

2017 NEC has 4 new code requirements!

The 2017 NEC changes provide directives for the installation of additional Surge Protective Devices in additional Critical Applications adding to the existing Code Requirements of 2008-14

Surge protection

NEC code requirements for surge protection

620.51(E) "Where any of the disconnecting means in 620.51 has been designated as supplying an emergency system load, surge protection shall be provided". This article was added to address emergency system loads such as elevators, escalators, moving sidewalks, chairlifts and associated equipment.

645.18 "Surge protection shall be provided for Critical Operations Data Systems." Critical Operation Data Systems is defined by the NEC® as "Information technology equipment systems that require continuous operation for reasons of public safety, emergency management, national security or business continuity."

670.6 "Industrial machinery with safety interlock circuits shall have surge protection installed". The concern is failure of safety interlocks on machinery, causing safety risk to operators who may not be aware of disabled safety mechanisms.

694.7(D) "A surge protection device shall be installed between a wind electric system and any loads served by the premises electrical system." The surge device can be on the circuit serving the wind electric system or on the load side of the service disconnect.

695.15 "A listed surge protection device shall be installed in or on the fire pump controller." A new NEC provision requires a listed surge protection device (SPD) to be installed in or on the fire pump controller. An SPD is necessary to provide protection for the fire pump controller.

700.8 "A listed SPD shall be installed in or on all emergency systems switchboards and panelboards." The NEC defines emergency power systems as systems legally required to automatically supply power to designated loads upon loss of normal power. This requirement will help ensure emergency electrical-distribution systems continue to deliver reliable power to vital life-safety loads in the event of damaging surges.

708.20 "Surge protection devices shall be provided at all facility voltage distribution levels" for Critical Operation Power Systems (COPS). COPS systems include but are not limited to power systems, HVAC, fire alarms, security, communications and signaling for designated critical operations areas. Surge protection ensures that these systems will operate in an emergency situation.

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2017 NEC – 620.51(E) – Elevators, moving sidewalks, escalators, and more…

- Article 620.51(E) was added to address emergency system loads, such as elevators, escalators, moving walkways, and chairlifts. These are systems that are a matter of public safety. It states, "Where any of the disconnecting means in 620.51 has been designated as supplying an emergency a standby system load, surge protection shall be provided."
- The 2014 NFPA sponsored survey to determine the damaging effects of voltage surges in various applications found 24% of responders to the survey reporting damage to elevator equipment from surge activity.

2017 NEC – 645.18 – Critical Data Systems

- Article 645.18 - Surge protection is required for critical operations data systems. The NEC defines these as “information technology equipment systems that require continuous operation for reasons of public safety, emergency management, national security, or business continuity.”
- The NFPA survey conducted found (48%) of respondents noted that their facility had experienced unexplained process interruptions. More than a third (38%) noted the occurrence of lockup of computer or industrial process systems

examples

2017 NEC – 670 – Industrial Machinery

- Article 670.6 addresses industrial equipment with safety interlock circuits. It states that “industrial machinery with safety interlock circuits shall have surge protection installed.”

- The NFPA found that 27% of safety interlocking mechanism on machinery was defective due to surge activity in the facility

examples

2017 NEC – 695.15 - Fire Pumps

- 695.15 – A listed surge protection device shall be installed in or on the fire pump.
- A study conducted by the NFPA concluded that 12% of fire pumps tested had damage due to surge activity. Surge can damage motor windings and pump controls leaving critical equipment vulnerable during an critical emergency

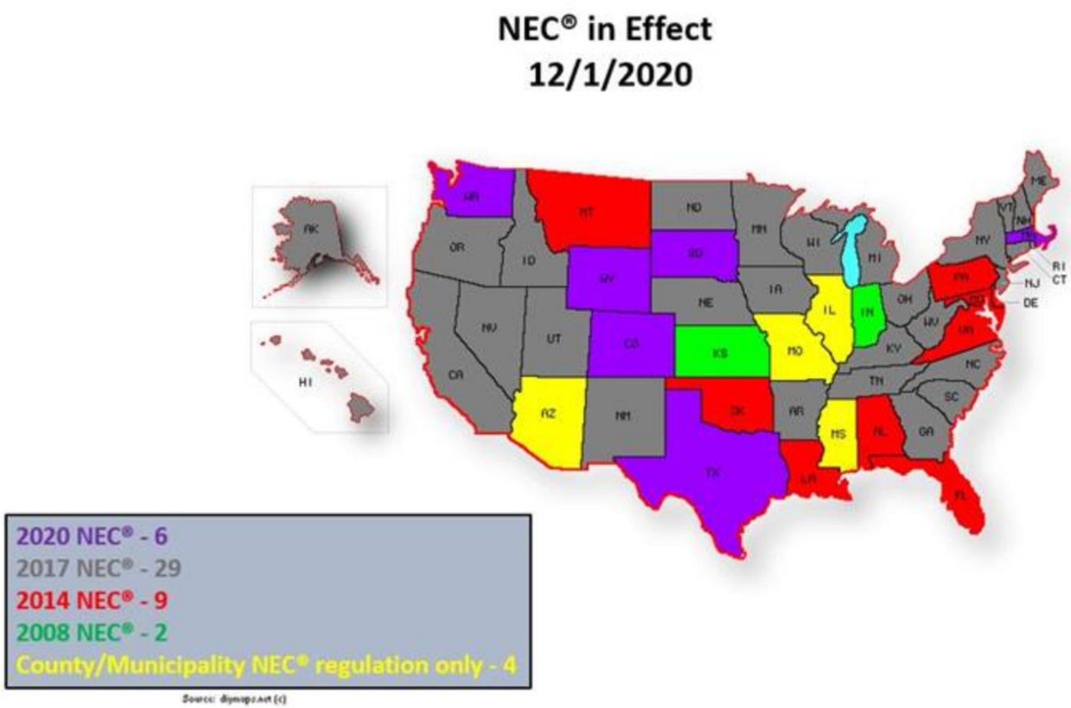
examples

2017 NEC Rollout

- 29 States have adopted the 2017 NEC Code as of August 1st 2019. The adoption rate was dramatically faster than the 2014 code!
- Demand on Manufacturers has increased with the introduction of NEC SPD additions.
- Activities at engineering firms discussing NEC Education has increased for new construction
- Trained Electrical **Service** Contractor demand has increased, Leading to the Eaton Surge Certified Contractor (ESCC) Program.
- Interest in Distributor Socking Programs has increased

NEC Requirements

- NEC Code Requirements
  - 2017 Code has total of Seven surge requirements, 2020 added One.
  - Impossible to construct building without surge protection
  - Eaton has marketing literature for each major code change



- The 2019 California Electrical Code, California Code of Regulations Title 24, Part 3 is based on the 2017 edition of NFPA 70®, National Electrical Code®.
- The 2011 New York City Electrical Code is based on the 2008 edition of NFPA 70®, National Electrical Code®.

NEC 2017 – What *Didn't* Make the Cut?

- Proposal 4-65 Log #3318 NEC-P04 – New Article 225.41 Surge Protection. A Type 1 or Type 2 listed SPD shall be installed on all outside branch circuits and feeders and shall be located at the point where the outside branch circuits and feeders receive their supply.

- Proposal 4-143 Log #3319 NEC-P04 – Article 230.67 Surge Protection. A Type 1 or Type 2 listed SPD shall be installed on all services.

- Proposal 4-143a Log #3504 NEC-P04 – Article 230.67 Dwelling Unit Surge Protection.
  - (A) Surge Protective Device. All dwelling units shall be provided with a surge protective device (SPD) installed in accordance with Article 285. Now An NEC 2020 requirement.
  - (B) Location. The surge protective device shall be an integral part of the service disconnecting means or shall be located immediately adjacent thereto.
  - (C) Type. The surge protective device shall be a Type 1 or Type 2 SPD.
  - (D) Replacement. Where service equipment is upgraded, all of the requirements of this section shall apply.

NEC 2017 – What *Didn't* Make the Cut?

Proposal 5-244 Log #3320 NEC-P05 – New Article 285.2 Required uses. A listed SPD shall be installed in or on the following equipment that is rated at 1000 volts or less.

- (1) Switchboards and panelboards
- (2) Motor control centers
- (3) Industrial control panels
- (4) Control Panels for elevators, dumbwaiters, escalators, moving walks, platform & stairway
- chairlifts
- (5) Power distribution units supplying information technology equipment in information
- technology rooms
- (6) Solar photovoltaic (PV) combiner boxes, re-combiner boxes, and inverters
- (7) Roof-top air conditioning and refrigerating equipment
- (8) Adjustable-speed drive systems
- (9) Burglar alarm panels
- (10) Fire alarm panels
- (11) Critical Operations Power Systems
- (12) Small Wind Electric Systems

Why the Omissions and NEC Next Gen?

- Omissions Reasoning
  - *"The proposal does not state what type or level of protection should be required. Further substantiation through a formal research report that presents evidence of the type of SPD and the level of protection required would present the opportunity for the panel to reconsider the proposal."*
- NEC Next Gen (Beyond 2020)
  - Expect progressive studies to focus on reason(s) for exclusion (i.e. surge levels and susceptibilities)
  - Could kA Definition and minimum standards be established in certain applications?
  - Expect some previously rejected proposals to include additional data and achieve adoption

How to Apply NEC Requirements

- Biggest Obstacle – No kA Guidance
- Solution – Apply Best Practices
  - Understand Surge Regulatory Standards and Ratings; Know What They Mean
  - Consider the Installation and how to realize Best Performance, including Cascading of SPD's per IEEE recommendations
  - Consider Outside and (very importantly) Internal potential sources of surge events
  - Consider panel/switchgear locations and ampacities

Surge Protection Nameplate Specifications

Surge Protection Specifications – Standard Nameplate Data

- **SPD Type**
- NRTL listing mark
- Peak surge current per phase (not required)
- Short circuit current rating
- Nominal Discharge Current Rating
- System voltages
- System frequency
- Voltage Protection Rating

examples

Nameplate Data – SPD Type Rating

- The SPD type refers to the location where the SPD can be used
  - Type 1 – before the service disconnect overcurrent device
  - Type 2 – after service disconnect overcurrent device
  - Type 3 – at least 10m (30 ft) of conductor between service disconnect overcurrent device and SPD
  - Type 4 – component SPD (must be tested to the appropriate installation location where it will be installed)

Nameplate Data – NRTL Listing

- SPD Type
- **NRTL listing mark**
- Peak surge current per phase (not required)
- Short circuit current rating
- Nominal Discharge Current Rating
- System voltages
- System frequency
- Voltage Protection Rating

examples

Nameplate Data - Nationally Recognized Testing Laboratory Mark (NRTL)

- Other laboratories besides Underwriters Laboratories can test and list devices to be compliant with any standard, including UL 1449
- Only an SPD that is tested by UL is “UL Listed”
- An SPD tested by another NRTL can be “Compliant to UL 1449” but will be “Listed” by the NRTL – e.g. “ETL Listed”, “CSA Listed”

Nameplate Data – Peak Surge Current, SSCR, Nominal Discharge Current

- SPD Type
- NRTL listing mark
- **Peak surge current per phase (not required by UL)**
- **Short circuit current rating**
- **Nominal Discharge Current Rating**
- System voltages
- System frequency
- Voltage Protection Rating

examples

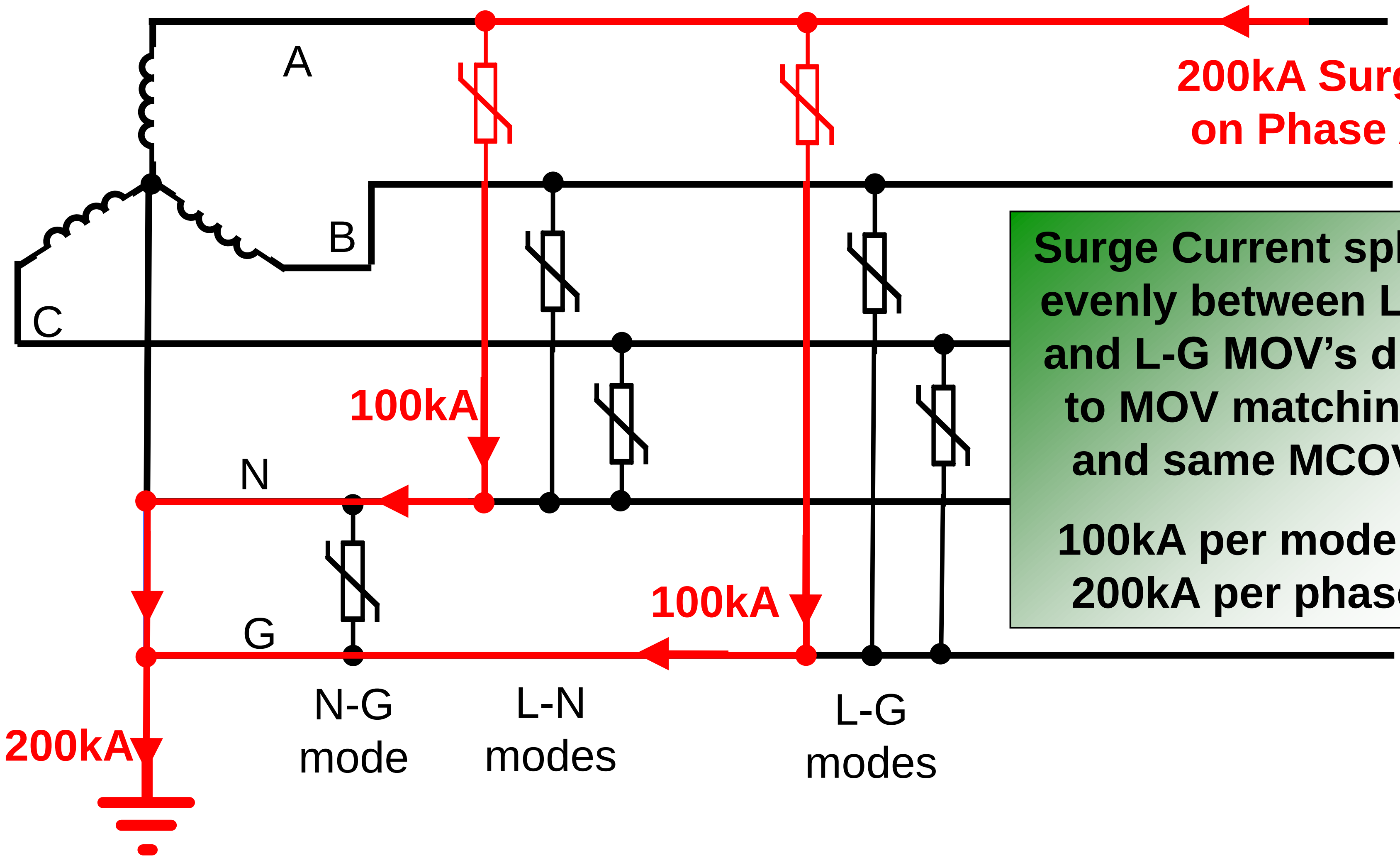
Nameplate Data - Applicable current ratings for SPDs

- Peak surge current rating
  - Measure of life or longevity expectations of SPD
  - Also referred to as “single impulse rating”, “maximum surge current rating” or “life rating”
- Nominal discharge current rating
  - Measure of ruggedness or durability of SPD in the electrical system (can be UL tested at various current levels)
- Short circuit current rating SCCR
  - Measure of how much current the electrical utility can supply during a fault condition

Nameplate Data - Peak surge current rating

- This is how virtually all manufacturers rate or size their SPDs
- Also called:
  - Surge current capacity
  - Single pulse surge current
  - Maximum surge current
  - Peak surge current
- **Important note: it is never intended that an SPD is ever subjected to the peak surge current in actual installed conditions!!!**

Nameplate Data – Peak surge current - 3 Phase – 4 Wire System split of surge current



Surge Current splits evenly between L-N and L-G MOV's due to MOV matching and same MCOV

100kA per mode = 200kA per phase

Nameplate Data - Peak surge current rating

- The peak surge current is a predictor of how long an SPD will last in a given environment
  - The higher the kA, the longer the life of the MOVs
- Similar to the tread on a tire
  - The thicker the tread, the longer the tire will last

Nameplate Data - Nominal Discharge Current - I_n

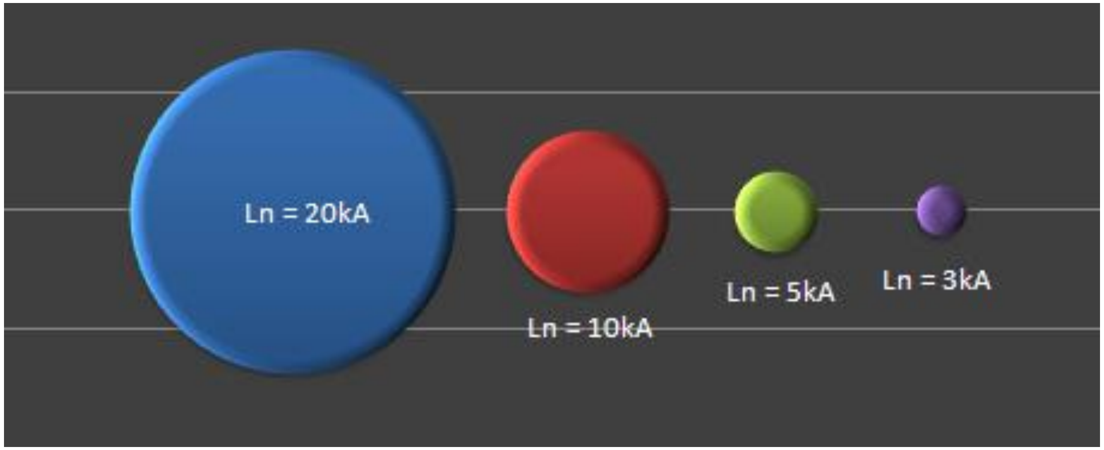
- New rating introduced with UL 1449 3rd Edition
- Measure of the “ruggedness” or “robustness” of an SPD
- Measure of how the SPD performs when installed and subjected to operating scenarios closer to real life situations
- “Stress test” – SPD is subjected to 15 surges, one minute apart, with rated voltage applied between surges
- Provides the customer a durability rating

Nameplate Data - Nominal Discharge Current test

- Manufacturer chooses a current they want to test with:
  - Type 1 – 10kA or 20kA
  - Type 2 – 3kA, 5kA, 10kA or 20kA
- Complete SPD is tested along with any required overcurrent devices (fuse or breaker)
- Measured let through voltage for a 6000V 3000A surge is recorded
- SPD is subjected to 15 surges at chosen current one minute apart with rated voltage applied between surges
- Measured let through voltage for a 6000V and 3000A surge is recorded again – let through voltage must not deviate more than 10% from original voltage

Nameplate Data – Nominal Discharge Current Recommendation

Customers and specifying engineers should choose I_n of 20kA



Energy = $I^2 * R$

- 10kA SPD can only take 25% of the energy of 20kA
- 5kA SPD can only take 6.25% of the energy of 20kA
- 3kA SPD can only take 2.25% of the energy of 20kA

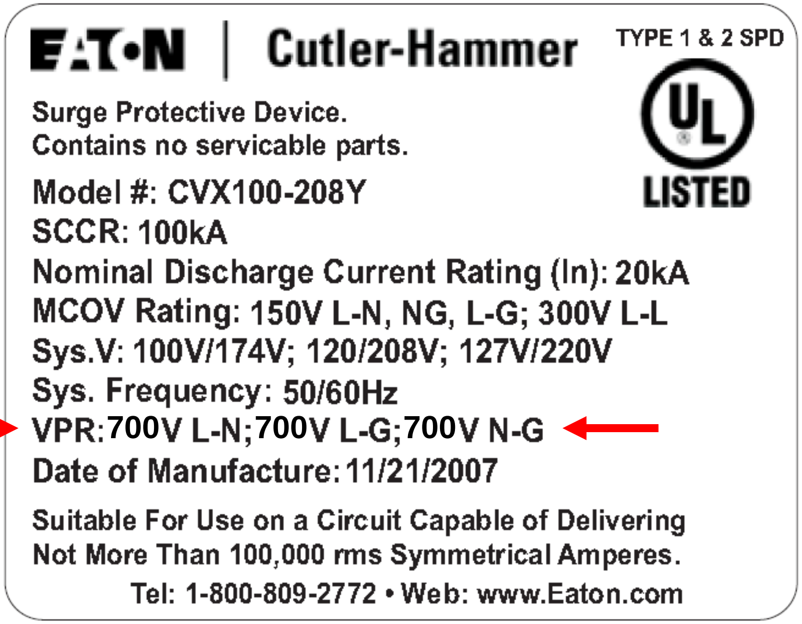
Nameplate Data – Voltage Protection Rating (VPR)

- SPD Type
- NRTL listing mark
- Peak surge current per phase (not required)
- Short circuit current rating
- Nominal Discharge Current Rating
- System voltages
- System frequency
- **Voltage Protection Rating**

examples

Nameplate Data – Voltage Protection Rating (VPR)

- VPR is a rating published and marked on all UL 1449 listed SPDs
- Residual voltage for a 6000 V, 3000 A 8/20 μs surge waveform impulse



examples

Nameplate Data – Voltage Protection Rating (VPR)

- In order to have consistency in VPR voltage levels, UL specifies that 6" inches of lead length is protruding from SPD

examples

Nameplate Data – Voltage Protection Rating (VPR)

- Voltage Protection Rating is assigned to an SPD model by UL from a table based on the average of the measured limiting voltage from 3 impulses of a 6000V/3000A surge

Measured Limiting Voltage	Voltage Protection Rating
330 or less	330
331 - 400	400
401 - 500	500
501 - 600	600
601 - 700	700
701 - 800	800
801 - 900	900
901 - 1000	1000
1001 -1200	1200
1201 - 1500	1500
1501 - 1800	1800
1801 - 2000	2000
2001 - 2500	2500
2501 - 3000	3000
3001 - 4000	4000
4001 - 5000	5000
5001 - 6000	6000

Surge Performance, Application and Basic Design Practices

Best Practices – Maximize the Install

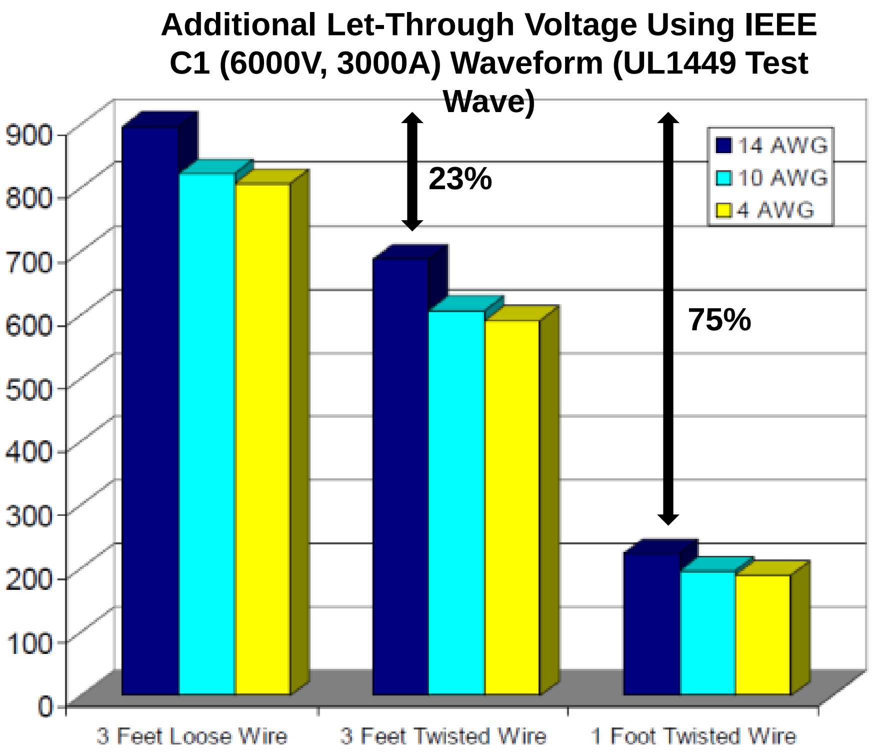
What is the best way to optimize surge protective device performance?

- Minimizing lead length
- Twisting wires
- Eliminating sharp bends
- Using a thicker wire
- Design utilizing Thermally Protected Metal Oxide Varistor (TPMOV).

Minimizing lead length improves surge protective device performance

Lead length directly effects surge protection. Installation lead length can increase let-through voltage by 15-25V per inch.

Install the surge protective device as close as possible to the electrical assembly to maximize surge protection.



Twisting Wire Reduces Reactive Resistance

Performance/Application – Does it Matter?

- Customer asked, “Why am I having surge damage even though I have an SPD?”
  - Note: was not and Eaton Surge Device

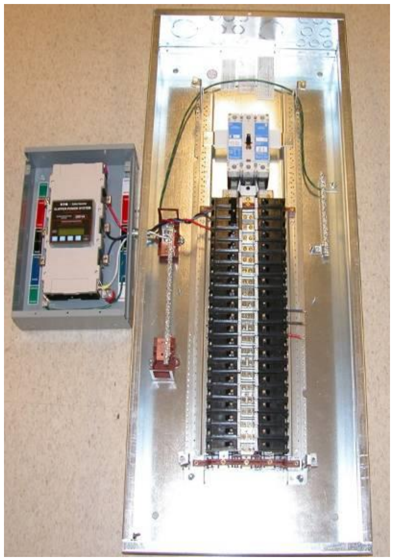
Performance/Application - Calculation of $VPR_{Installed}$

- $VPR_{Installed} = VPR_{SPD}$ + Voltage Drop of Leads
- VPR_{SPD} = 700V
- Voltage drop of leads = 20ft x 107V per foot (#10 AWG untwisted wire) = 2140V
- $VPR_{Installed}$ = 2840V

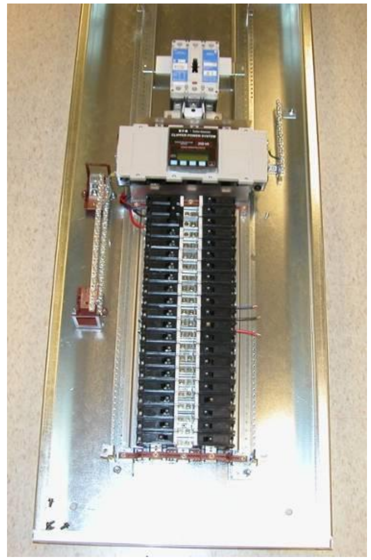
Very high let-through voltage – SPD is not effective due to installation method!!

Performance/Application - Independent tests confirm better performance with integrated SPDs

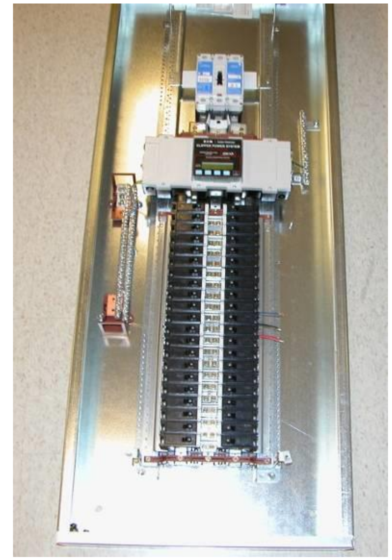
Good → **Better** → **Best**



Side mount
Good let-though
If short leads.



Integrated with Disconnect
Better let-through than sidemount.



Direct bus connected
Up to **46%** better let-though compared to sidemount.

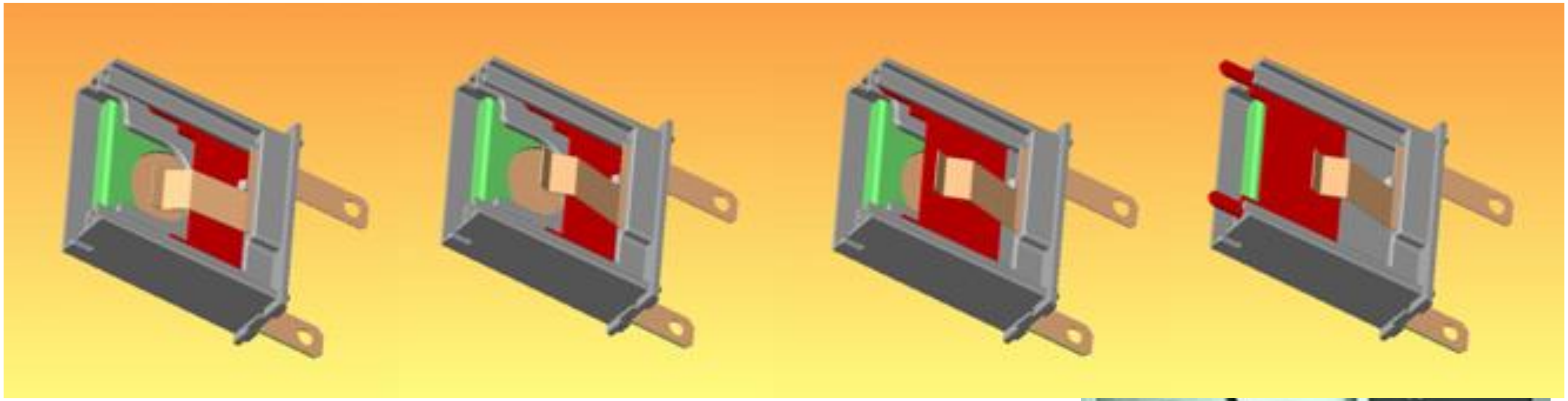
examples

When SPD's Fail – Containment & Prevention

When MOV's Fail How is the System Protected?

- MOV's are Self-Sacrificing Devices
- As MOV's Age their Maximum Continuous Operating Voltage (MCOV) declines
- Containment Method uses Epoxy, Sand covered with Epoxy or Sand to contain contaminants in the event of a Thermal Event, however, 100% containment is not guaranteed.
- Prevention Method using thermally protected MOV's providing passive failure characteristics therefore eliminating potential to introduce contaminants.

Thermally Protected MOV's



Introduction of the Thermally Protected MOV prevents thermal runaway and provides for unparalleled safety for internal and external surge units employing the technology

The SPD to the right is ***NOT*** using the same or similar Containment methods of the Eaton IT SPD Series

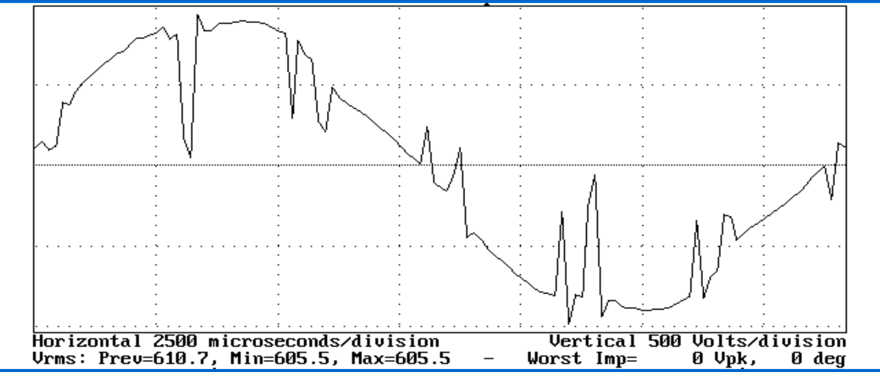
Summary

- **THE INSTALLATION OF THE PRODUCT MAKES SIGNIFICANT DIFFERENCE!**
- **Cascade SPD Devices** – this is an IEEE recommendation, the whole is greater than the sum of the parts, for longevity, surge clamping characteristics and EMI filtering.
- **Technologies Vary** – Understand what they are and how they are deployed in accordance with the load characteristics and environment

Thank You For Your Time

Questions?

Harmonics Introduction



January 2021
Nick Caffas
PQ Marketing Engineer- Eaton
nickccaffas@eaton.com

Purpose and learning objectives

Purpose of this class is:

- Learn about harmonics
- Introduce IEEE 519-2014 recommended practice for harmonic compliance
- Learn about mitigation techniques for harmonic distortion for industrial applications

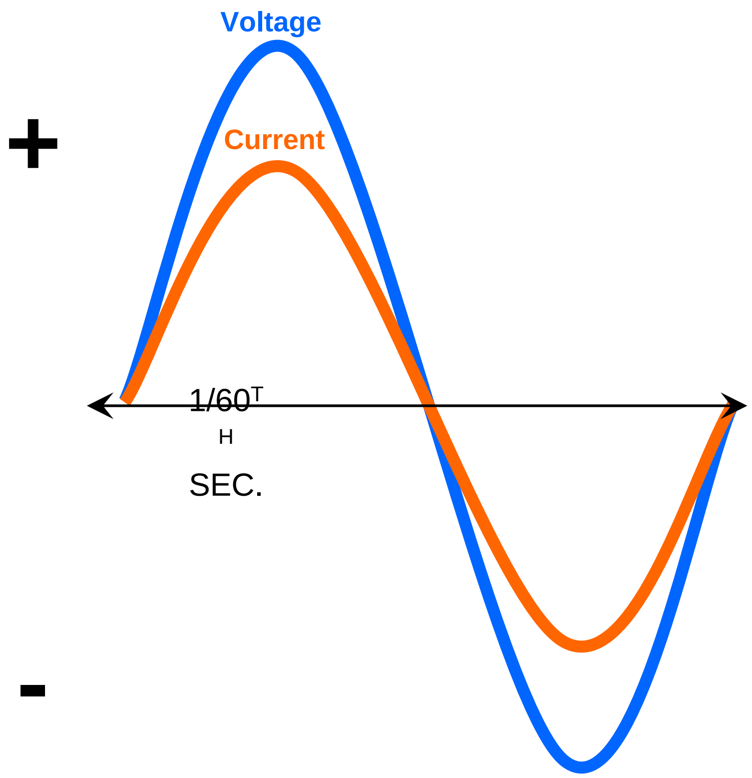
Two Types of Electrical Loads

- Linear

- Non-Linear

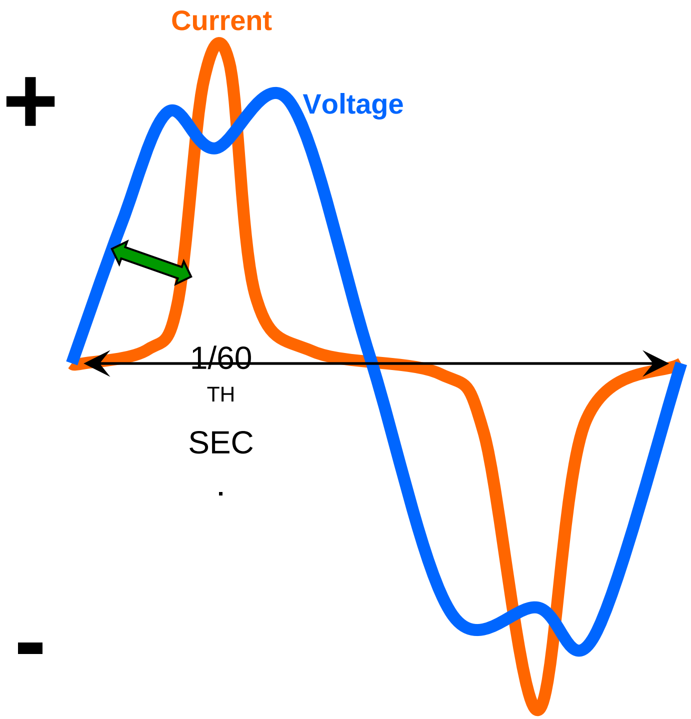
Linear Loads Draw Power Linearly

- Electrical voltage and current "ebbs and flows" from plus to minus 60 times per second.
- Voltage and Current follow the same rhythm perfectly in a linear load

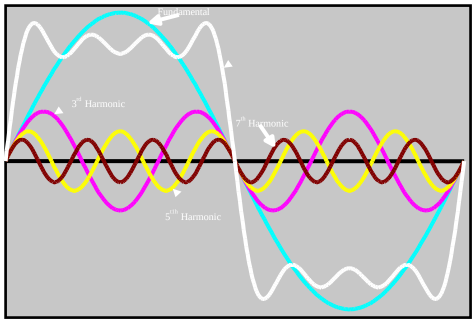


Non-Linear Loads Draw Power Unevenly

- Current is drawn in short “gulps” or pulses.
- Voltage and Current waveforms are irregular and don’t match – waveforms are said to be “DISTORTED”
- NON-LINEAR LOADS PRODUCE HARMONICS
- Harmonics cause mis-operation of equipment and WASTE ENERGY.



Harmonic Basics

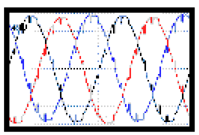


Harmonic	Frequency	Sequence
1	60Hz	+
2	120Hz	-
3	180Hz	0
4	240Hz	+
5	300Hz	-
6	360Hz	0
7	420Hz	+
:	:	
19	1140Hz	+

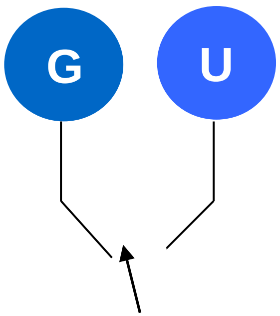
What are harmonics?

- A harmonic is a component of a periodic wave with a frequency that is an integer multiple of the fundamental frequency
- Proliferation of power semiconductor devices
  - Converts power (AC to DC)
- Amplitude is inverse of harmonic order (perfect world)

Harmonics – it’s not that complicated….



$$V_d = I_d Z_h$$



Misoperation Problems

Heating Problems (Load Related)

Source Impedance

Which came first?

Voltage Distortion **Current Distortion**

In this case…the Egg!

- Current distortion causes Voltage distortion
- Voltage distortion is created by pulling distorted current through an impedance
- Amount of voltage distortion depends on:
  - System impedance
  - Amount of distorted current pulled through the impedance
  - If either increases, V_{THD} will increase

Sources of harmonics

General sources of harmonics

- Power electronic equipment (drives, rectifiers, computers, LED lights, etc.)
- Arcing devices (welders, arc furnaces, florescent lights, etc.)
- Iron saturating devices (transformers)
- Rotating machines (generators)

Most prevalent and growing harmonic sources

- Variable frequency drives (VFD)
- Switch-mode power supplies (computers)
- Fluorescent lightning
- LED lighting

Harmonic symptoms and concerns

- Equipment failure and misoperation
  - Notching (electronic control malfunctioning, regulator misoperation)
  - Overheating/Failure (transformers, motors, cables/neutral)
  - Nuisance Operation (fuses, breakers)
  - Insulation deterioration
  - Audible noise in electrical equipment
- Economic considerations
  - Oversizing (equipment is sized larger to accommodate harmonics)
  - Losses/Inefficiencies/PF Penalties
  - Inconsistent meter reading
- Harmonic resonance with power factor correction capacitors

Internal vs. external sources

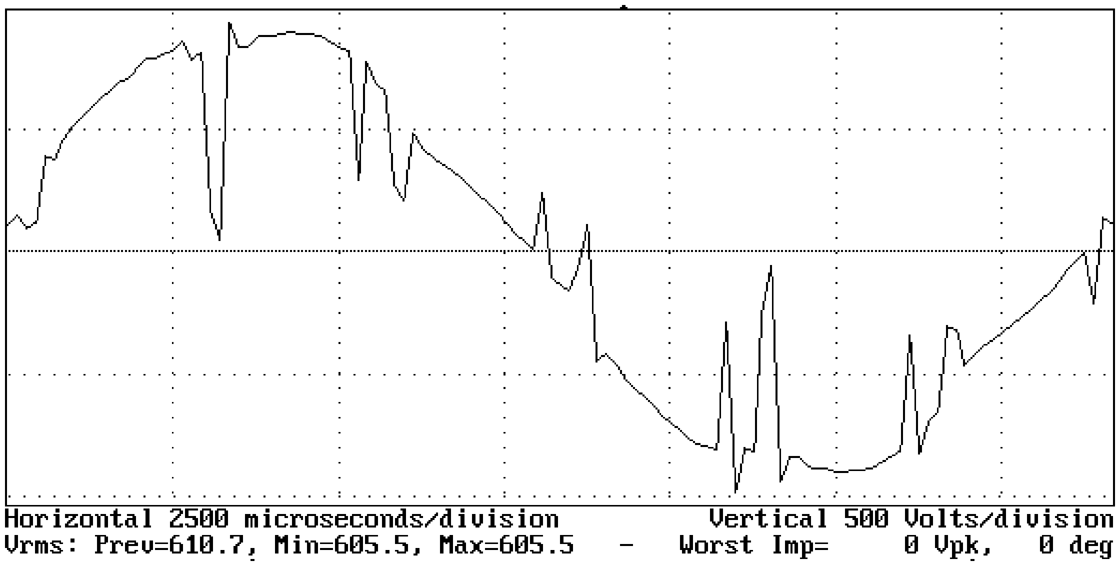
Some harmonic sources are internal
- VFDs, switch mode power supplies, etc.

Other harmonic sources are external
- Customers sharing the same line

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

… But Remember

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



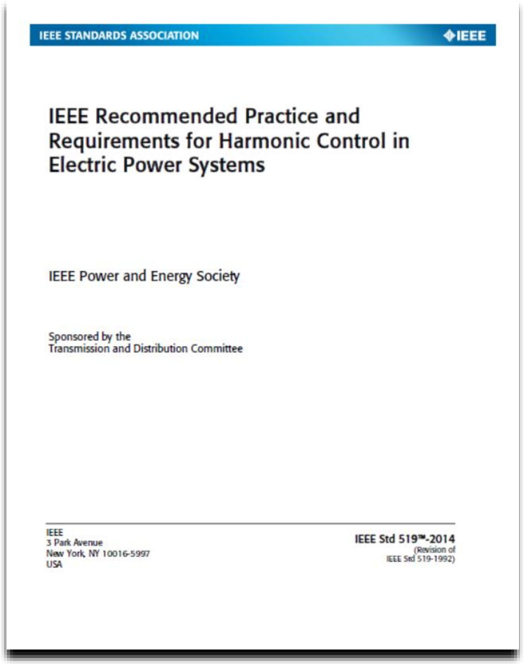
What is harmonic compliance

- Utility is responsible for providing “clean” voltage
- Customer is responsible for not causing excessive current harmonics
- Utility can only be fairly judged if customer is within its current limits
- Harmonics cause voltage and current problems in power systems
- IEEE Std 519-2014 provides a basis for limiting harmonics
- Multiple methods exist for mitigating harmonics and “one size does not fit all”

IEEE Std 519-2014 - overview

Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

- ***Finally*** replaced IEEE 519-1992!
- More concise document
- PCC clarified
- New voltage range
  - 1.0 kV and below
    - 8% THD_V
    - 5% individual voltage harmonics
- Statistical limits for harmonic measurements



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)

IEEE Std 519-2014 - purpose

- Establishes goals for the design of electrical systems that include both linear and nonlinear loads
- Addresses steady-state limitations - transient conditions exceeding these limitations may be encountered
- Limit values given in this document are recommendations and should not be considered binding in all cases
- Some conservatism is present that may not be necessary in all cases

IEEE Std 519-2014 – harmonic control

- Managing harmonics in a power system is considered a joint responsibility involving both endusers and system owners/operators
- Some level of voltage distortion is generally acceptable
- Both must work cooperatively to keep actual voltage distortion below objectionable levels
- Underlying assumption – by limiting harmonic current injections by users, voltage distortion can be kept below objectionable levels
- Limits in this standard apply only at the PCC and should not be applied to either individual pieces of equipment or at locations within a user's facility

IEEE Std 519-2014 – voltage limits

- Limit line-to-neutral voltage harmonics at PCC
- New voltage range

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]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

IEEE Std 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

Expected harmonics

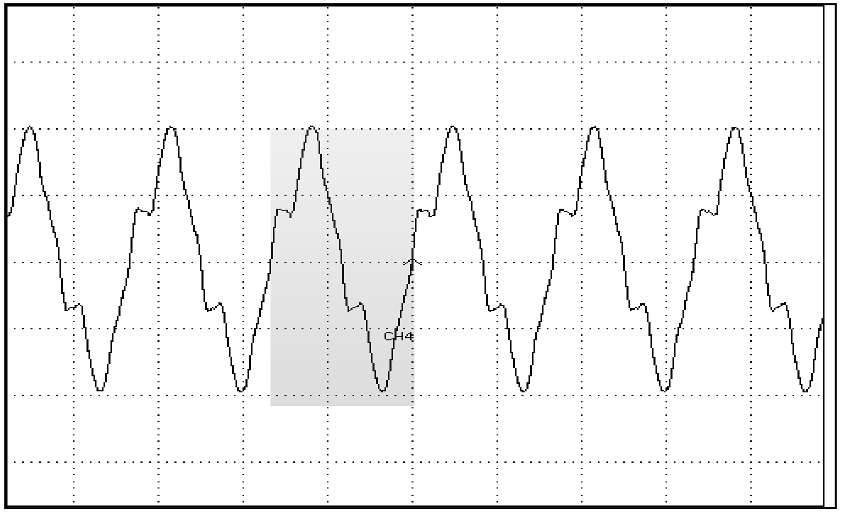
Source	Typical Harmonics*
6 Pulse Drive/Rectifier	5, 7, 11, 13, 17, 19…
12 Pulse Drive/Rectifier	11, 13, 23, 25…
18 Pulse Drive	17, 19, 35, 37…
Switch-Mode Power Supply	3, 5, 7, 9, 11, 13…
Fluorescent Lights	3, 5, 7, 9, 11, 13…
Arcing Devices	2, 3, 4, 5, 7...
Transformer Energization	2, 3, 4

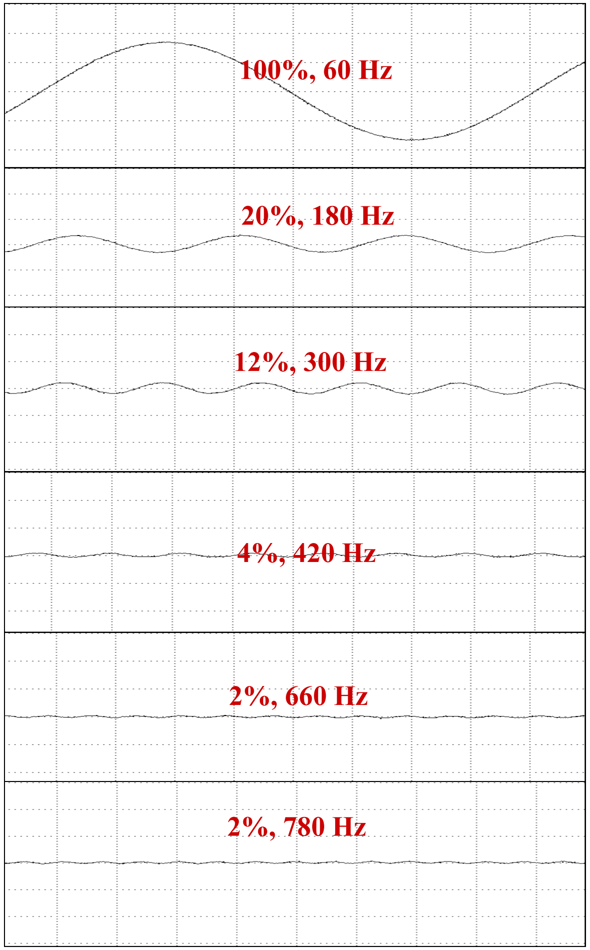
* Generally, magnitude decreases as harmonic order increases

H = NP+/-1

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

Harmonics – total harmonic distortion (%THD)



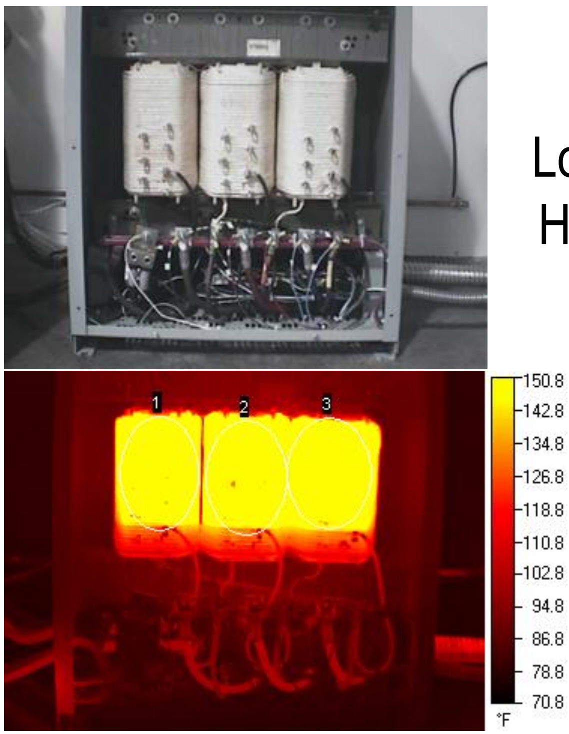


$$\%THD_I = \frac{\sqrt{I_2^{\ 2} + I_3^{\ 2} + I_4^{\ 2} + \ldots}}{I_1} \times 100\%$$

Harmonic “problems”

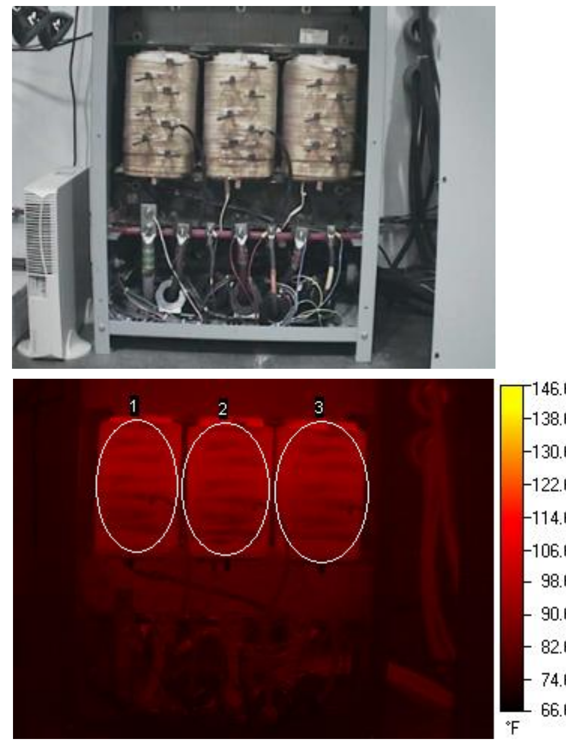
- IEEE 519 compliance
- Equipment overheating/failure
- Equipment misoperation
- Excessive cost for mitigation

Harmonics and heating



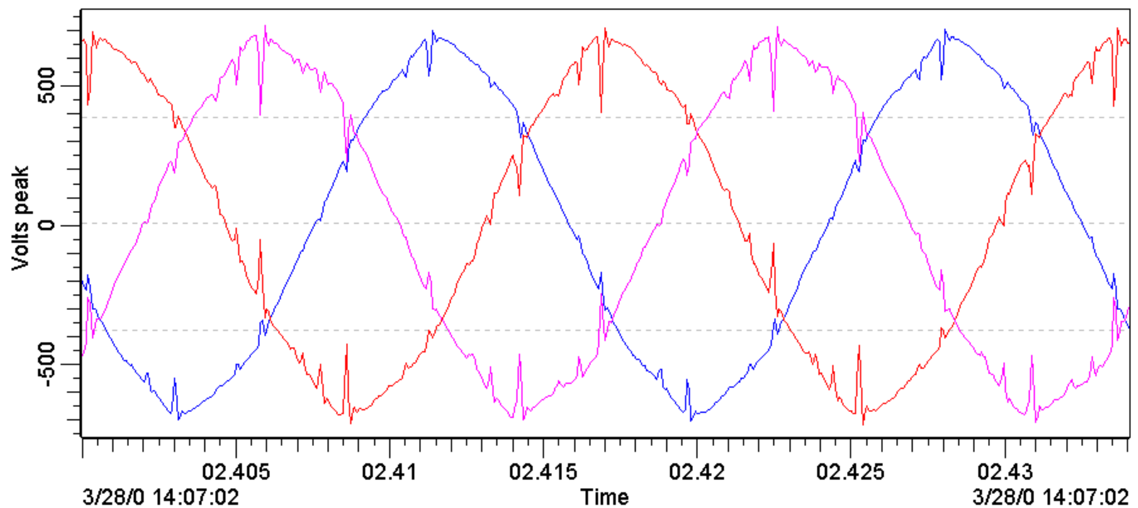
Std Transformer – Max Temp – 176 F

Load 100%
Harmonics



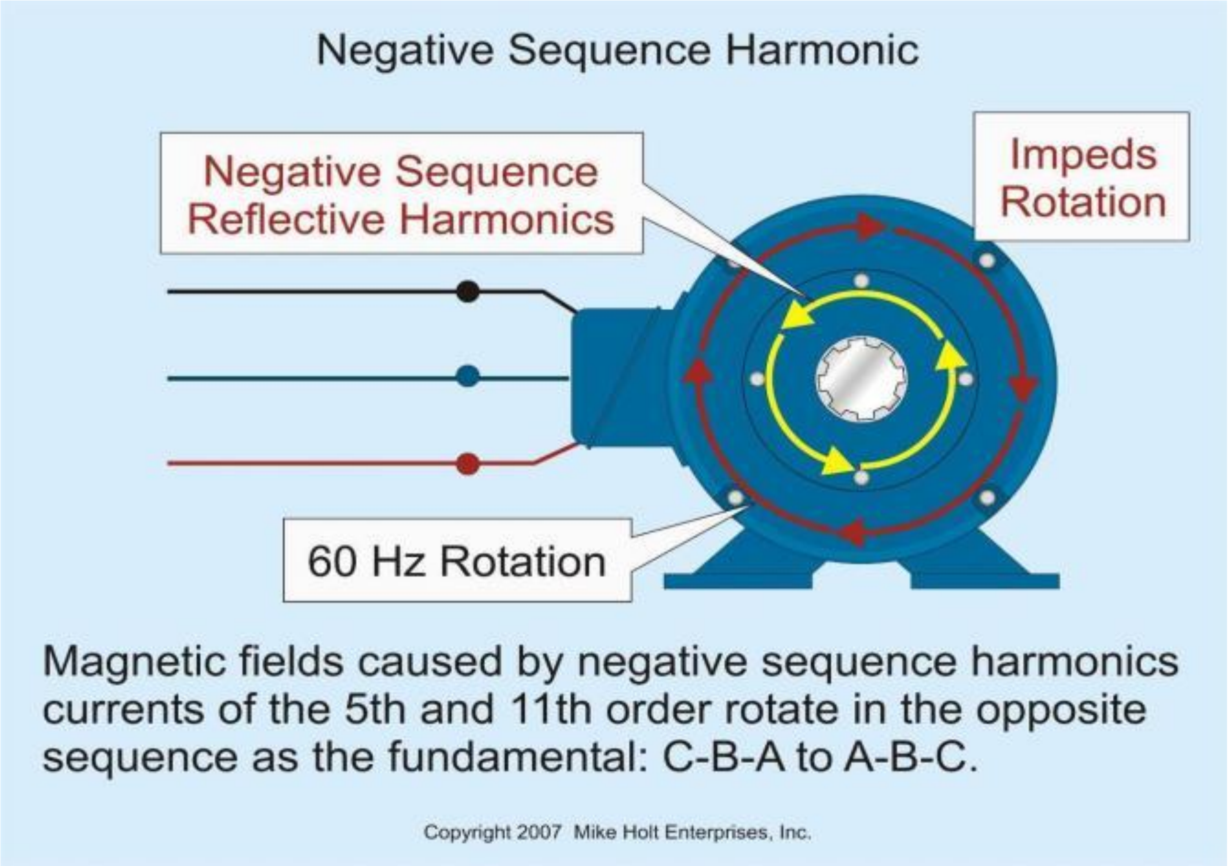
HMT – Max Temp – 105 F

Voltage notching



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

Motor heating and vibrations

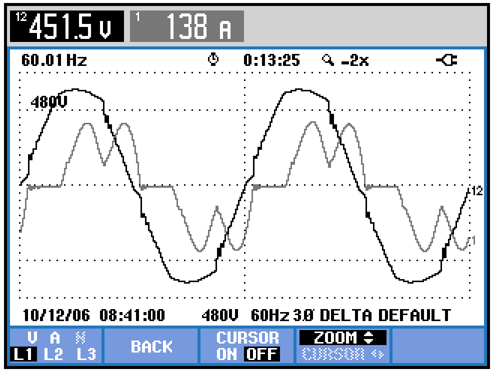


- Motor Heating
- Vibrations
- System Losses

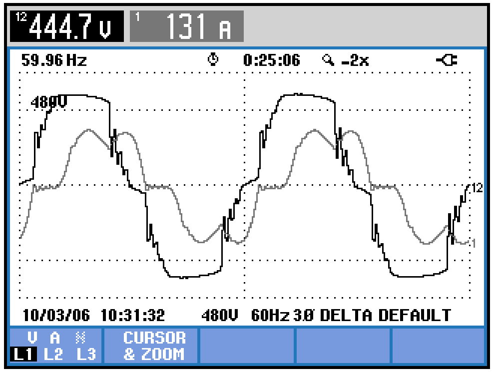
Like driving with one foot on the gas and one on the brake …

Harmonics and generators

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



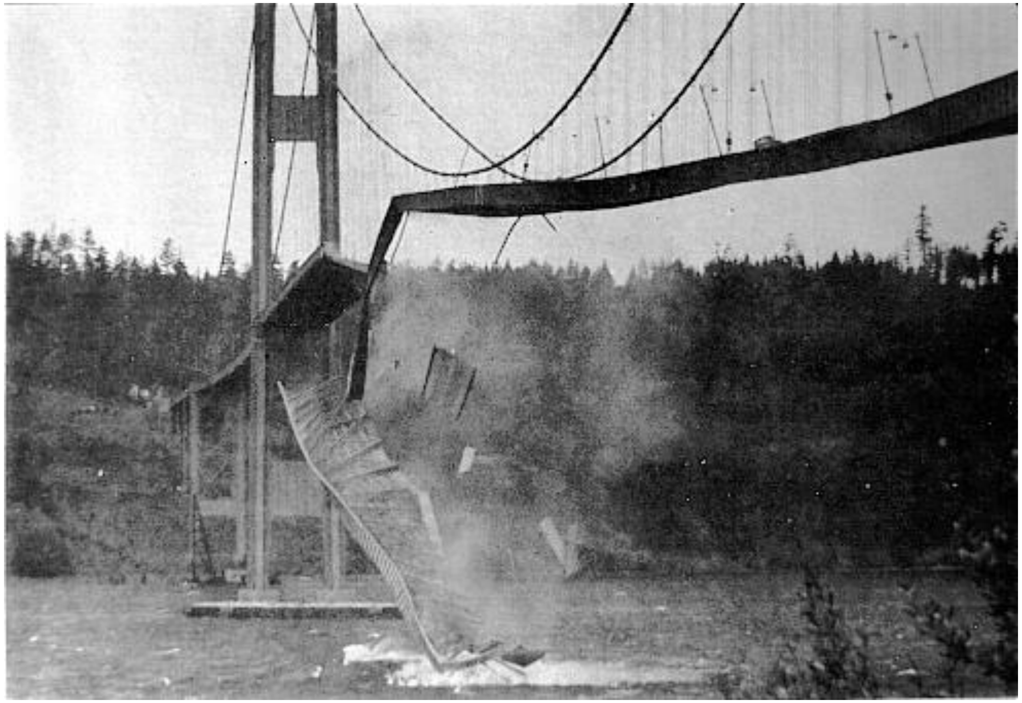
4.4% Vthd



13% Vthd

Same Load (all Drives)

Harmonic resonance

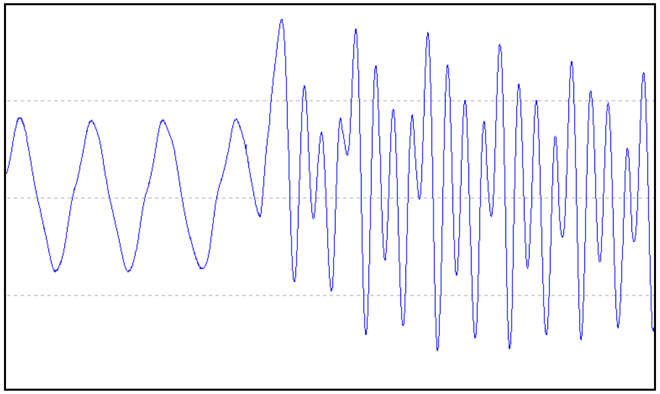


On November 7, 1940, at approximately 11:00 AM, the Tacoma Narrows suspension bridge collapsed due to **wind-induced vibrations**…the bridge had only been open for traffic **a few months**.

Harmonic resonance

The “Self Correcting” Problem

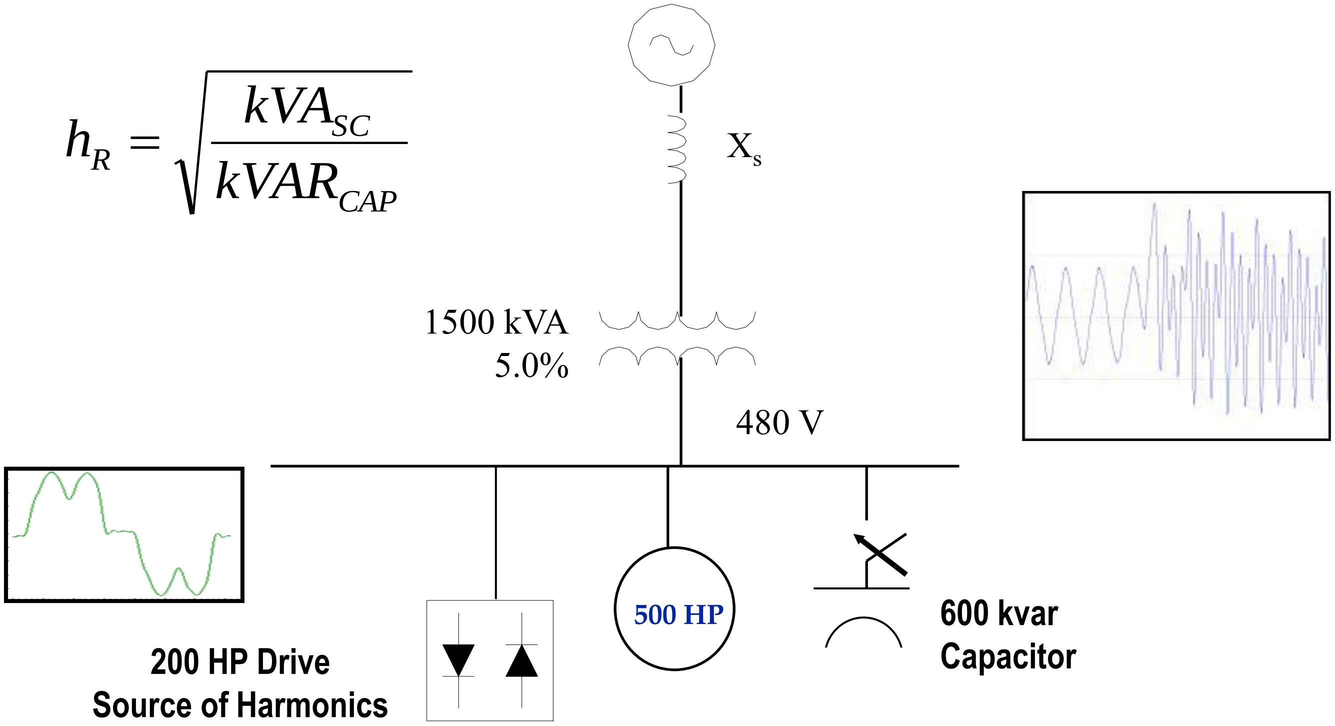
- Blown Fuses
- Failed Capacitors
- Damaged Transformer



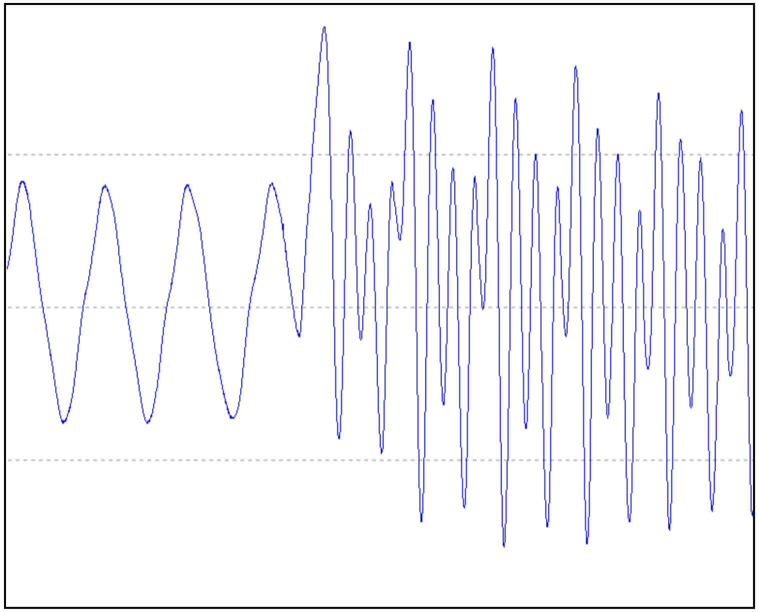
Harmonics = Wind (Excites Resonance)

Harmonic resonance

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



Harmonic resonance



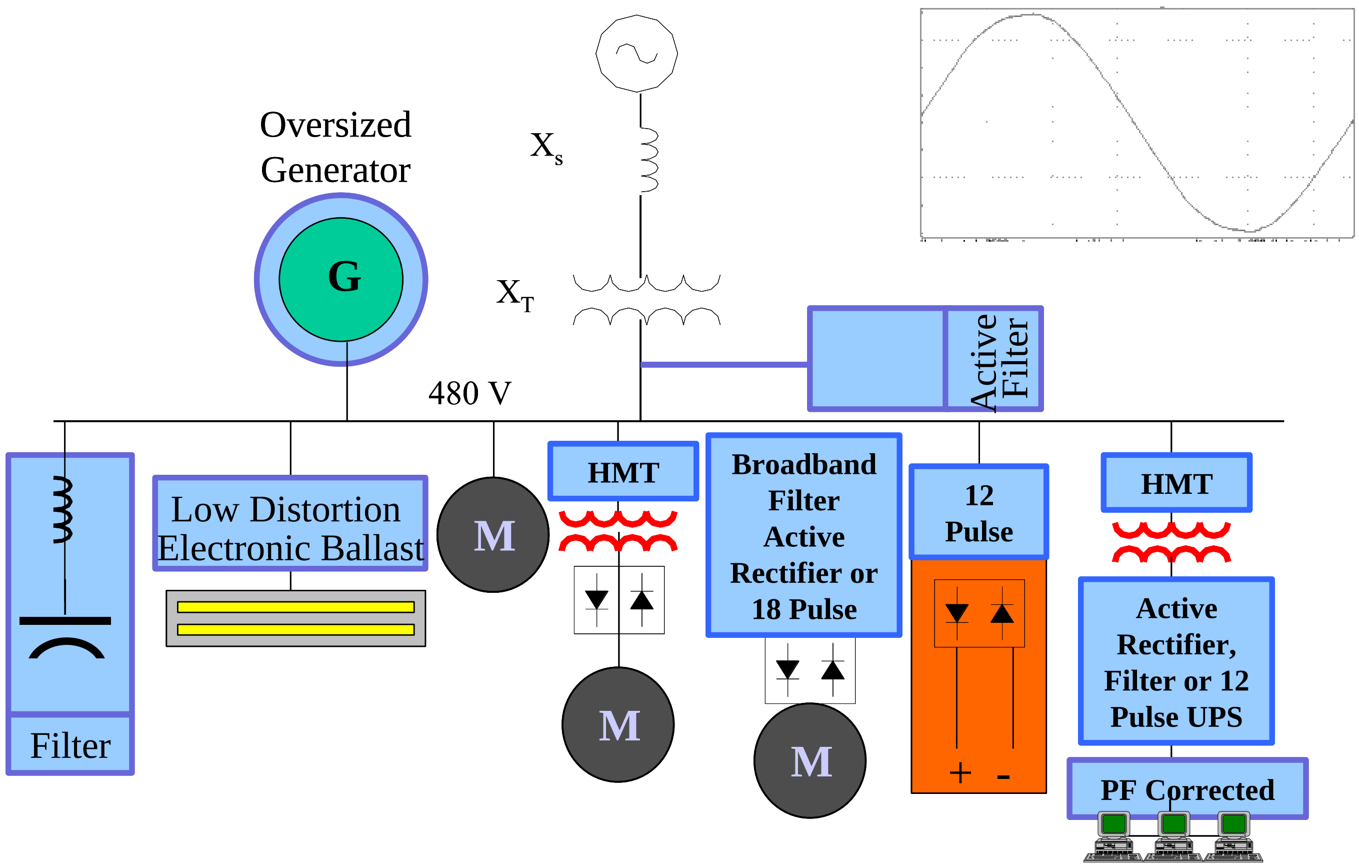
If a capacitor exists on the power system

AND

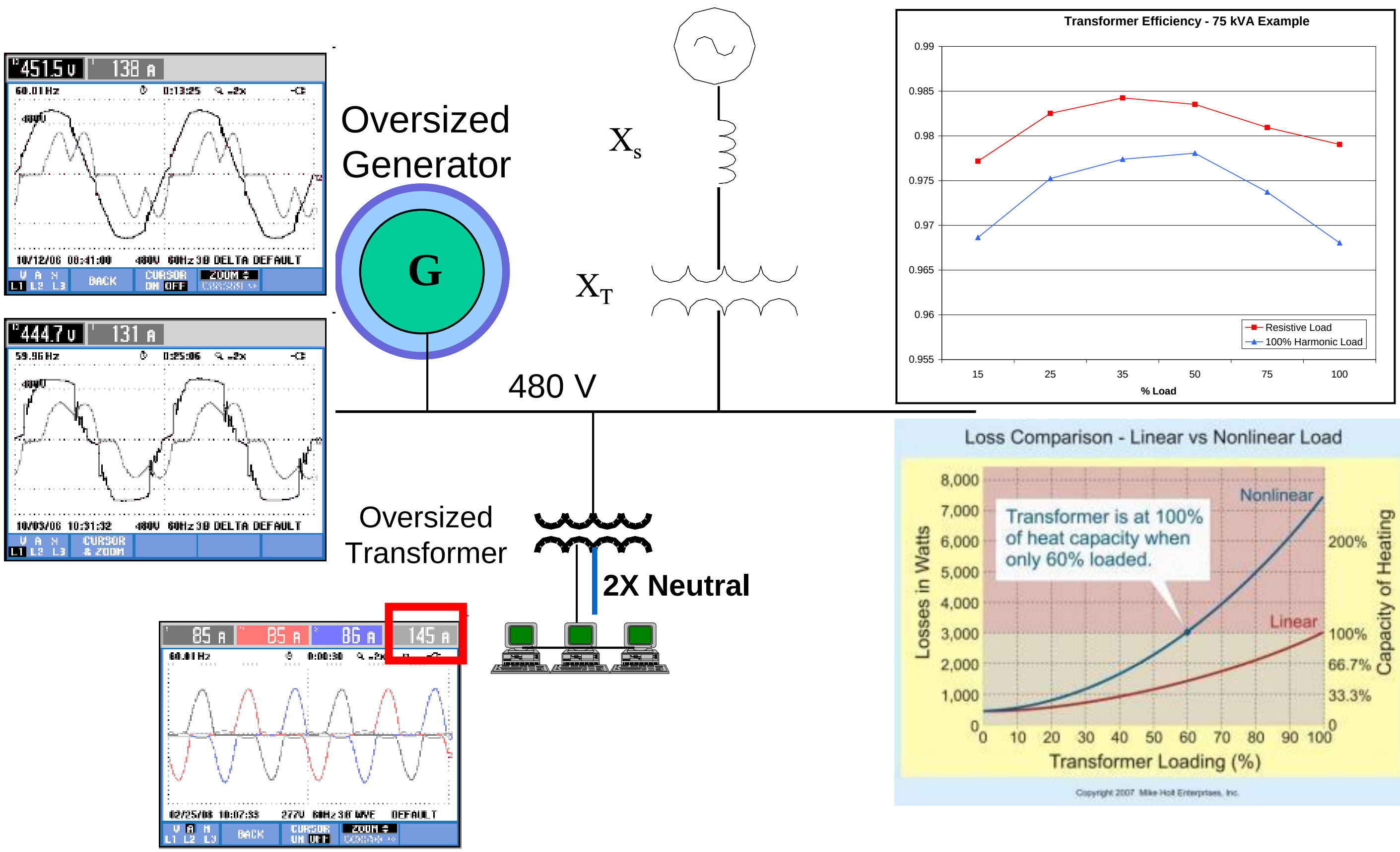
Harmonic producing loads are in use

You MUST check for harmonic resonance (series and parallel)

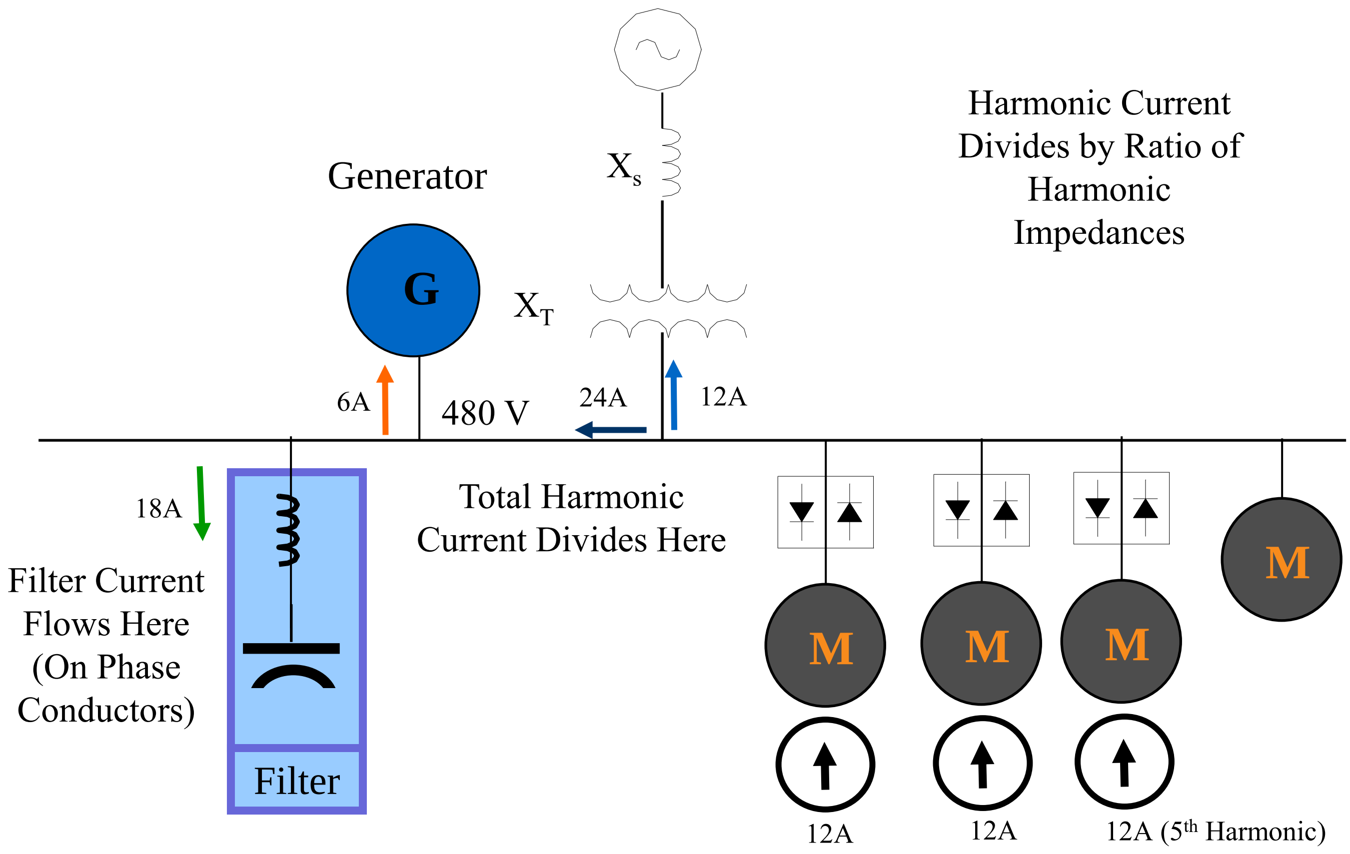
Harmonic solutions



Oversized equipment



Harmonic filters - how does a filter work?



Harmonic filters – design considerations

- Harmonic filters are “typically” designed/sized to correct power factor first
- Harmonic filters can filter some of the harmonic current on the system by providing a low impedance path
- Harmonic filters can be “tuned” or “detuned” to take more or less harmonic current
- Harmonic filters are NOT connected to ground (i.e. – harmonics flow like 60 Hz current in lines)

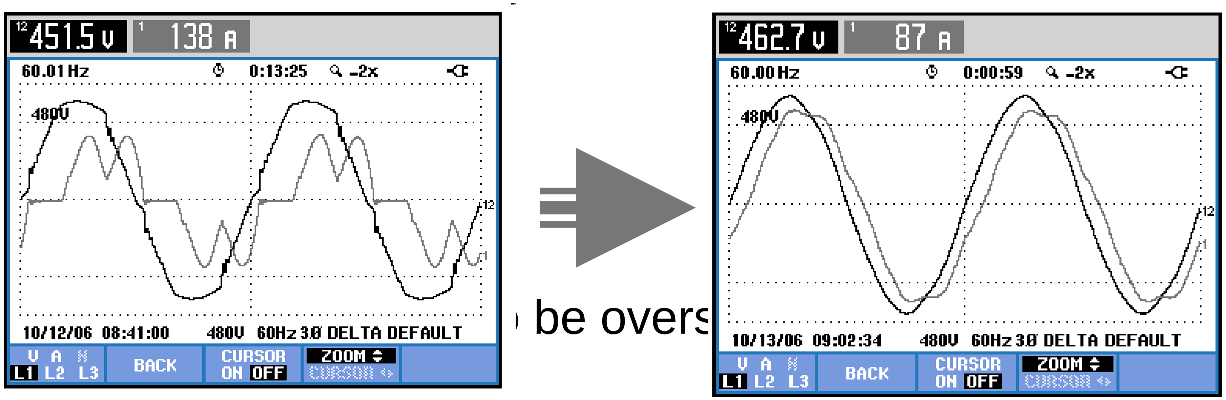
Harmonic solutions for industrial systems

Industrial System (Drives and Rectifiers)

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

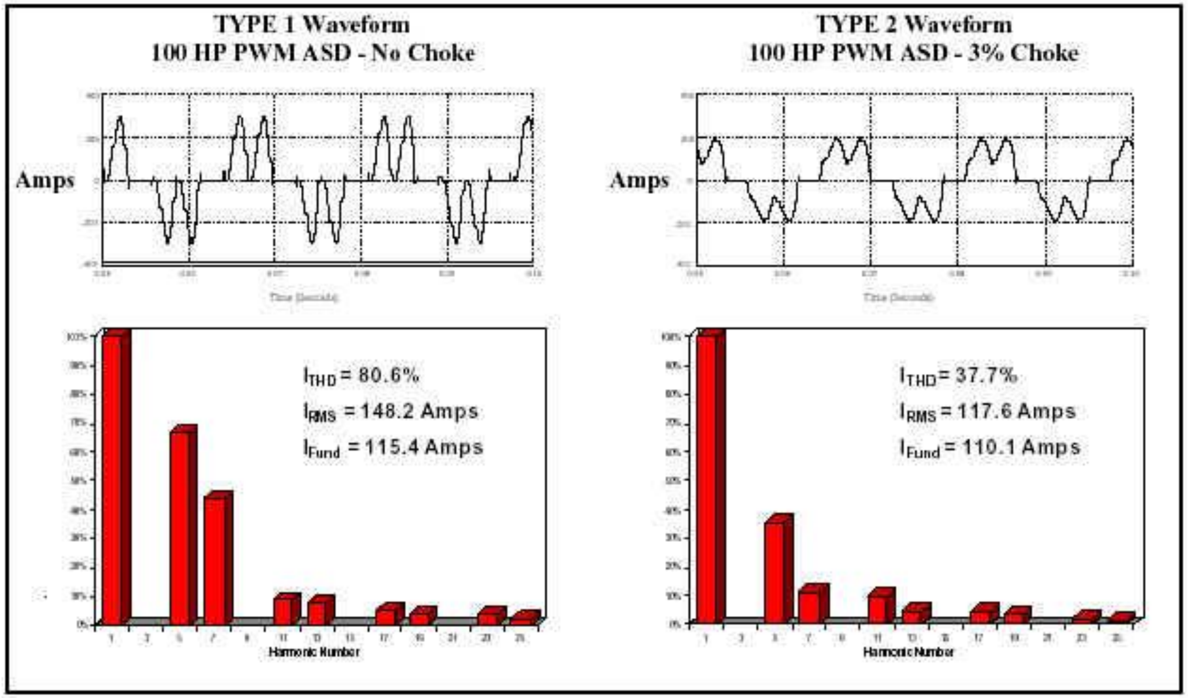
Low distortion loads (load solution)

- Rectifier Solutions – UPS, Drives, Battery Chargers
  - Active front end on UPS (93PM/9395) and some drives, computer power supplies
  - Industry driven toward component (load) solutions

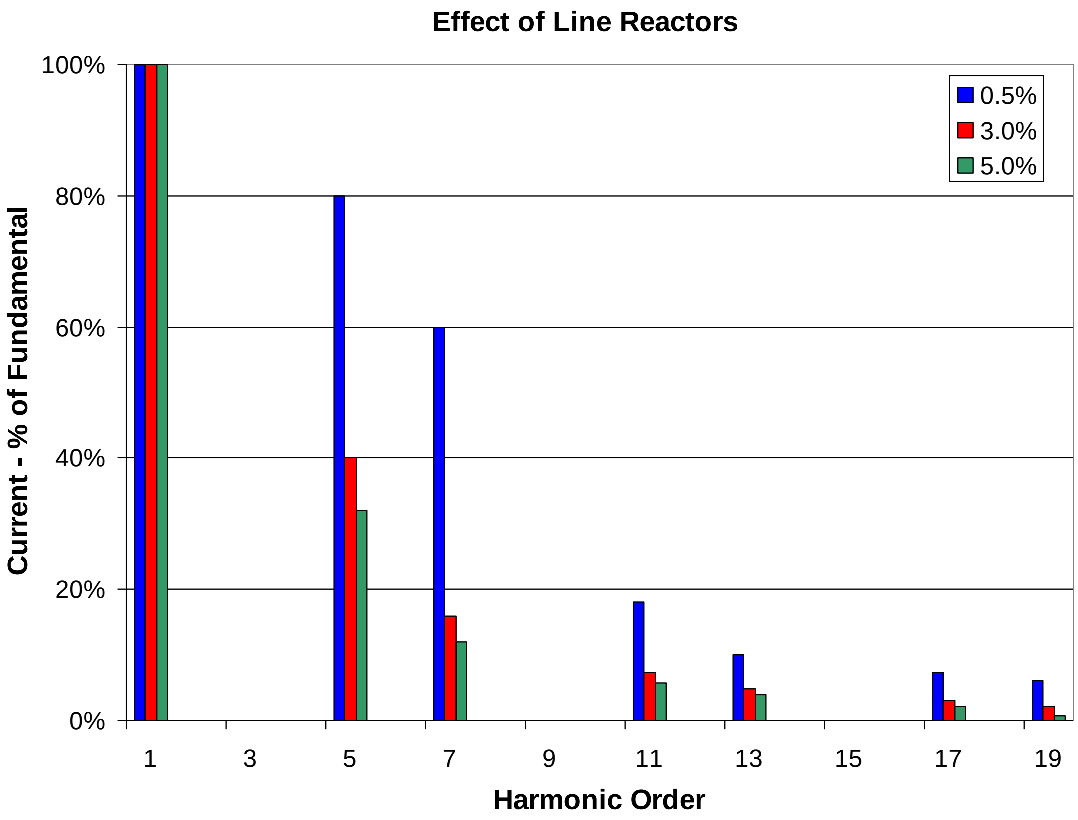


- G … be overs … UPS

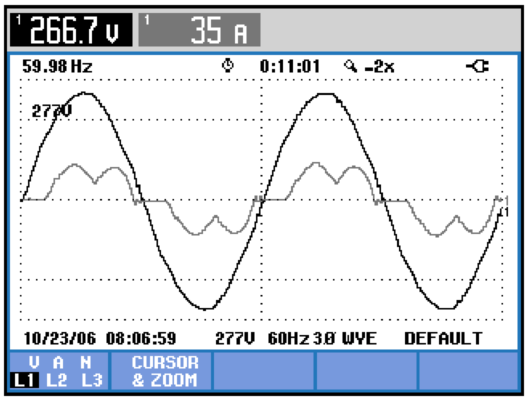
AC line reactors and DC chokes (load solution)

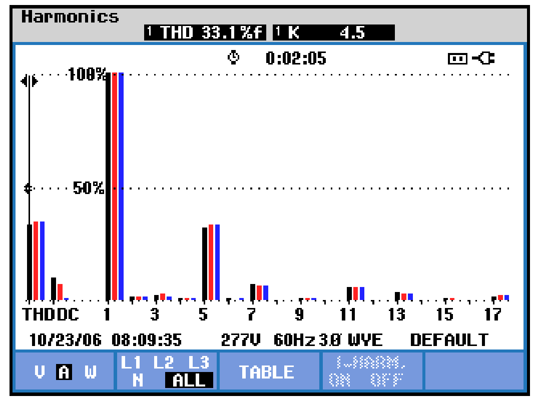


Effect of line reactors (load solution)



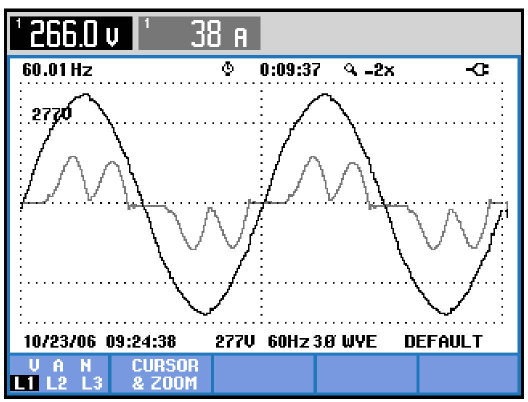
Isolation transformers (load or groups of load solution)

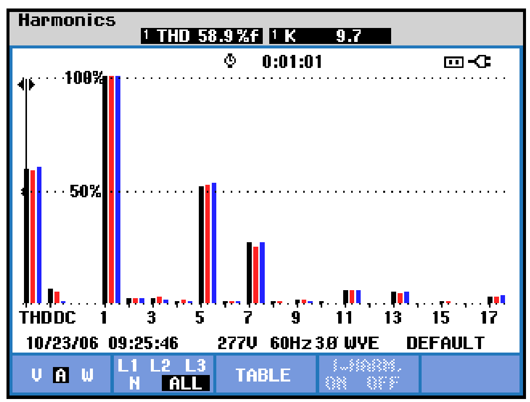




w/ isola trans

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



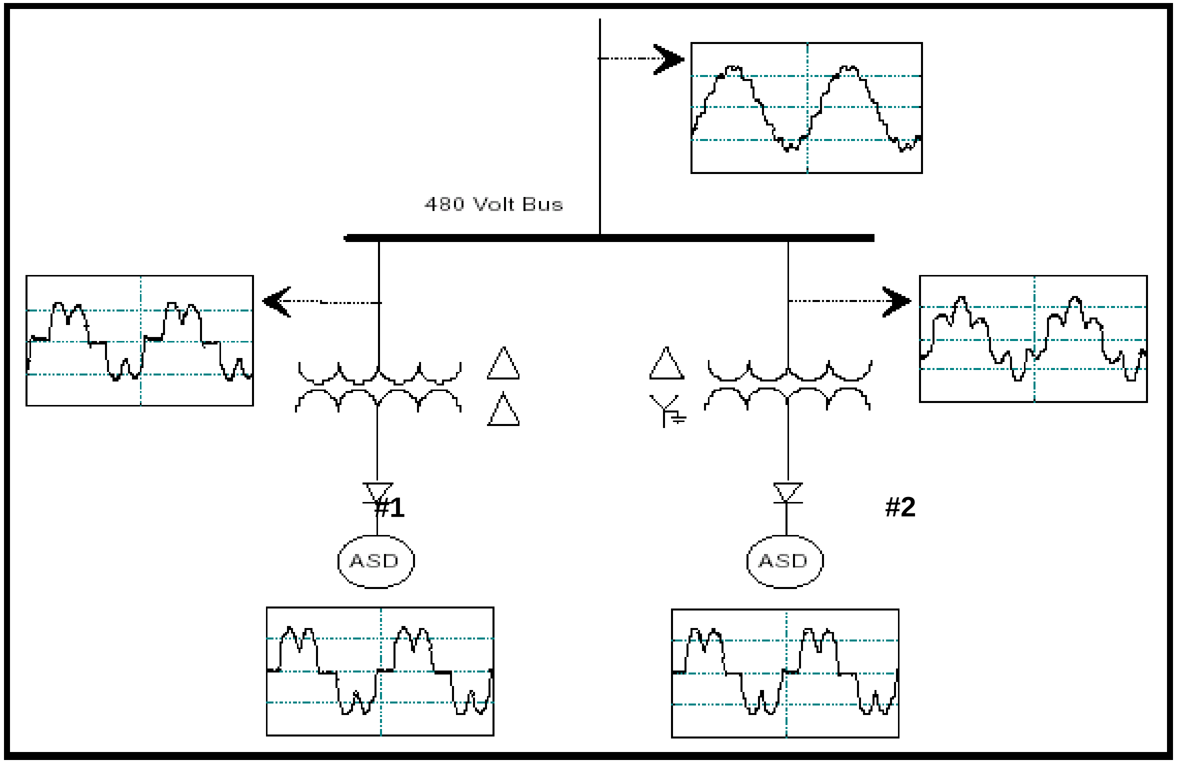


w/o isola trans

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

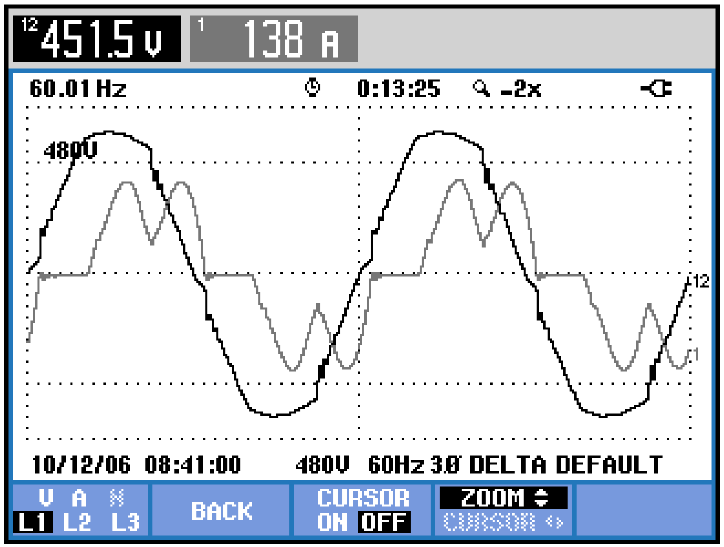
Phase shifting/harmonic cancellation (system approach)

12 Pulse, 18 Pulse or 24 Pulse Cancellation by Design

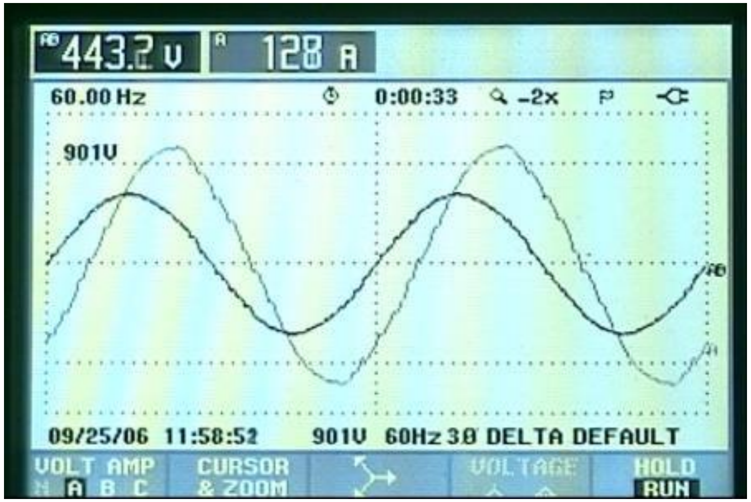


Phase shifting/harmonic cancellation (system approach)

Without Cancellation

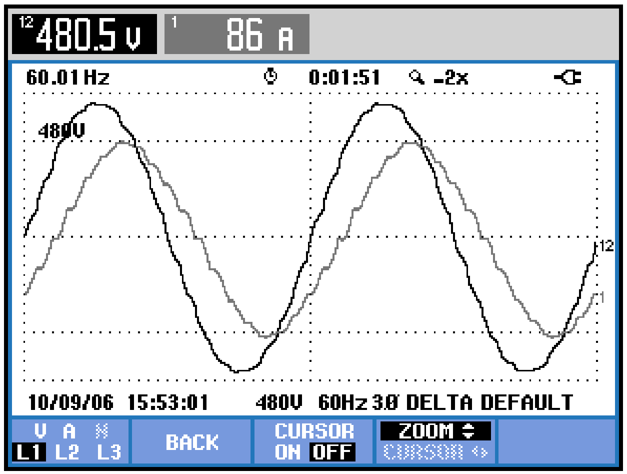


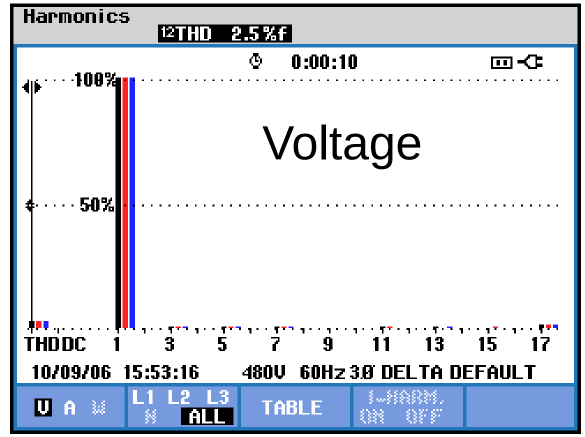
24 Pulse Cancellation

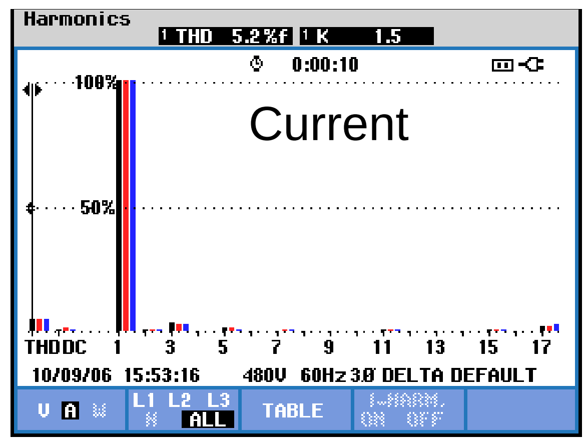


18 pulse drive (large load solution)

18 Pulse Design

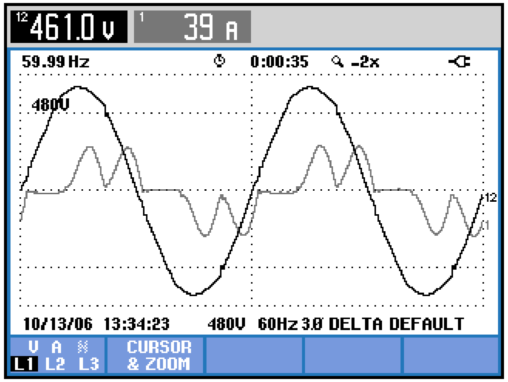


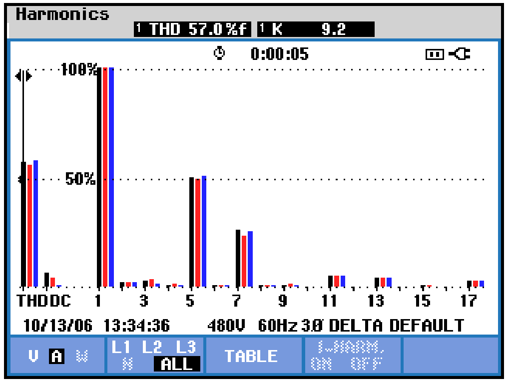




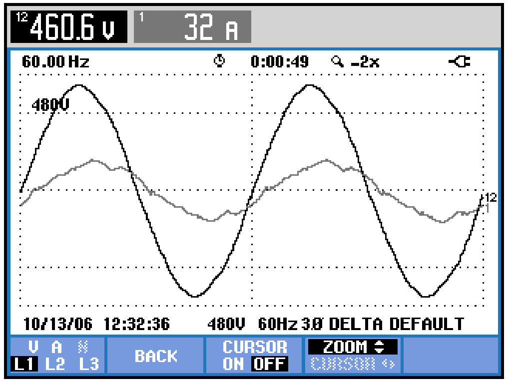
Drive dedicated (broadband) filter (load solution)

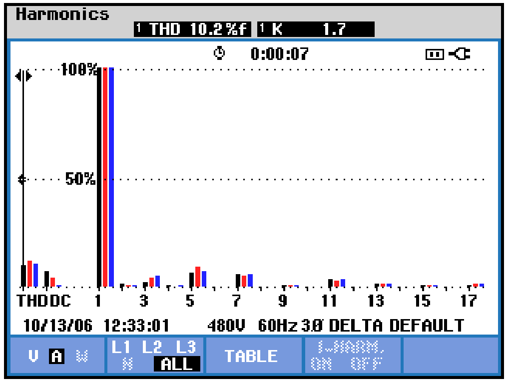
Standard Drive





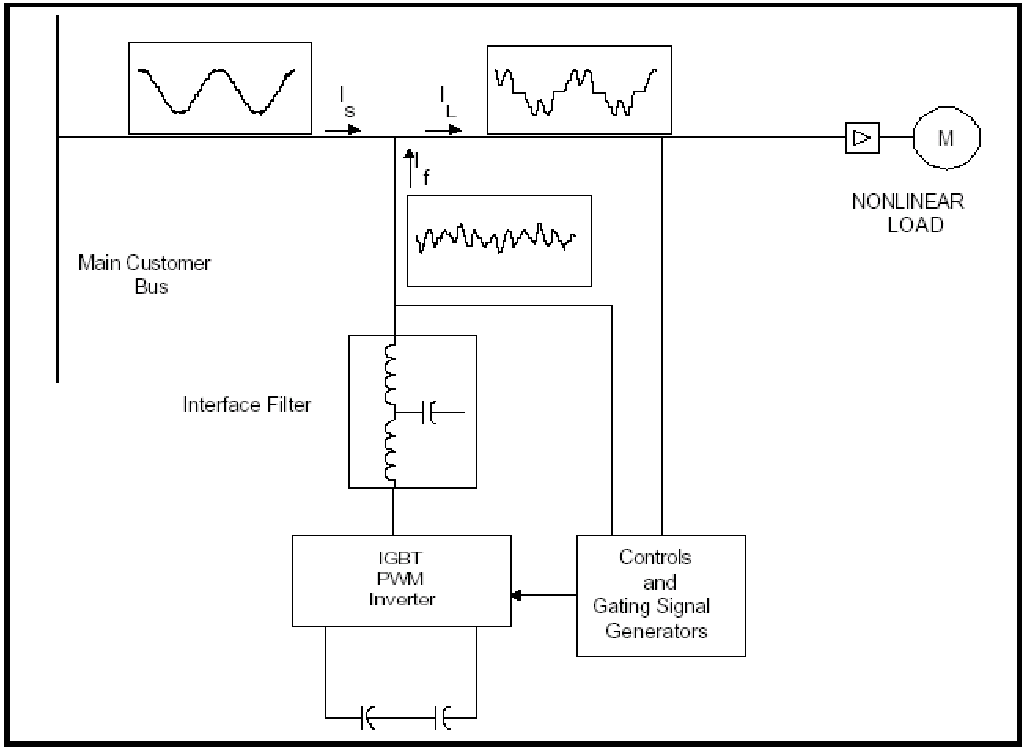
Drive with Dedicated Filter





Active filters (system approach)

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



Cost of harmonic correction

Description	Cost $/kVA	Cost p.u.
Line Reactor/DC Choke	3	1
Capacitors (LV)	12	4
Filter (MV)	15	5
Switched Filter (MV)	20	7
K-Rated Tranformer	25	8
Switched Capacitors (LV)	30	10
Fixed Filter (LV)	45	15
Harmonic Mitigating Transformer	50	17
Switched Filter (LV)	75	25
Static Switched Filter (LV)	85	28
Broadband Filter (Drives)	100	33
AFE Drive	150	50
Active Harmonic Filter	200	67
Assumed 1 HP = 1 kVA		
Per unit cost compared to reactor price per kVA (HP)		
Note that prices are generaized for comparison only		
Some equipment must be fully rated for loads - others can be partially rated		
Capacitors are shown for reference		

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