Harmonics and mitigation techniques

Power & Energy Institute of Kentucky

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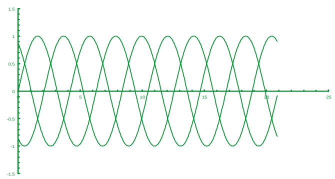
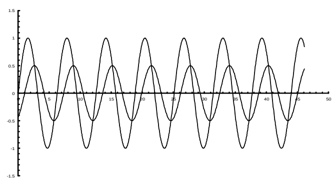
Digital Power B.U. - Schneider Electric

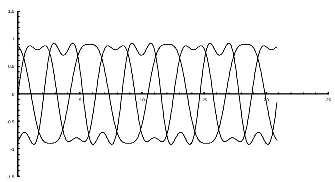
The ideal voltage supply does not exist



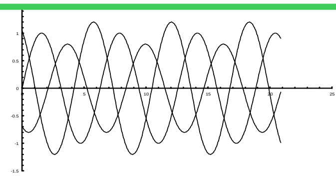
3-phase balanced



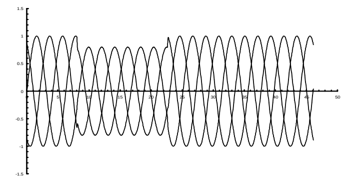
Power Factor



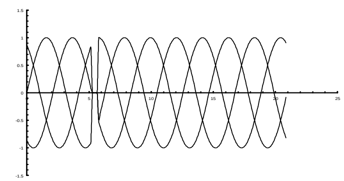
Harmonics



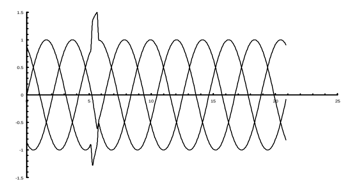
Phase unbalanced



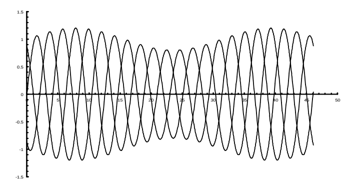
Sags/swells
Overvoltage



Notches

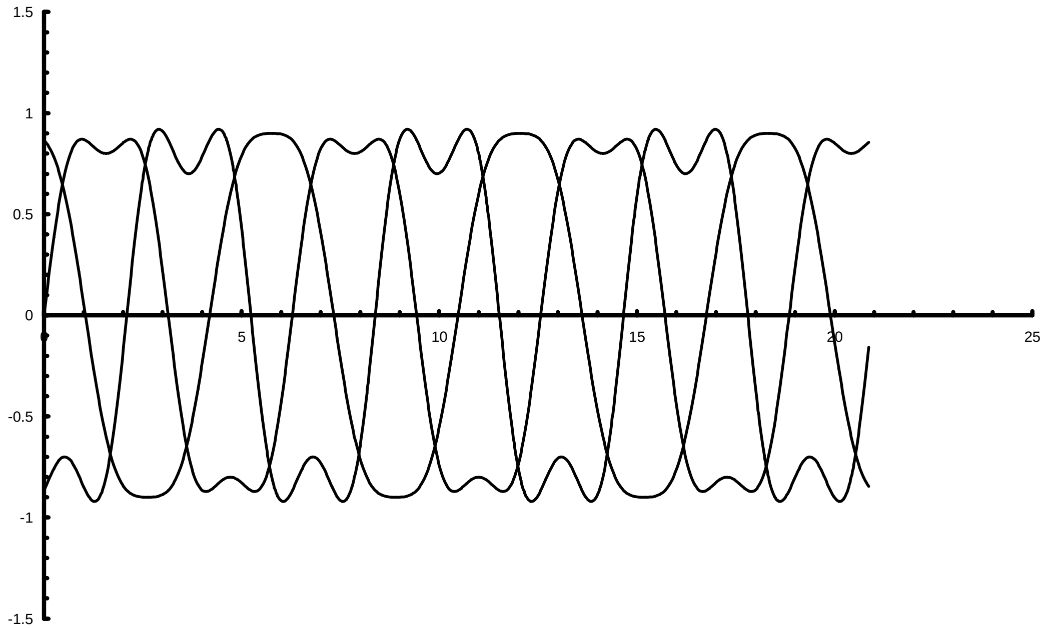


Spikes



Flicker

Introduction to Harmonics



Harmonics in electrical systems increase business operating costs…….

Increased system downtime

- Nuisance tripping of overloads and circuit breakers
- Bus failures
- Distortion of control signals

Increased maintenance

- Excessive heat places burden on electrical infrastructure from transformers to cables and bussing

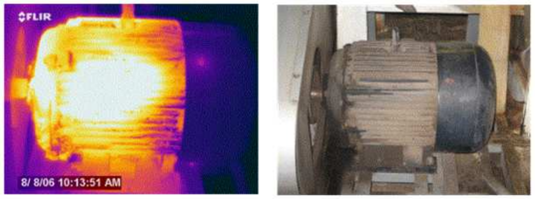
Lower Quality and Efficiency

- Interrupt production causing downtime, rework and scrap

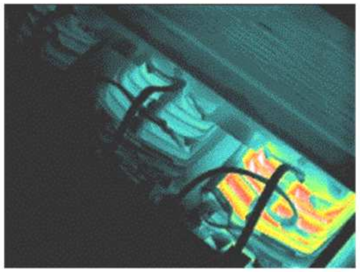
Reduced system capacity

- Requires costly equipment upgrades to support expansion

Harmonics are a circumstance of progress and they effect almost every business in today's environment…



Above thermal and daylight images show a three phase motor which has overheated. Power quality analysis proved condition was caused by negative sequence harmonics.



Above thermal image shows overheated windings on a step-down transformer, possibly caused by harmonics.

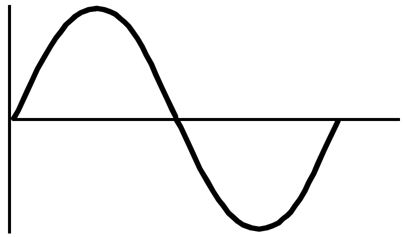
Harmonics: Fundamentals

Definition:

Harmonics are integer multiples of the fundamental frequency that, when added together, result in a distorted waveform

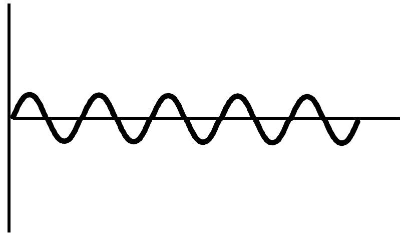
Harmonics: Fundamentals

Sinewave of a specific frequency supplied by the utility (a "clean" sinewave):



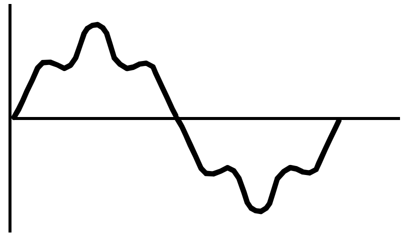
$f(x) = \sin(x)$

…plus a "5th" Harmonic Sinewave:



$f(x) = \frac{\sin(5x)}{5}$

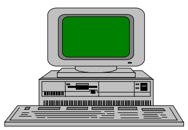
…results in a harmonic rich, non-linear wave shape:



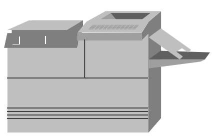
$f(x) = \sin(x) + \frac{\sin(5x)}{5}$

Harmonics: Fundamentals

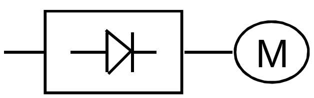
What produces "Non-linear" Current?



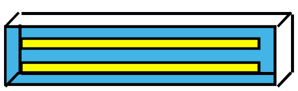
• Computers



• Copiers

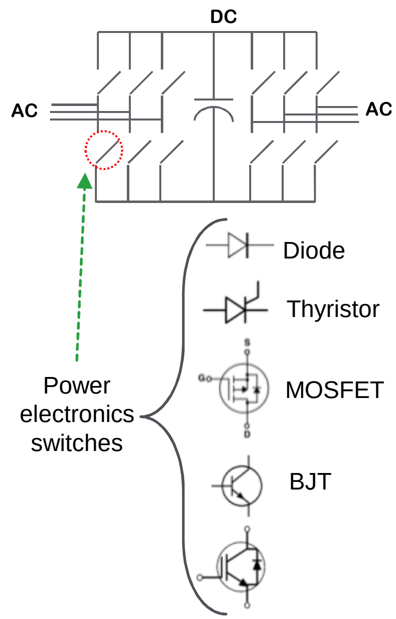


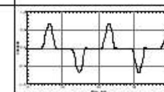
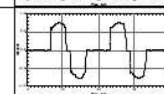
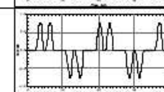
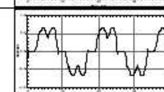
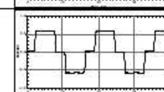
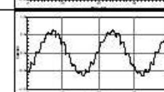
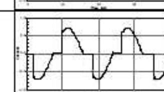
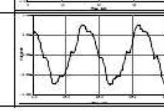
• AC or DC drives



• Electronic Ballasts

Nonlinear loads:



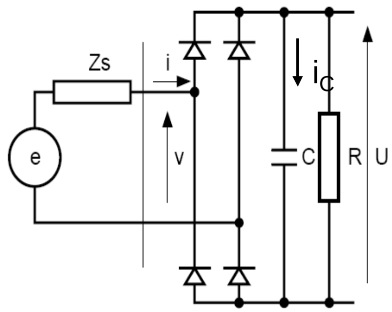
Type of Load	Typical Waveform	Current Distortion
Single Phase Power Supply		80% (high 3rd)
Semiconverter		high 2nd,3rd, 4th at partial loads
6 Pulse Converter, capacitive smoothing, no series inductance		80%
6 Pulse Converter, capacitive smoothing with series inductance > 3%, or dc drive		40%
6 Pulse Converter with large inductor for current smoothing		28%
12 Pulse Converter		15%
ac Voltage Regulator		varies with firing angle
Fluorescent Lighting		20%

Harmonics: Fundamentals

Single phase

full-bridge rectifier

circuit



h = np +/- 1

h	+/-/0
1	+
2	-
3	0
4	+
5	-
6	0
7	+
8	-
9	0
10	+
11	-
12	0
13	+
14	-
15	0

Single Phase Load (p = 4)

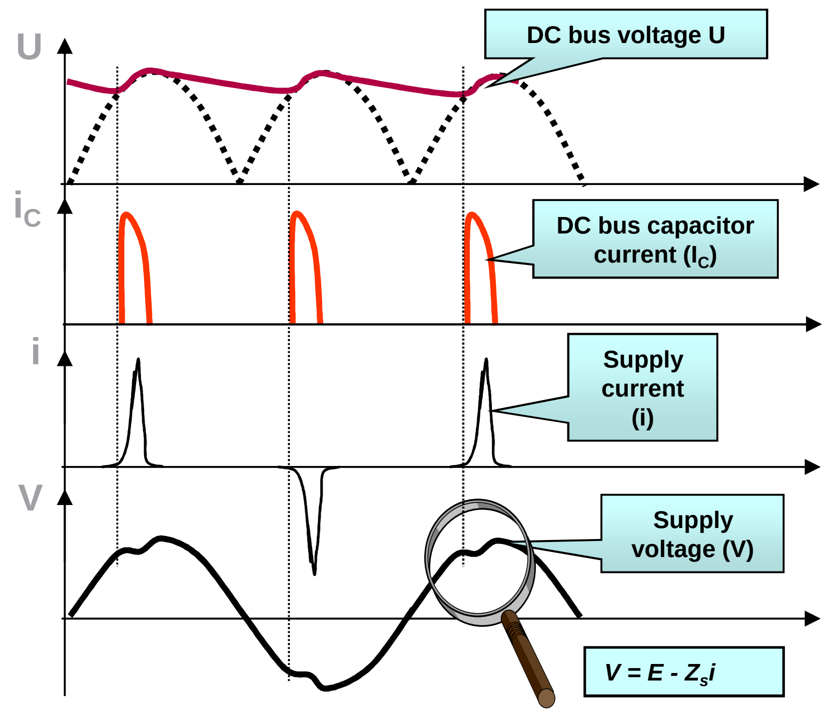
n	h(-)	h(+)
1	3	5
2	7	9
3	11	13
4	15	17

Requiring Neutral Compensation

Three Phase Load (p = 6)

n	h(-)	h(+)
1	5	7
2	11	13
3	17	19
4	23	25

NO need neutral compensation

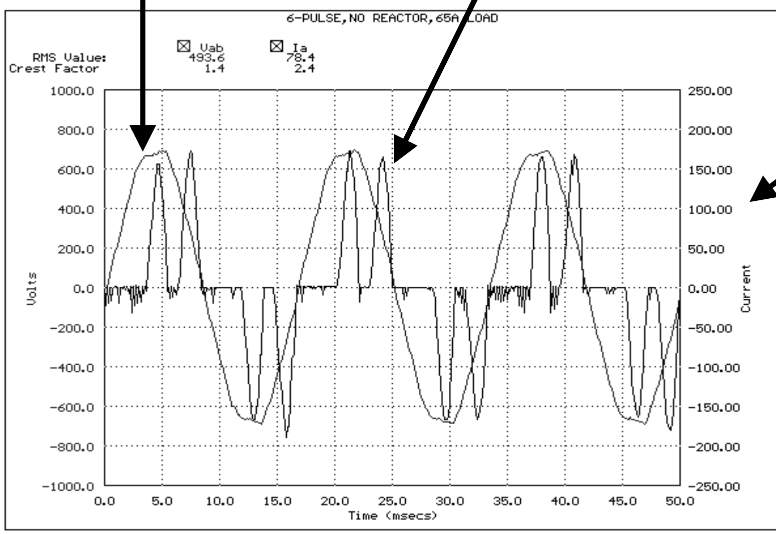


Harmonics: Fundamentals

- **Nonlinear loads draw harmonic current from source**
  - Does no work

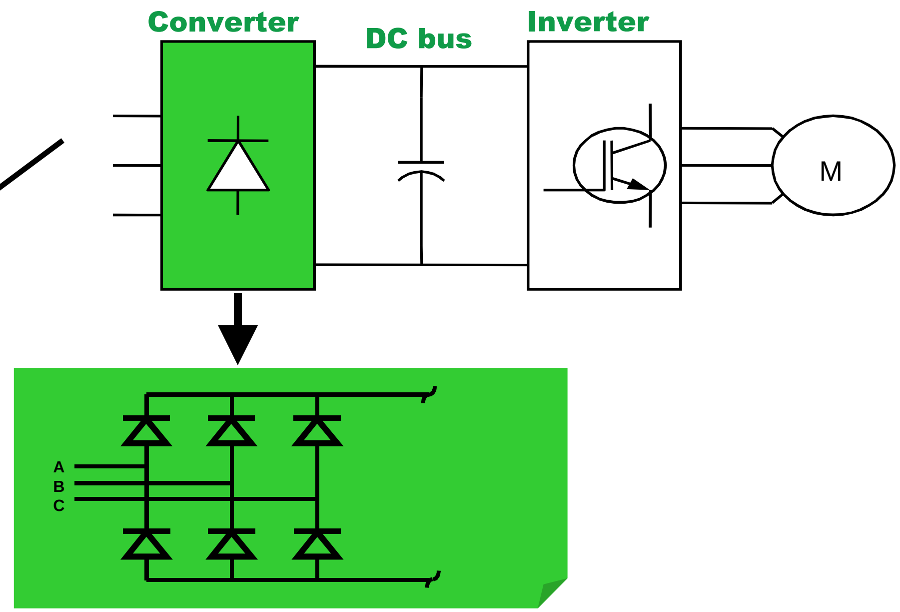
Voltage: flat topping of waveform

Current: high TDD between 90-100%



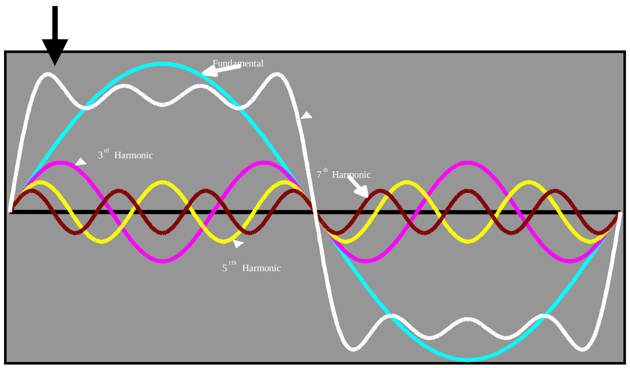
Basic three phase

PWM VSD



Harmonics: Fundamentals

Waveform seen with oscilloscope



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

- Characteristic harmonics are the predominate harmonics seen by the power distribution system
  - Predicted by the following equation:

$$H_c = np \pm 1$$

– H_C = characteristic harmonics to be expected
– n = an integer from 1,2,3,4,5, etc.
– p = number of pulses or rectifiers in circuit

- Amplitude is inverse of harmonic order (perfect world)

Harmonics: Fundamentals

Harmonic signature

Harmonics present by rectifier design					
	Type of rectifier				
Hn	1 phase 4-pulse	2 phase 4-pulse	3 phase 6-pulse	3 phase 12-pulse	3 phase 18-pulse
3	x	x			
5	x	x	x		
7	x	x	x		
9	x	x			
11	x	x	x	x	
13	x	x	x	x	
15	x	x			
17	x	x	x		x
19	x	x	x		x
21	x	x			
23	x	x	x	x	
25	x	x	x	x	
27	x	x			
29	x	x	x		
31	x	x	x		
33	x	x			
35	x	x	x	x	x
37	x	x	x	x	x
39	x	x			
41	x	x	x		
43	x	x	x		
45	x	x			
47	x	x	x	x	
49	x	x	x	x	

$H_c = np +/- 1$

H_c = characteristic harmonic order present

n = an integer

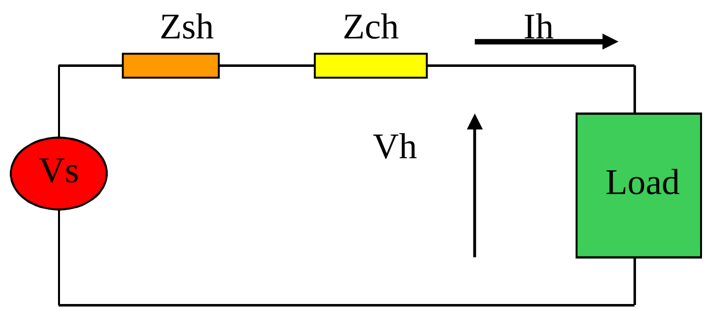
p = number of pulses

Multi-pulsing (ie: 12 & 18 pulses):

Elimination of lower order harmonic

removes largest amplitude harmonics

Harmonics: Fundamentals



Vh = Harmonic voltage

Ih = Harmonic current

Zsh = Source impedance for harmonic current

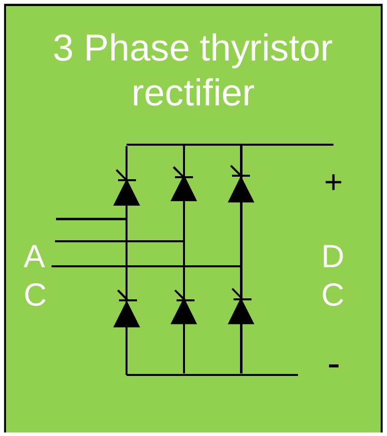
Zch = Cable impedance for harmonic current

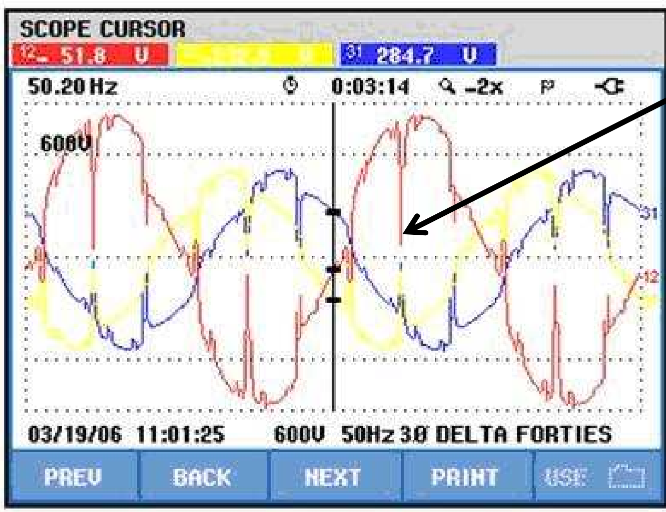
Vh = Ih * (Zsh + Zch)

Harmonic voltages (Vn):

- Develop as the harmonic current traverses the electrical system.
- Each harmonic order has its own system impedance (Zn) and thus develops its own harmonic voltage.
- The root-mean-square (rms) of all harmonic orders equals the total amplitude of harmonic current or voltage.
- Ohm's Law applies: Vn = In * Zn
- To reduce Vh: Reduce system impedance (Zsh & Zch) or reduce current (Ih)

Harmonics: Fundamentals





3 Phase thyristor rectifier (parallel, phase to phase)

Converts **AC** to controlled **DC**

Max harmonics at full load

Best PF at full load

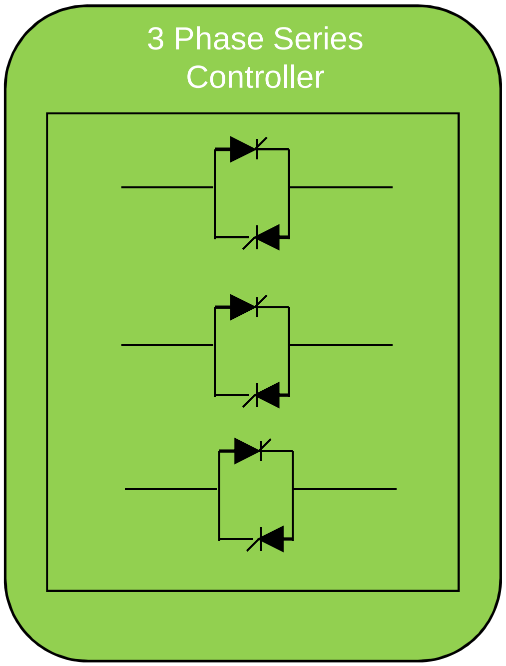
Harmful characteristic

Causes voltage notching (THDv)

> Requires input line reactors (inductance) to reduce notch depth

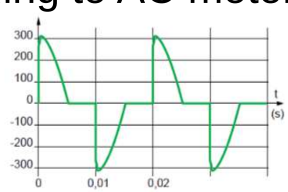
Notch created by a momentary short circuit when SCR commute from one phase to the other

Harmonics: Fundamentals



Transitions are short duration (2-3 seconds)

PF according to AC motor design



3 Phase controller (series)
Opposing (anti-parallel) thyristors per phase (not a rectifier)

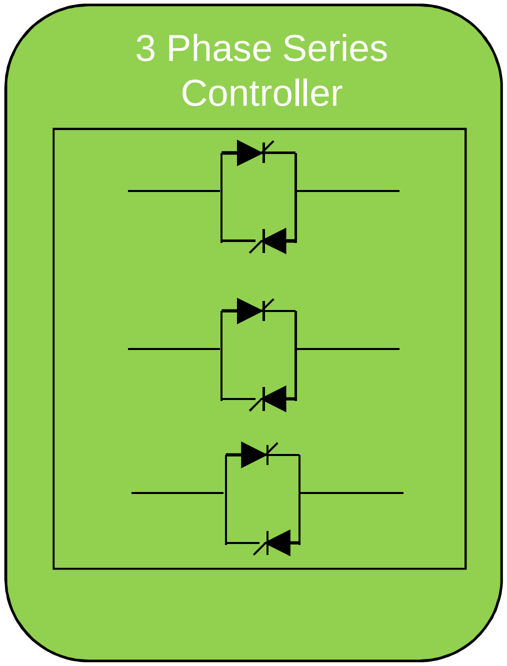
AC to **AC (variable volts)**
No harmonics at full output
PF is load dependent
i.e. AC Motor

Solid State Starters (SSS)
Transition harmonics only
During acceleration and deceleration

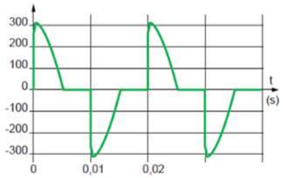
- Transition lagging PF
  - At full voltage – AC motor characteristics apply
  - Thyristors are full ON or Bypass contactor used to bypass

No snubbers (R-C) on thyristors

Harmonics: Fundamentals



Harmonics and PF increase and decrease together



Resistive & Inductive Heaters

Same thyristor configuration as SSS
Different use as compared to SSS

- Designed to control current through resistor banks or inductive coils to control heating
- ***High*** harmonics - except at full load
- ***Poor*** PF – except at full load

Harmonic Standard

IEEE 519-2014

Harmonic Standard

IEEE 519-2014

- Defines current distortion as **TDD (Total Demand Distortion)**
  - Largest amplitude of harmonic current occurs at maximum load of nonlinear device – if electrical system can handle this it can handle all lower levels of amplitudes
  - Always referenced to full load current
  - Effective meaning for current distortion

$$TDD = \frac{\sqrt{\sum I_h^2}}{I_{f\,(FLA)}}$$

- Defines voltage distortion as THD
  - Total harmonic voltage distortion

$$THDv = \frac{\sqrt{\sum V_h^2}}{V_f}$$

- Does not use THD(I)
  - Total harmonic current distortion
  - Instrument measurement (instantaneous values)
  - Uses measured load current to calculate THD(I)

$$THDi = \frac{\sqrt{\sum I_h^2}}{I_f}$$

Harmonic Standard

IEEE 519-2014

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

%TDD limits on users

%THDv limits on suppliers

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.

Harmonic Standard

IEEE 519-2014

Note: THDi is not used in IEEE 519-2014

Harmonic distortion terms used

total demand distortion (TDD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

total harmonic distortion (THD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included when necessary.

The recommended limits in this clause apply only at the point of common coupling and should not be applied to either individual pieces of equipment or at locations within a user's facility. In most cases, harmonic voltages and currents at these locations could be found to be significantly greater than the limits recommended at the PCC due to the lack of diversity, cancellation, and other phenomena that tend to reduce the combined effects of multiple harmonic sources to levels below their algebraic summation.

Harmonic Standard

IEEE 519-2014

Supplier standard for THDv

New category for <1.0 kV (applies at 480 & 600 VAC)

New voltage class

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]

Harmonic Standard

Limited to 50th order

IEEE 519-2014

USER standard for

TDD limits

Same as 519-1992

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

TDD versus THD(I)

•TDD and THD(I) are not the same except at 100% load

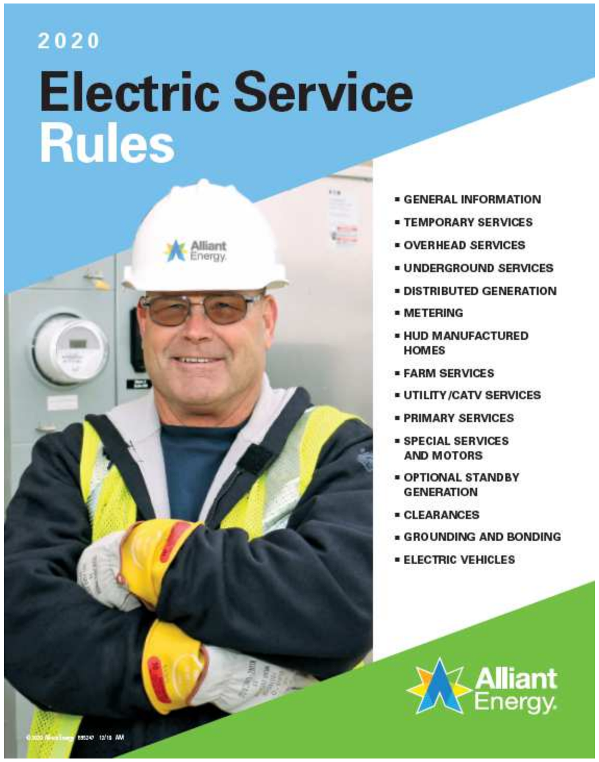
Example: with AccuSine PCS+ operating

	Measured				
	Total I, rms	Fund I, rms	Harm I, rms	THD(I)	TDD
Full load →	936.68	936.00	35.57	3.8%	3.8%
	836.70	836.00	34.28	4.1%	3.7%
	767.68	767.00	32.21	4.2%	3.4%
	592.63	592.00	27.23	4.6%	2.9%
	424.53	424.00	21.20	5.0%	2.3%
	246.58	246.00	16.97	6.9%	1.8%
	111.80	111.00	13.32	12.0%	1.4%

As load decreases, TDD decreases while THD(I) increases.

Examples of grid code requirements

PQ Guidelines - What does Alliant Energy have to say?



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Alliant Energy

ELECTRIC SERVICE RULES

SPECIAL EQUIPMENT & MOTORS — Issued Jan 2020

CHAPTER 11

ELECTRIC SERVICE RULES – SPECIAL EQUIPMENT & MOTORS

1100. SCOPE

This chapter covers the requirements for customer-owned equipment that may affect the quality of the service provided by Alliant Energy.

1101. SERVICE IMPAIRING EQUIPMENT

A. Service impairing equipment, because of its use, can lower the quality of power to other customers. Equipment that cannot be modified to prevent this shall be eliminated or controlled within performance limits required by Alliant Energy. If the customer meets these limits but still causes issues, such as but not limited to: flicker, harmonic distortion, voltage fluctuation, the customer causing the issues shall install equipment that addresses the service impairment.

1. Common types of service impairing equipment includes welders, arc furnaces, electric motors, augers, conveyors, plasma cutters, motor driven compressors, instantaneous water heaters, distributed generation, power factor correction equipment or other equipment having highly fluctuating or large instantaneous demands.
2. Other types of service impairing equipment include those with loads that cause harmonic distortion, such as data centers, inverter based equipment, rectifiers and variable frequency drives.
3. Equipment causing high-frequency current or harmonic distortion must comply with IEEE 519-2014.

B. The customer shall obtain pre-approval from Alliant Energy before installing equipment such as those listed in Section 1101.A above.

C. In most circumstances, Alliant Energy's electrical supply facilities are adequate to serve normal load additions. Customers installing service impairing equipment shall be billed the costs for additional facilities, metering and alterations specifically required to preventing impairment of service to other customers caused by this service impairing equipment.

1102. PHASE BALANCE

The customer shall balance electrical loads on their service. Each phase conductor shall carry a minimum of 25% of the total kVA at maximum load conditions.

PQ Guidelines - What does Oncor have to say?

CHAPTER 25. SUBSTANTIVE RULES APPLICABLE TO ELECTRIC SERVICE PROVIDERS.

Subchapter C. QUALITY OF SERVICE.

§25.51. Power Quality.

(a) **Voltage variation.**

(1) **Standard nominal voltages to be adopted.** In addition to the nominal voltages that each electric utility has already adopted, each nominal voltage adopted by an electric utility after approval of this rule shall be a voltage indicated by the version of the American National Standards Institute, Incorporated (ANSI) Standard C84.1, *Electrical Power Systems and Equipment-Voltage Ratings (60Hz)*, or equivalent ANSI standard as later amended, in effect at the time of adoption of the nominal voltages. An electric utility may adopt different nominal voltages to serve specific customers if such action does not compromise prudent transmission and distribution system operation.

(2) **Nominal voltage limitations**. So far as technologically practicable, each electric utility shall maintain its standard distribution system nominal voltages within the limits specified in the *current version* of ANSI Standard C84.1, or equivalent ANSI standard as later amended. Each electric utility offering service at transmission voltages to customers who have their own transformation equipment shall maintain such voltages within a range of plus or minus 10% of its adopted nominal voltages. Variations in distribution system voltage in excess of the limits specified in ANSI C84.1 and transmission system voltages in excess of plus or minus 10% caused by action of the elements and infrequent and unavoidable fluctuations of short duration due to station or system operation shall not be considered violations of this subsection.

(b) **Frequency variation**. Each electric utility supplying alternating current shall adopt a standard frequency of 60 Hertz. This frequency shall be maintained within the limits stated in the current version of the North American Electric Reliability Council (NERC) operating manual, or succeeding NERC document that may subsequently replace the operating manual.

(c) **Harmonics.** In 60 Hertz electric power systems, a harmonic is a sinusoidal component of the 60 Hertz fundamental wave having a frequency that is an integral multiple of the fundamental frequency. "Excessive harmonics," in this subsection, shall mean levels of current or voltage distortion at the point of common coupling between the electric utility and the customer outside the levels recommended in the IEEE standard referenced in paragraph (1) of this section. Each electric utility shall assist every customer affected with problems caused by excessive harmonics and customers affected in exceptional cases as described in paragraph (5) of this section.

(1) **Applicable standards.** In addressing harmonics problems, the electric utility and the customer shall implement to the extent reasonably practicable and in conformance with prudent operation the practices outlined in IEEE Standard 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems,* or any successor IEEE standard, to the extent not inconsistent with law, including state and federal statutes, orders, and regulations, and applicable municipal regulations.

https://www.puc.texas.gov/agency/rulesnlaws/subrules/electric/25.51/25.51.pdf

5.5.5 POWER FACTOR

If the Power Factor of Retail Customer's load is found to be less than 95% lagging as measured at the Meter, Company may require Retail Customer to arrange for the installation of appropriate equipment on Retail Customer's side of the Meter necessary to correct Retail Customer's Power Factor between unity and 95% lagging as measured at Meter, or, if Retail Customer fails to correct its Power Factor consistent with this standard, the demand associated with Retail Customer's use of Delivery Service, as determined in the appropriate Rate Schedules in Section 6.1 RATE SCHEDULES, may be increased according to the following formulas:

(1) Calculation of Power Factor Adjusted NCP kW.
The NCP kW applicable under the Monthly Rate section shall be modified by the following formula:

Power Factor Adjusted Monthly NCP kW= (Actual Monthly NCP kW x 0.95)/Current Month Power Factor

(2) Calculation of Power Factor Adjusted 4-CP kW.
Each of the Retail Customer's monthly coincident peak kW Demands used to calculate the Retail Customer's average 4 CP kW Demand applicable under the Monthly Rate section shall be calculated using the following formula:

TXU Energy

Request for Proposal
Sachem, Inc.,
Cleburne, Texas

PQ Guidelines - What does Rio Grande have to say?

RIO GRANDE ELECTRIC COOPERATIVE, INC.

HIGHWAY 90 & SH 131
P.O. BOX 1509
BRACKETTVILLE, TEXAS 78832

ELECTRIC COOPERATIVE

TARIFF

RIO GRANDE ELECTRIC COOPERATIVE, INC.

Industrial Consumer Inspection Report

Consumers utilizing nonlinear loads, such as, but not limited to, adjustable speed drives and uninterruptible power supplies, must employ devices that limit the harmonic voltage and current distortion limits to those set out in IEEE standard 519 5.1 and 5.2 per the Rio Grande Electric Cooperative, Inc. Tariff.

RGEC will perform a field inspection at the point of delivery to ensure IEEE 519 compliance. Noncompliance will result in immediate disconnection of meter. Re-energization is contingent upon IEEE 519 compliance.

☑ Power quality data analysis

Performed by: Gerry Delfin/Jesse Guerrero

Title: SSE/PSA 10/22/2019

Current Harmonics: Pass ☐ Fail ☑

Comments:

Ave. TDD @ 27.89% (IEEE 519 Compliance range are 7%, 3.5% for Individual & 8% for TDD)
Individual THD 3rd - 5th - 7th - 11th-13th-17th Harmonic = 18% - 59.8% - 24.35% - 11%-5.7% -4 3 %

https://www.riogrande.coop/info/Tariff/RGECTariff2018BoardApproved04.18.18.pdf

Relationship between capacitors and harmonics

How Harmonics Affect Capacitors:

Capacitors are naturally a low impedance to high frequencies:

- **Caps absorb harmonic in current**

As capacitor absorbs harmonic in current, the capacitor heats up

- **Reduced life expectancy**

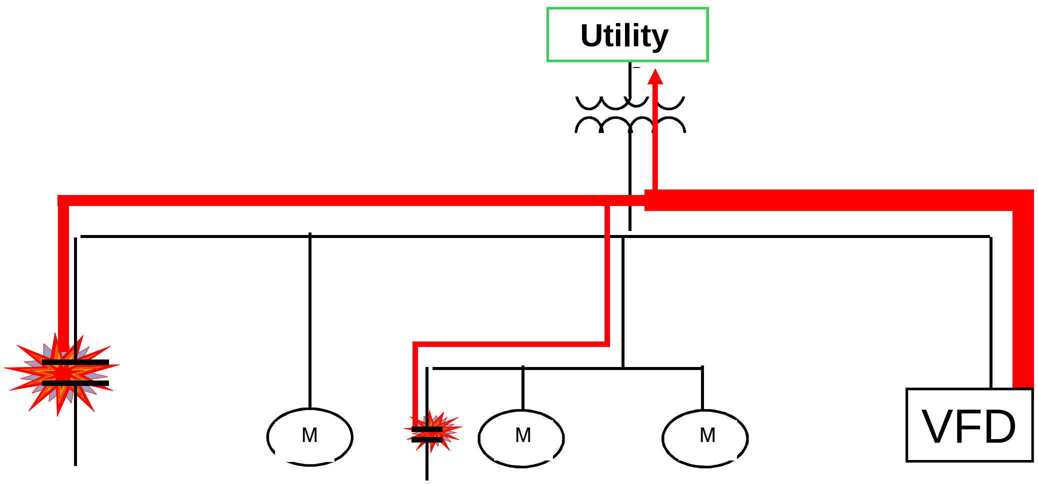
Voltage harmonics stress the capacitor dielectric

- **Reduced life expectancy**

Parallel combination of capacitors with motor or transformer can cause resonance.......

Capacitors Absorb Harmonic in current

The capacitor has lower impedance than the utility, therefore it absorbs the harmonics

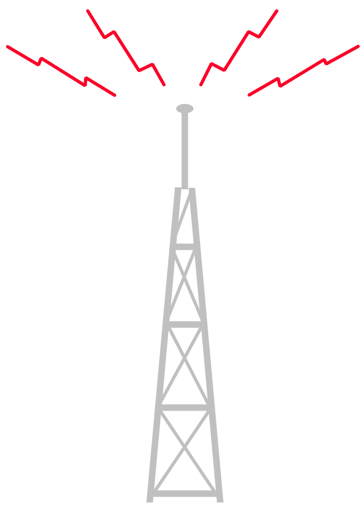


- capacitor diverts flow of harmonics
- Harmonic current increases
- capacitor absorbes harmonic current
- capacitor overheats & can fail over time

or worse.....

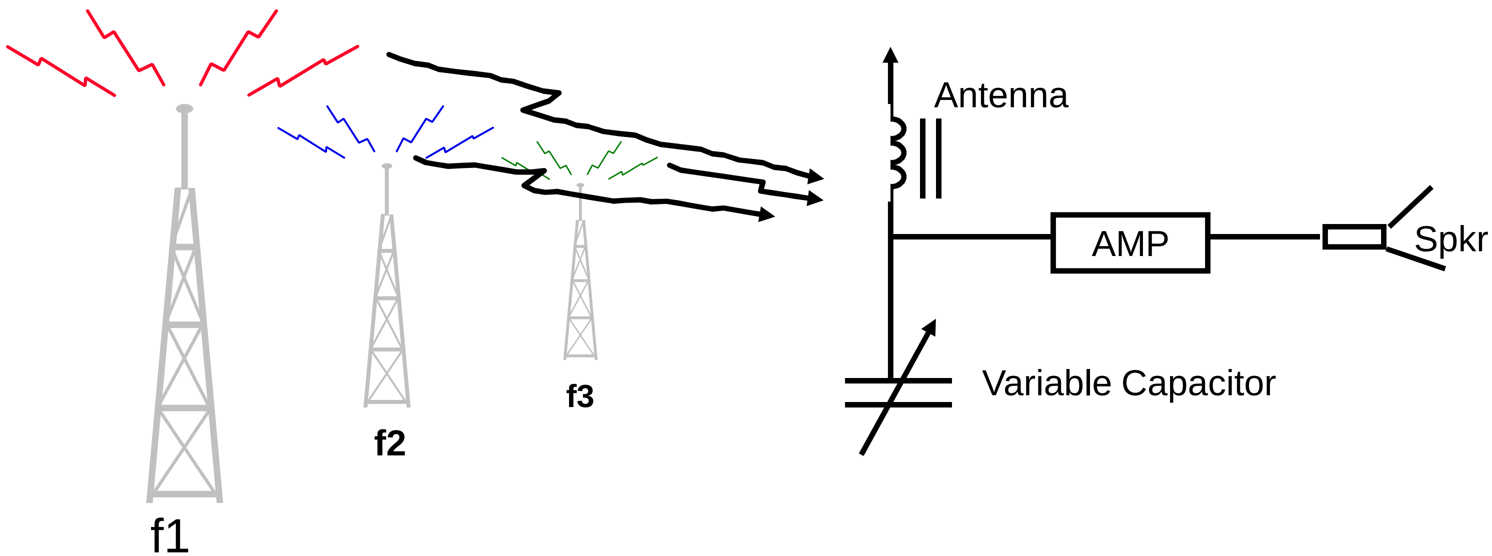
How Harmonics Affect Capacitors:

You use the principle of resonance every day!



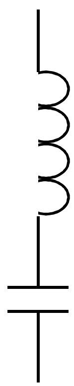
How Harmonics Affect Capacitors:

A Radio uses Resonance to Capture a Radio Station:



How Harmonics Affect Capacitors (Resonance)

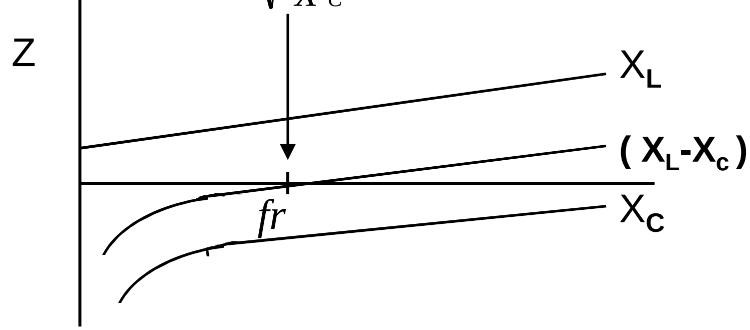
Resonance:



$$X_L = 2\pi fl$$

$$X_C = \frac{1}{2\pi fc}$$

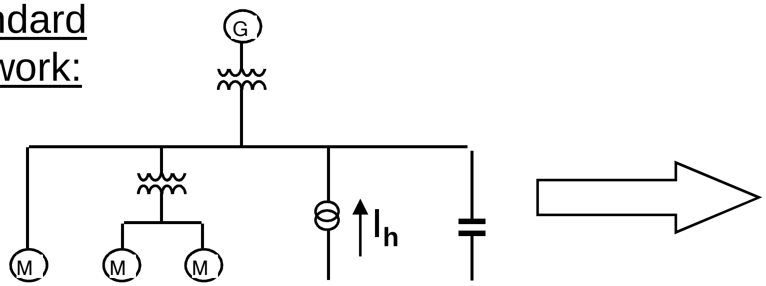
$$fr = f_1\sqrt{\frac{X_L}{X_C}}$$ ➡ Resonance



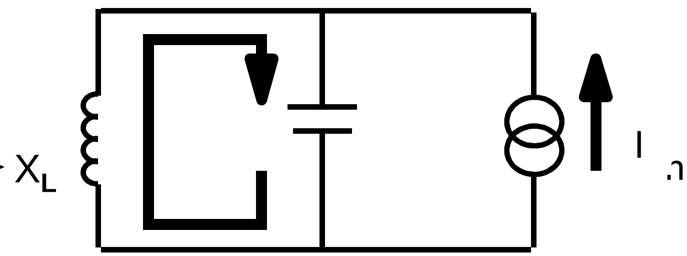
How Harmonics Affect Capacitors:

How Capacitors “Tune” a circuit:

Standard Network:



Equivalent circuit:



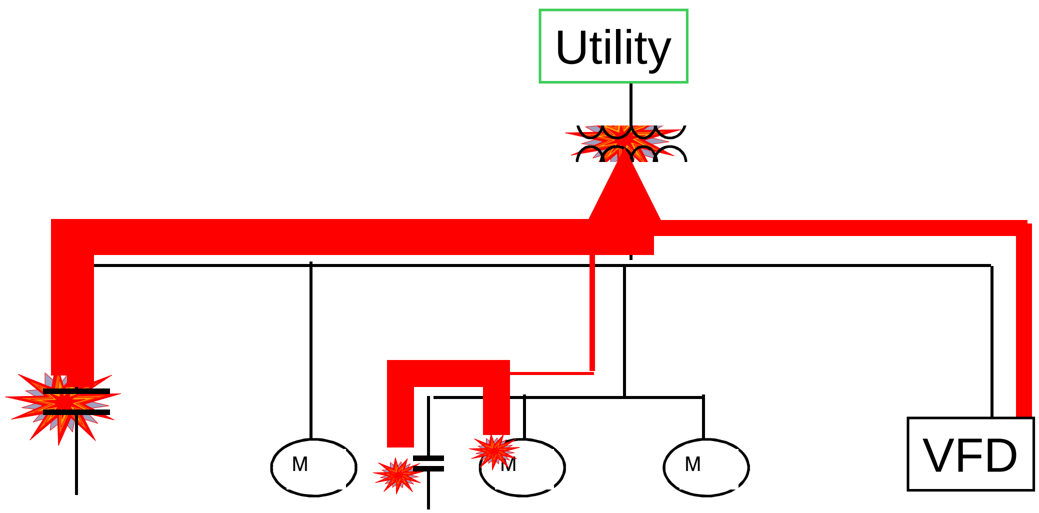
$$fr = 60 \times \sqrt{\frac{kVA \times 100}{kVAR \times Iz}}$$

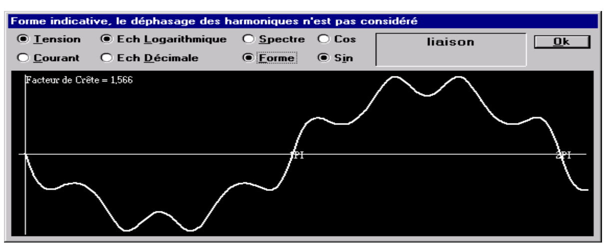
e.g... 1500 kVA
225 kVAR
5.5% Iz

$$\therefore fr = 60 \times \sqrt{\frac{1500 \times 100}{225 \times 5.5}} = 660\ hz = h_{11}$$

Parallel Resonance and harmonic magnification

- **Resonance:**

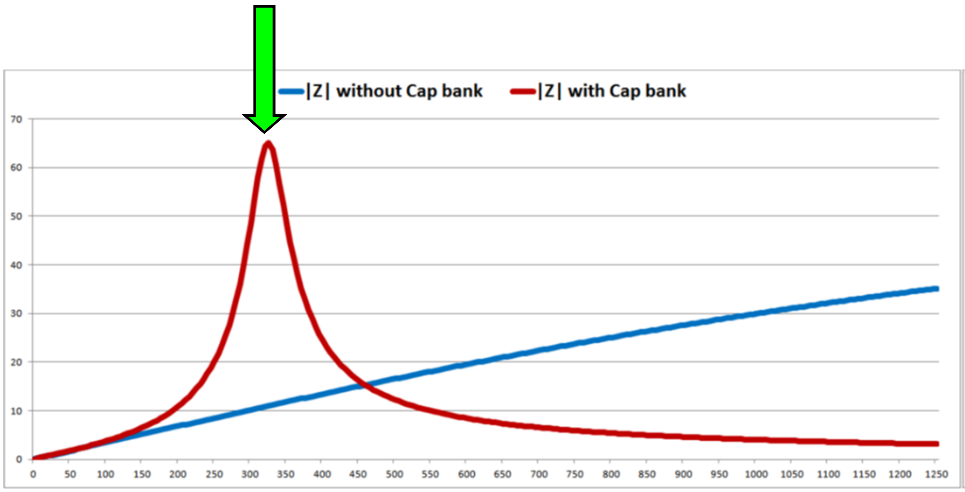


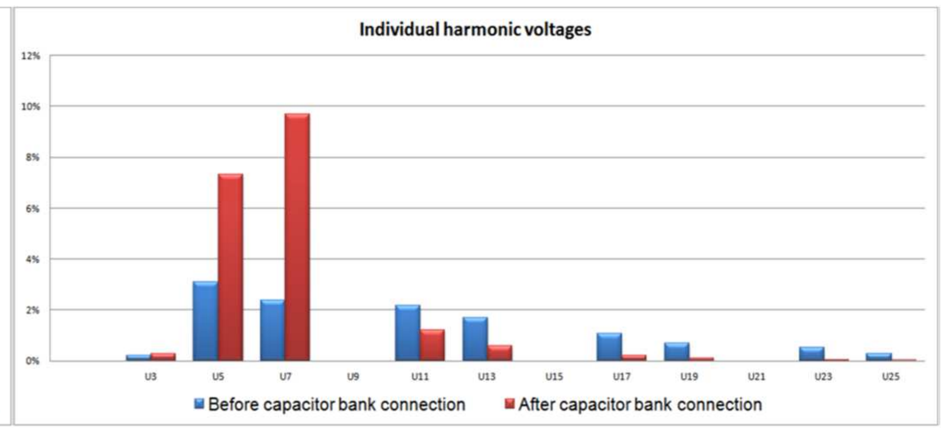


- **Amplification of current between capacitor and transformer**
- **Current distortion rises**
- **Voltage distortion rises**
- **Main transformer &/or capacitor fuses blow**
- **Equipment damage**

Parallel Resonance

Resonant Point likely to amplify dominant harmonic (typically 5th, 7th and 11th)

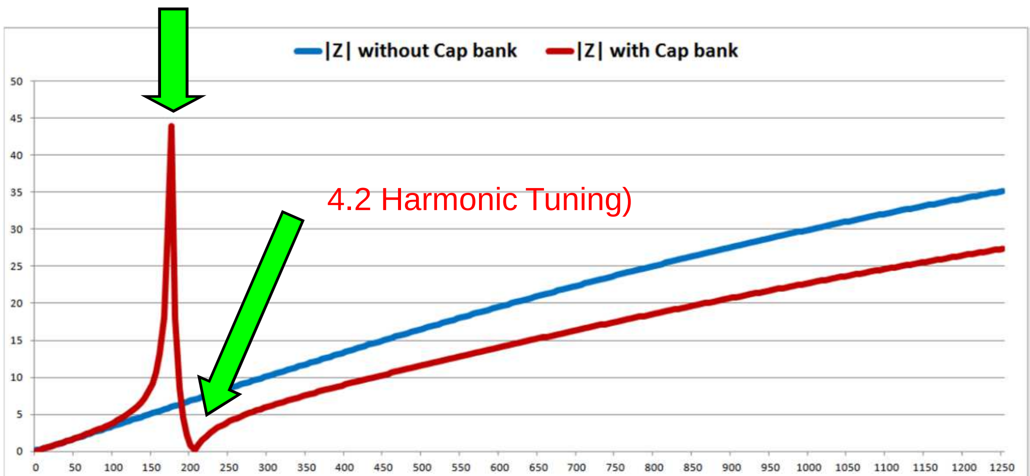


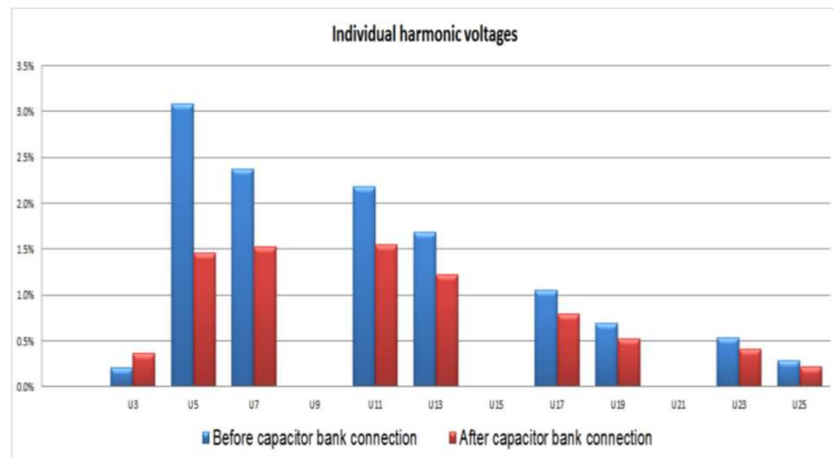


Magnification of Harmonic Current and Voltage when Standard Capacitor are Added to the Network

De-Tune to Avoid Resonance

Resonant Point where no Harmonic
Content present (3.7th typical)





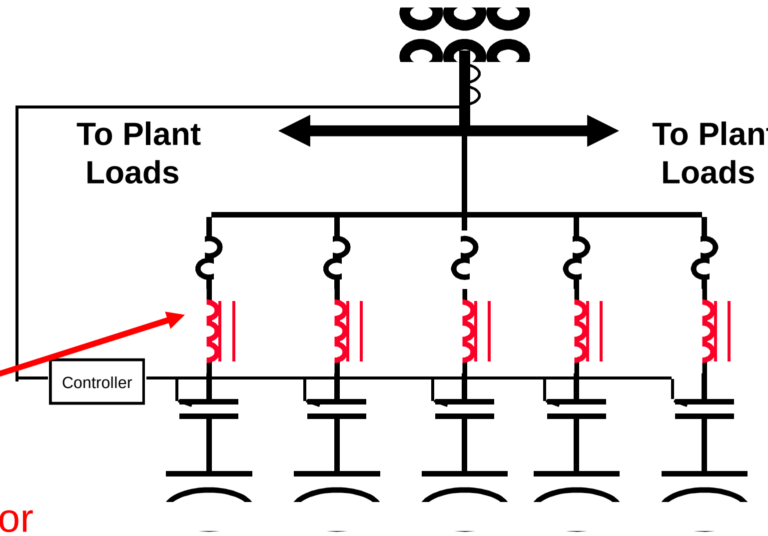
Effect on Harmonic Current and Voltage when De-Tuned Capacitor Bank
is Applied (AV6000 & AT6000)

Low Voltage Automatic Capacitor Bank with De-tuning reactors

De-Tuned (DR) automatic capacitor bank :

- Same as automatic capacitor bank with c/w De-Tuning reactors.
- Works like a standard automatic capacitor bank
- Avoid resonance between the capacitors and the supply transformer.

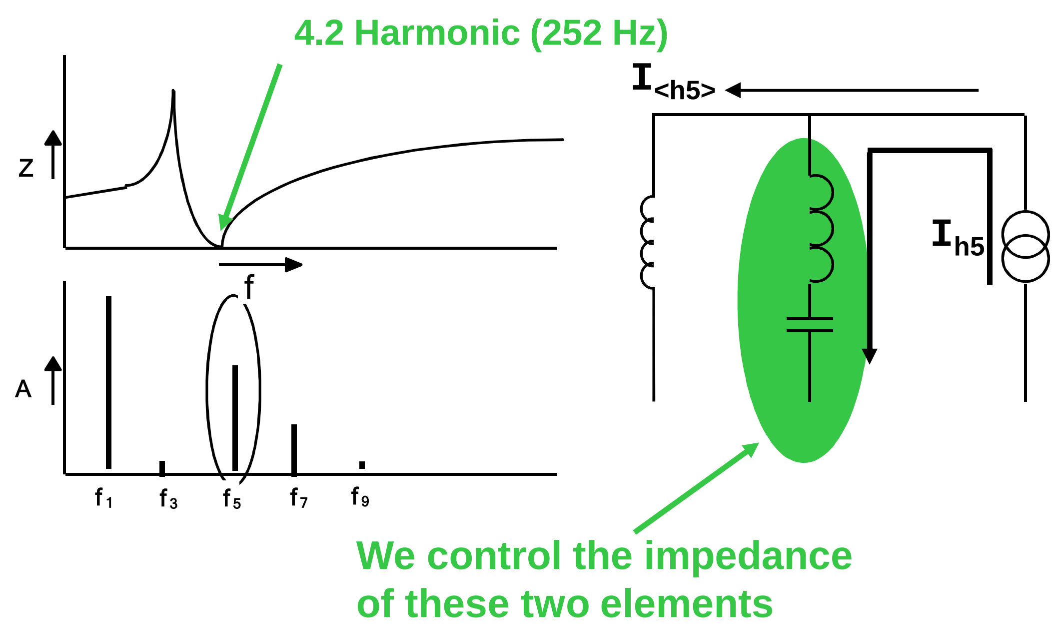
De-Tuning Reactor



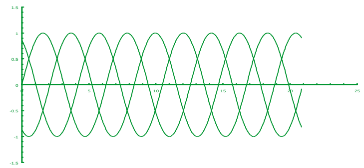
Power Factor Correction With Harmonics:

De-tuning a network:

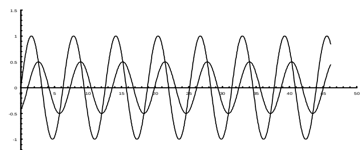
- “Force” the resonant point away from naturally occurring harmonics



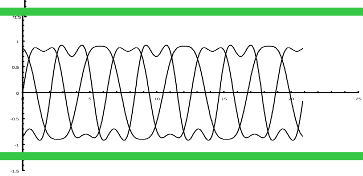
The ideal voltage supply does not exist, Active Harmonic Filters can correct 3 PQ problems



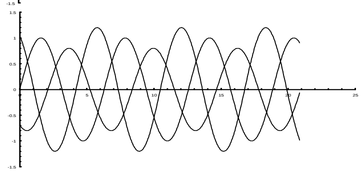
3-phase balanced



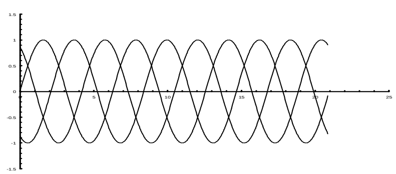
Power Factor



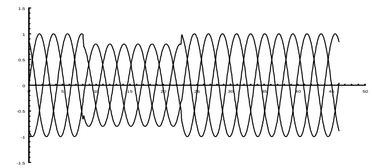
Harmonics



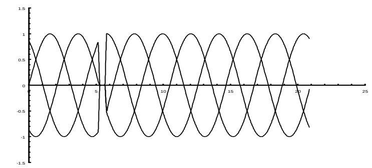
Phase unbalanced



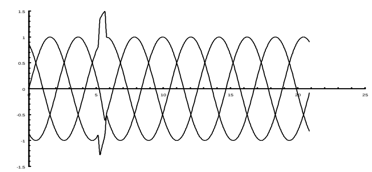
Blackout



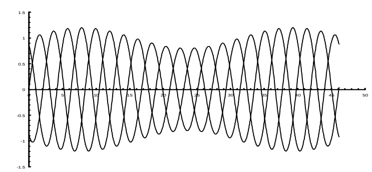
Sags/swells
Overvoltage



notches



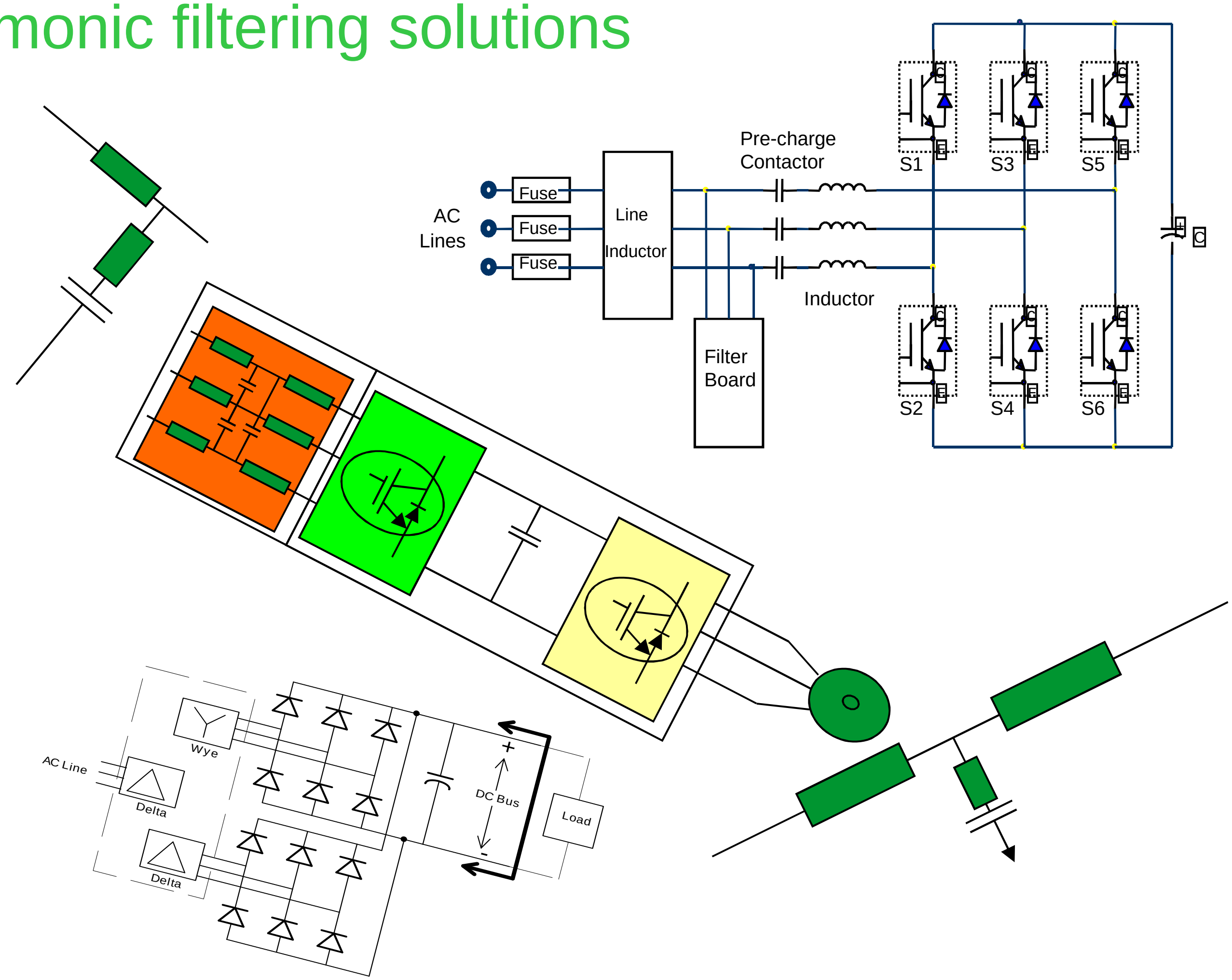
Spikes



Flicker

Harmonic mitigation methods

Various type of harmonic filtering solutions

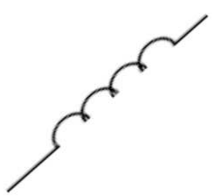


Applied per device

- Inductance
- 5th harmonic trap filters
- Broadband filters
- Multi-pulsing
- Active Front End converter

Applied per system

- Active harmonic filter(AHF)



Inductors/Transformers/DC Bus Chokes

Description:

Converter-applied inductors or isolation transformers.

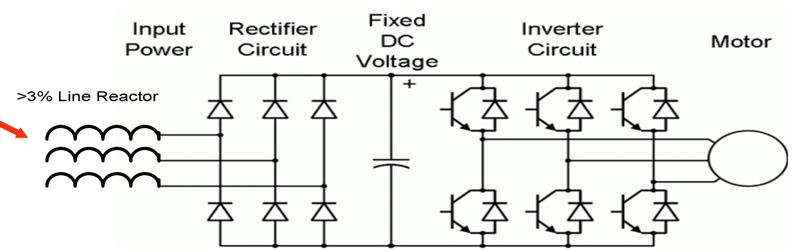
Pros:

- Inexpensive & reliable
- Transient protection for loads
- 1st Z yields big TDD reduction (90% to 35% with 3% Z)
- Complimentary to active harmonic control

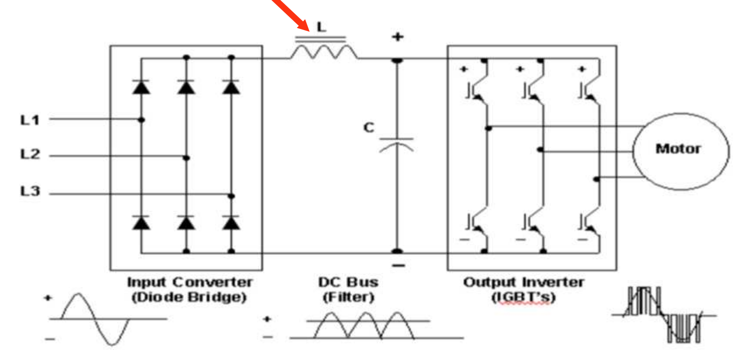
Cons:

- Limited reduction of TDD at equipment terminals after 1st Z
- Reduction dependent on source Z

3% line reactor

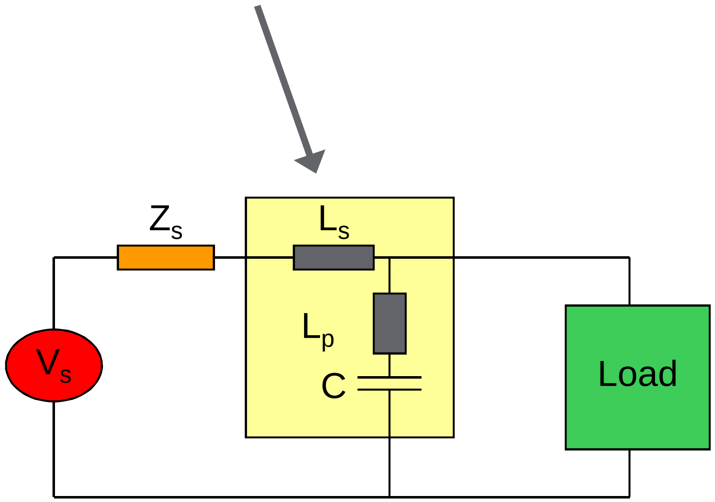


5% DC bus choke



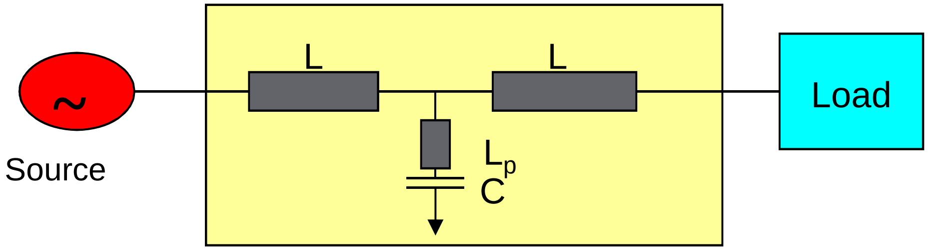
5th Harmonic Filter (Trap Filter)

- Inductor (L_p) and Capacitor (C) provide low impedance source for a single frequency (5^{th})
  - Must add more tuned filters to filter more frequencies
- Inductor L_s required to detune filter from electrical system and other filters
  - If L_s not present, filter is sink for all 5^{th} harmonics in system, that can result in overlaod.
  - If L_s not present, resonance with other tuned filters possible
- Injects leading reactive current **(KVAR) at all times** – may create leading PF and/or issues with back up generator



Broadband Filters

- Mitigates up to 13th order or higher
- Each inductor (L) > 8% impedance
    - V drops ~ 16% at load
    - Trapezoidal voltage to load
        - Can only be used on diode converters
    - Prevents fast current changes (only good for centrifugal loads)
    - When generators are present, re-tuning may be required
- Capacitor (C) designed to boost V at load to proper level (injects leading VARs)
- Physically large
- High heat losses (>5%)
- Series device



Multi-Pulse Drives

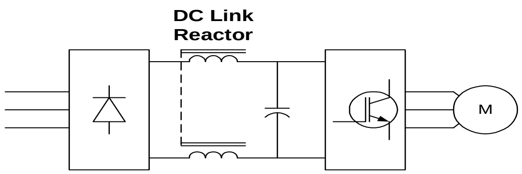
Description: Drives/UPS with two (12 pulse) or three (18 pulse) input bridges fed by a transformer with two or three phase shifted output windings.

- Pros:
  - Reduces TDD to **10% (12 pulse)** & **5% (18 pulse)** at loads
  - Reliable
- Cons:
  - High installation cost with external transformer
  - Large footprint (even w/autotransformer)
  - Series solution with reduction in efficiency
  - One required for each product
  - Cannot retrofit

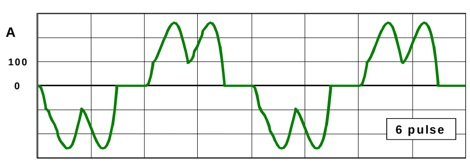
Harmonic mitigation methods

VFD mitigation topologies

6-Pulse converter

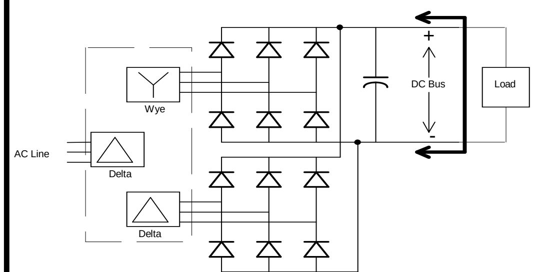


"C-less" or 3% reactance min (if included); small footprint, simplified cabling

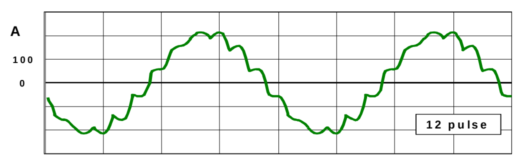


Current waveform distorted
TDD 30% to 40% with 3% reactor (depending on network impedance)

12-Pulse converter

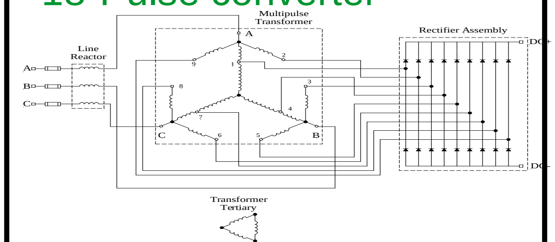


Externally mounted 3 winding transformer; more wire and cabling; complicated

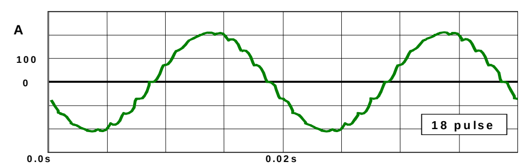


Current slightly distorted
TDD 8% to 15% (depending on network impedance)

18-Pulse converter



Large footprint, more steel & copper (losses)



Current wave form good
TDD 5% to 7% (depending on network impedance)

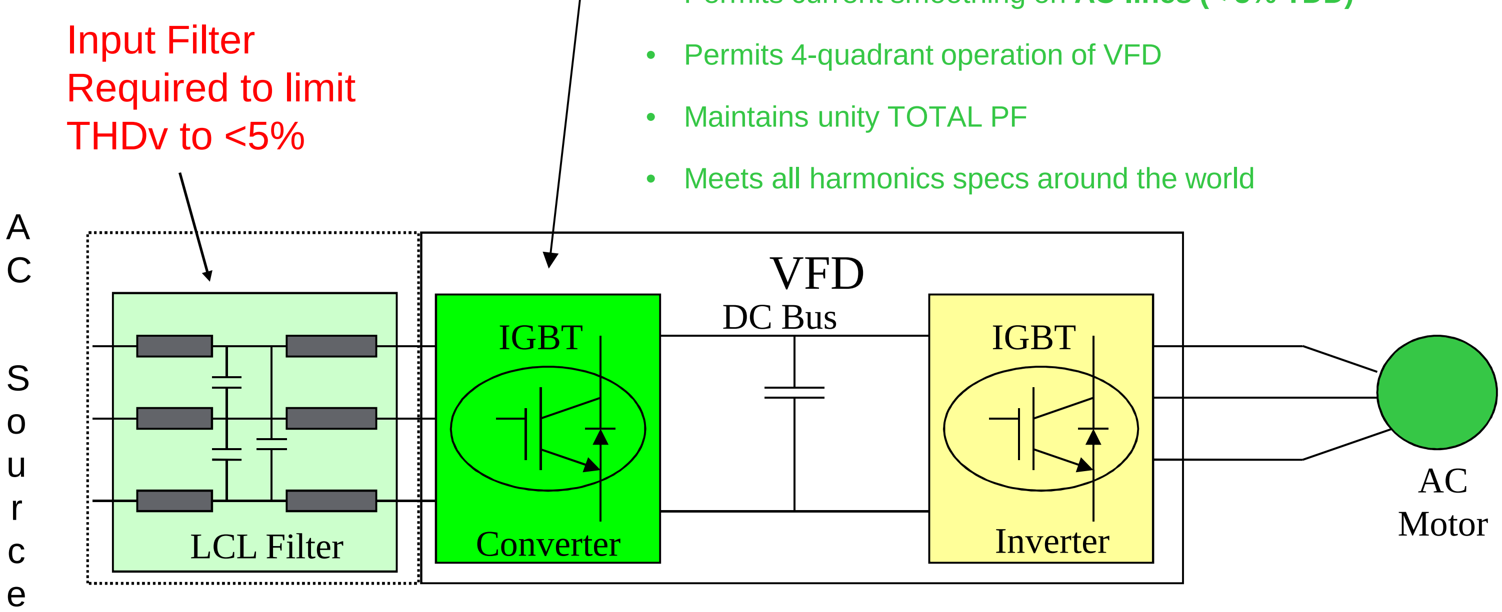
Active Front End (AFE) Converters

Used in UPS and VFD

Replaces diode converter with IGBT converter

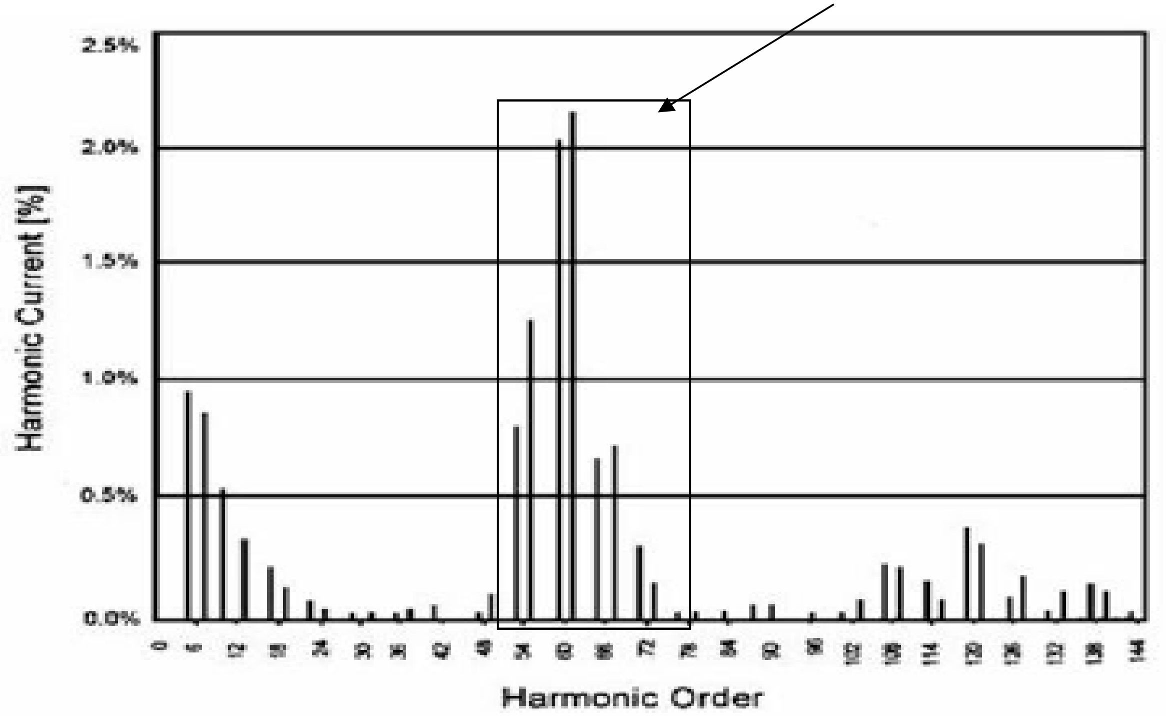
Pros

- Permits current smoothing on **AC lines (< 5% TDD)**
- Permits 4-quadrant operation of VFD
- Maintains unity TOTAL PF
- Meets all harmonics specs around the world



AFE Converters

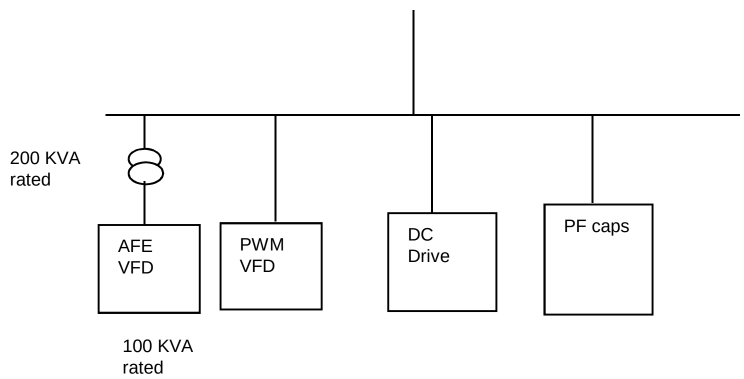
Significant harmonics above 50th order



American Bureau of Shipping (ABS) requires examination to 100th order when AFE applied

Higher frequencies yield higher heating of current path & potential resonance with capacitors

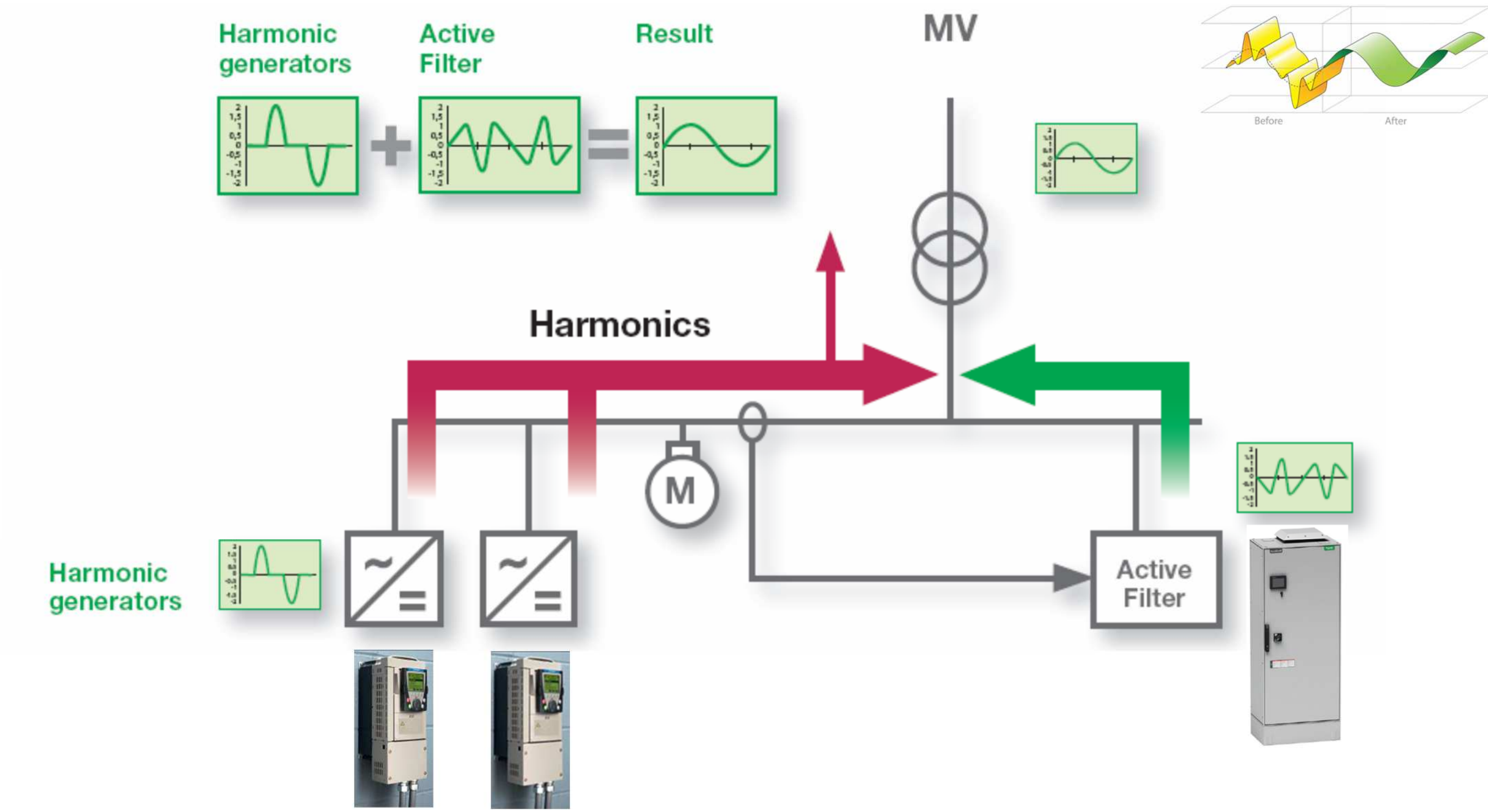
AFE Converters



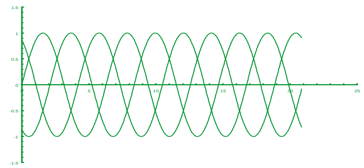
Cons

- Larger and more expensive than 6 pulse drives
  - Approximately twice the size & price
- Mains voltage must be free of imbalance and voltage harmonics
  - Generates more harmonics
- Without mains filter THD(V) can reach 40%
- Requires short circuit ratio $\geq$ 40 at PCC
- Switched mode power supplies prohibited
- Capacitors prohibited on mains
- IGBT & SCR rectifiers prohibited on same mains
  - No other nonlinear loads permitted

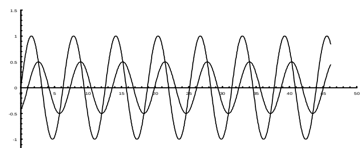
Active Harmonic Filter


Harmonic generators
Active Filter
Result
MV
Before
After
Harmonics
M
Active Filter
Harmonic generators

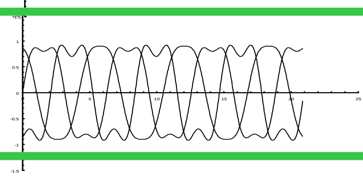
The ideal voltage supply does not exist, some AHF can correct 3 PQ problems



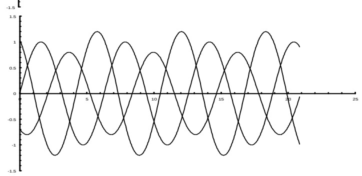
3-phase balanced



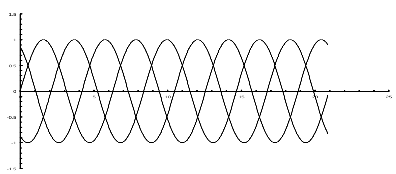
Power Factor



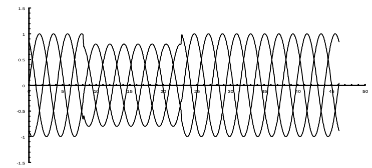
Harmonics



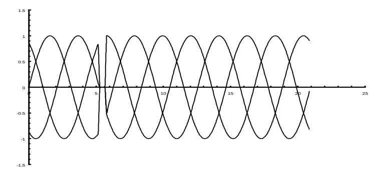
Phase unbalanced



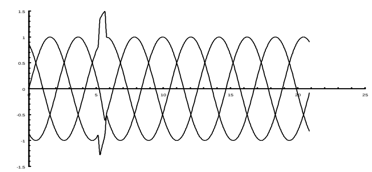
Blackout



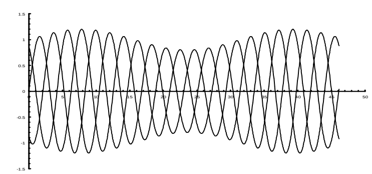
Sags/swells
Overvoltage



notches



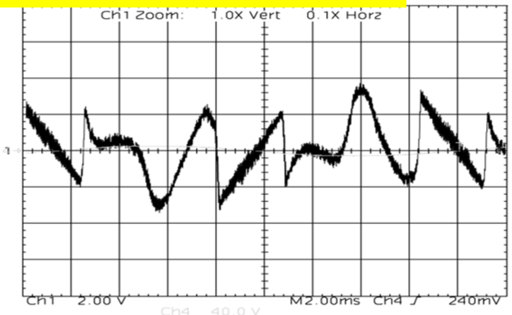
Spikes



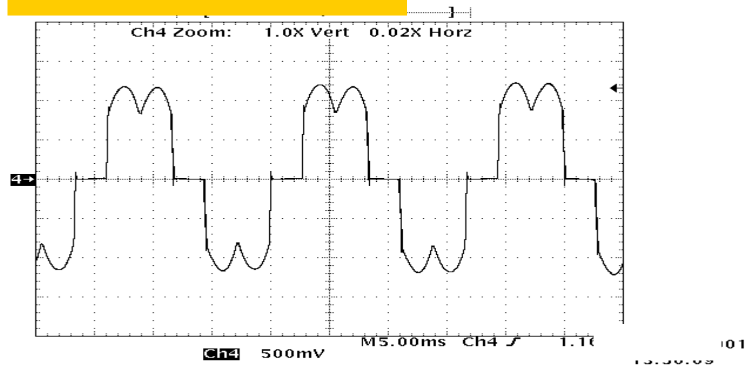
Flicker

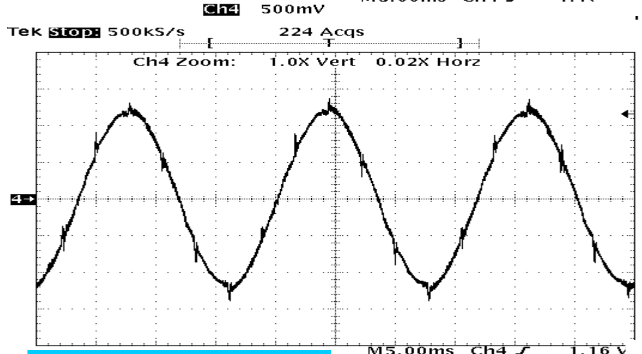
Harmonic Mitigation with AHF

AccuSine injection



At VFD Terminals

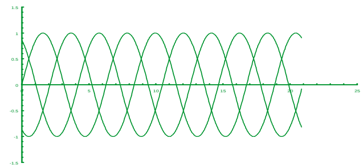




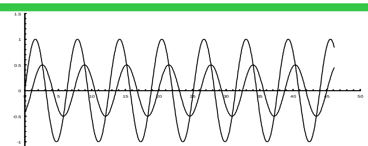
Source current

	OFF	ON
Order	% I fund	% I fund
Fund	100.000%	100.000%
3	0.038%	0.478%
5	31.660%	0.674%
7	11.480%	0.679%
9	0.435%	0.297%
11	7.068%	0.710%
13	4.267%	0.521%
15	0.367%	0.052%
17	3.438%	0.464%
19	2.904%	0.639%
21	0.284%	0.263%
23	2.042%	0.409%
25	2.177%	0.489%
27	0.293%	0.170%
29	1.238%	0.397%
31	1.740%	0.243%
33	0.261%	0.325%
35	0.800%	0.279%
37	1.420%	0.815%
39	0.282%	0.240%
41	0.588%	0.120%
43	1.281%	0.337%
45	0.259%	0.347%
47	0.427%	0.769%
49	1.348%	0.590%
% THD(I)	**35.28%**	**2.67%**

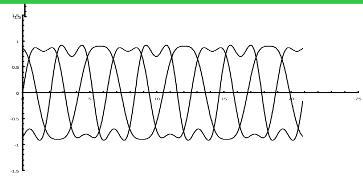
The ideal voltage supply does not exist, Active Harmonic Filters can correct 3 PQ problems



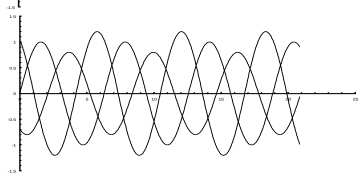
3-phase balanced



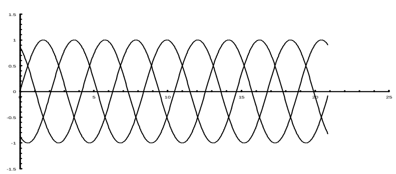
Power Factor



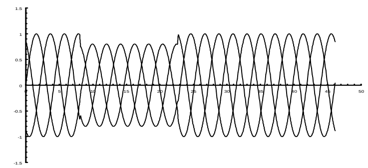
Harmonics



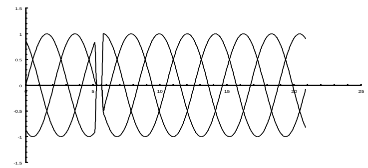
Phase unbalanced



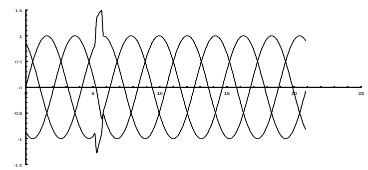
Blackout



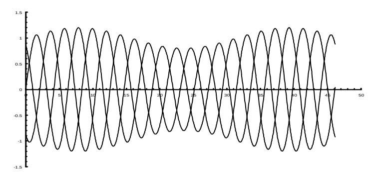
Sags/swells
Overvoltage



notches



Spikes

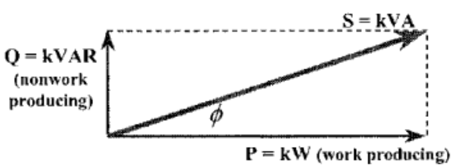


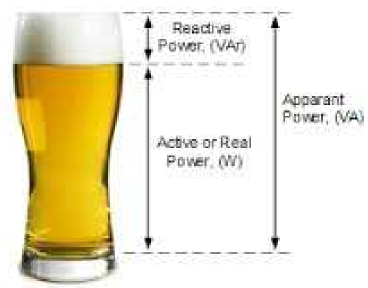
Flicker

Power Factor and Harmonics. What is "True " Power Factor?

With linear vs. nonlinear loads

Electrical system with ONLY linear loads (Displacement Power Factor)

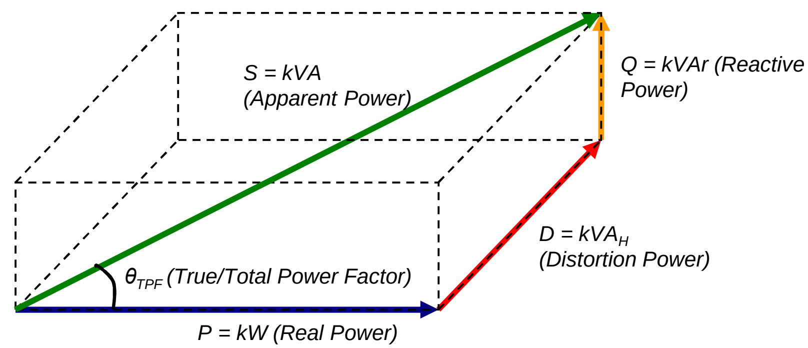




$$S(kVA) = \sqrt{P^2 + Q^2} = \sqrt{kW^2 + kVAr^2}$$

$$\text{power factor, } \cos\phi = \frac{P}{S} = \frac{kW}{kVA}$$

Electrical system with Nonlinear loads (True or Total Power Factor)



$$S(kVA) = V_{rms} I_{rms} = \sqrt{P^2 + Q^2 + D^2}$$

$$TPF = (DisplacementPF) * (DistortionFactor)$$

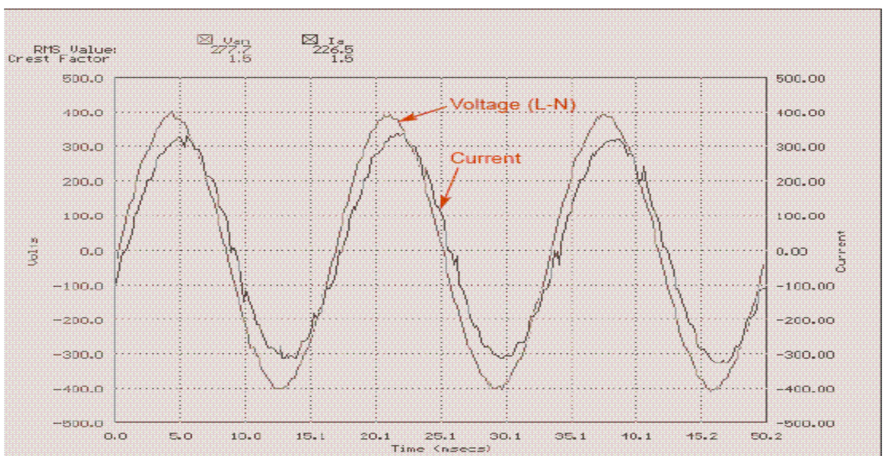
$$DPF = Cos\ \phi = \frac{KW}{KVA_f}$$

$$DF = Cos\delta = \frac{1}{\sqrt{(1 + (THDi)^2)}}$$

Active Harmonic Filter
PF correction

When PF mode is activated

- Assign priority to Harmonic or **PF (fundamental) modes.**
- **AccuSine injects fundamental current (60 Hz) to correct the Power Factor.**



$$I_{as} = \sqrt{I_h^{2} + I_f^{2}}$$

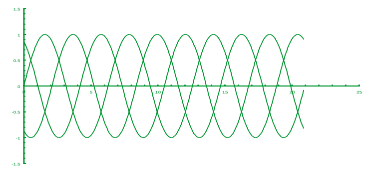
I_{as} = rms output current of AccuSine PCS

I_h = rms harmonic current

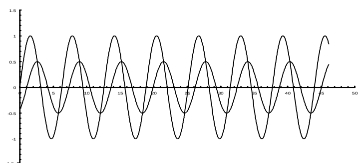
I_f = rms fundamental current

Examples		
I_{as}	I_h	I_f
100.0	10.0	99.5
100.0	20.0	98.0
100.0	30.0	95.4
100.0	40.0	91.7
100.0	50.0	86.6
100.0	60.0	80.0
100.0	70.0	71.4
100.0	80.0	60.0
100.0	90.0	43.6
100.0	95.0	31.2

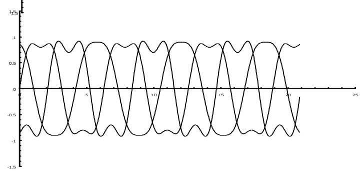
The ideal voltage supply does not exist, some AHF can correct 3 PQ problems



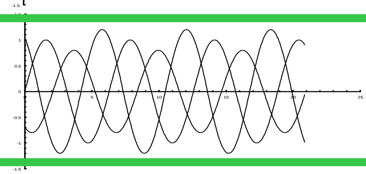
3-phase balanced



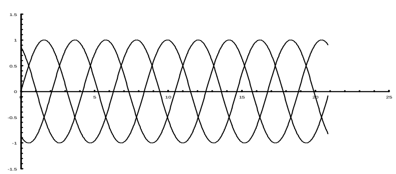
Power Factor



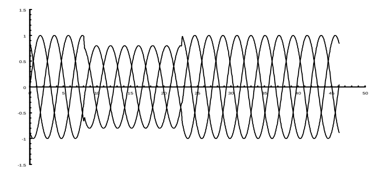
Harmonics



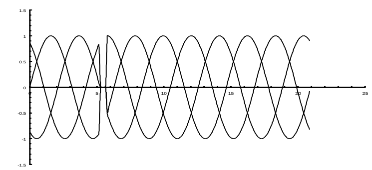
Phase unbalanced



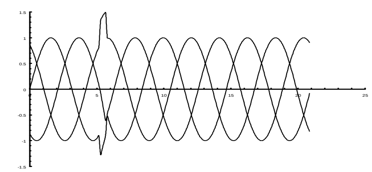
Blackout



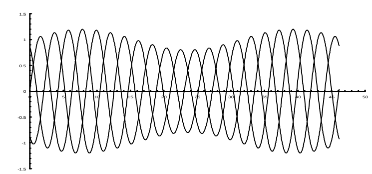
Sags/swells
Overvoltage



notches



Spikes

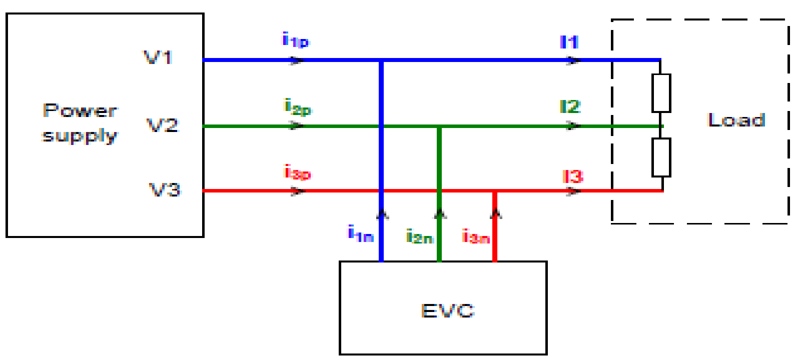


Flicker

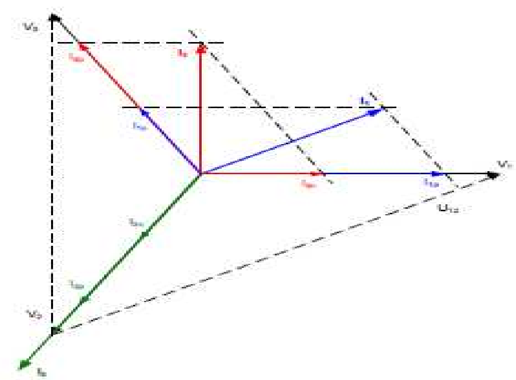
Load Balancing with some Active Harmonic Filter

Principle of load balancing

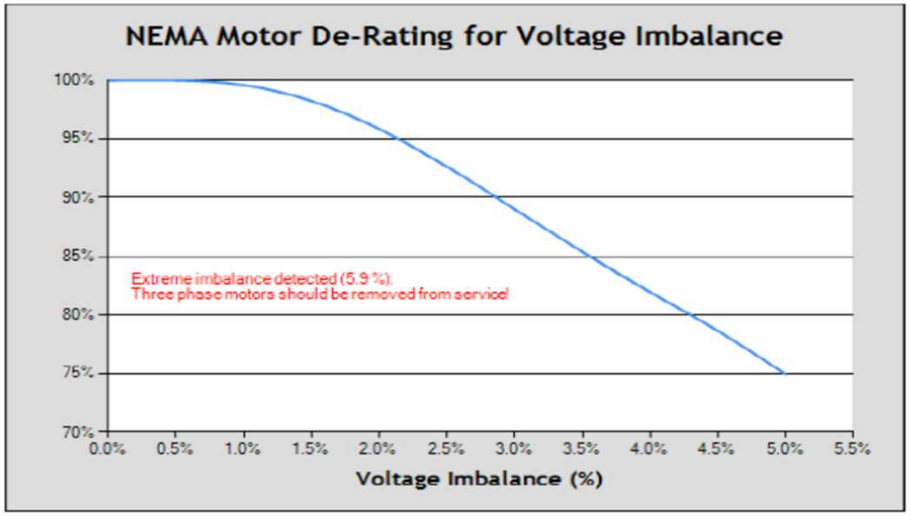
The principle of load current balancing is to inject a system of negative sequence current into the circuit (i_{1n}, i_{2n}, i_{3n}), so that only the system of positive sequence current (i_{1p}, i_{2p}, i_{3p}) has to be generated by the power supply.

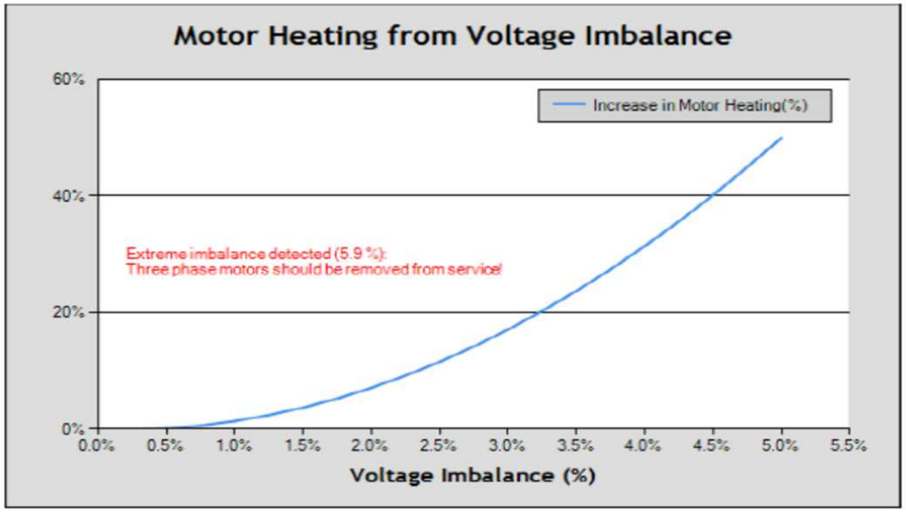


Vector construction of positive and negative sequence systems:



Load Balancing with some Active Harmonic Filter





Voltage unbalance standards:
ANSI C84.1: 3%
PG & E: 2.5%
NEMA MG-1-1998: 1%

Note: 1 % voltage unbalance can cause 6% to 10% current unbalance. Some motor manufacturer tried to require less than 5% current unbalance for a valid warranty.

Example of unbalance voltage calculation on a 480 V electrical distribution system:

Average voltage (Ph to PH): (475 + 473 + 455) / 3 = 468 V

Voltage deviation: 468 – 455 = **13 V**

Voltage unbalance: 100 x (13 / 468) = **2.78%**

Example of Active Harmonic Filter ratings & performance

AHF ratings:

- Dynamic Harmonic mitigation form the 2nd to the 51st harmonic order
- Can meet a THD(I) of 3%, THD(V) and THD(I) target set point
- Standard Voltage, 208,240, 480, 600 and 690 V, 50-60 Hz
- Wall Mount or Free Standing, Main Lugs or Main Breaker incoming
- 60, 120, 200 and 300 A @ 480 V or 47, 94, 157 and 235 A @ 600 V per cubicle
- Enclosure type: NEMA 1, NEMA 2 and NEMA 12
- 3 levels IGBT design with optimized losses
- Closed loop c/w FFT digital logic
- 2 cycle response time for harmonic correction and ¼ of a cycle for reactive power injection
- cULus and CE certified
- And much more…

Questions ?