POWER QUALITY

Understanding Power Quality

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Agenda

1. Financial impact due to Power Quality issues
2. Causes of Power Quality
3. Correcting Power Quality issues
4. Voltage Sags and Swells
5. Harmonic Distorsion

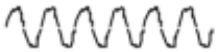
FINANCIAL IMPACT DUE TO POWER QUALITY ISSUES

What is Power Quality?

In an ideal case, the voltage and current each have the following caracteristics:

- nominal magnitude
- Nominal frequency
- Sinusoidal waveform
- 3 phases symetrical

One or more of these constitutes a Power Quality issue.

Disturbance category	Waveform	Effects	Possible causes
Transients		Equipment malfunction and damage	Lightning or switching of inductive / capacitive loads
Interruption		Downtime, equipment damage, loss of data possible	Utility faults, equipment failure, breaker tripping
Sag		Downtime, system halts, data loss	Utility or facility faults, startup of large motors
Swell		Equipment damage and reduced life	Utility faults, load changes
Undervoltage		Shutdown, malfunction, equipment failure	Load changes, overload, faults
Overvoltage		Equipment damage and reduced life	Load changes, faults, over compensation
Harmonics		Equipment damage and reduced life, nuisance breaker tripping, power losses	Electronic loads (non-linear loads)
Unbalance		Malfunction, motor damage	Unequal distribution of single phase loads
Voltage fluctuations		Light flicker and equipment malfunction	Load exhibiting significant current variations
Power frequency variations		Malfunction or motor degradation	Standby generators or poor power infrastructure
Power Factor *		Increased electricity bill, overload, power losses	Inductive loads (ex. motors, transformers...)

How much can one hour of downtime cost?

Industry	Hourly Downtime Costs
Brokerage Operations	$6,450,000
Energy	$2,817,846
Credit Card Sales Authorizations	$2,600,000
Telecommunications	$2,066,245
Manufacturing	$1,610,654
Financial Institutions	$1,495,134
Information Technology	$1,344,461
Insurance	$1,202,444
Retail	$1,107,274
Pharmaceuticals	$1,082,252
Banking	$996,802
Food/Beverage Processing	$804,192
Consumer Products	$785,719
Chemicals	$704,101
Transportation	$668,586
Utilities	$643,250
Healthcare	$636,030
Metals/Natural Resources	$580,588

How much does one Power Quality event cost?

How much are poor Power Quality events costing you?

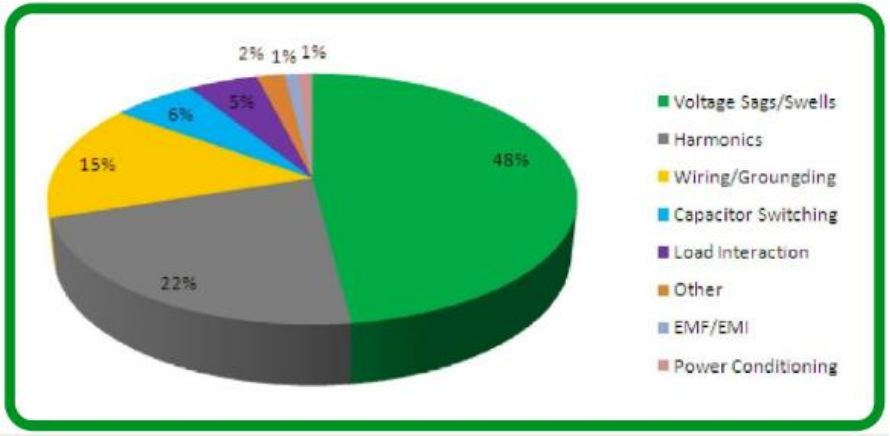
The following average costs by type of poor Power Quality event were calculated from the survey results:

Surge or transient:	€120,000 - 180,000
Long interruption:	€90,000
Short interruption, service sectors:	€18,000 - 36,000
Short interruption, industry:	€7,000 - 14,000
Voltage dip:	€2,000 - 4,000

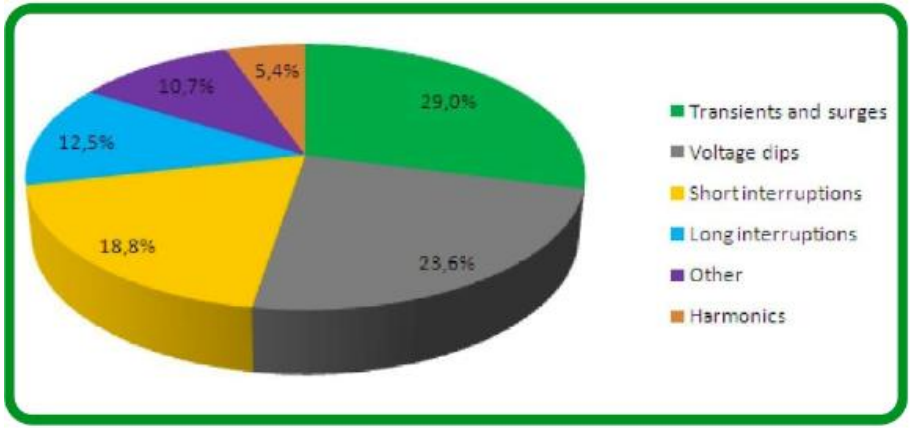
Source: LPQI 2015 (Leonardo Power Quality Initiative)_

Power Quality issues cause many of these interruptions

30-40% of unplanned interruptions are due to Power Quality issues



Most common power quality issues (US)



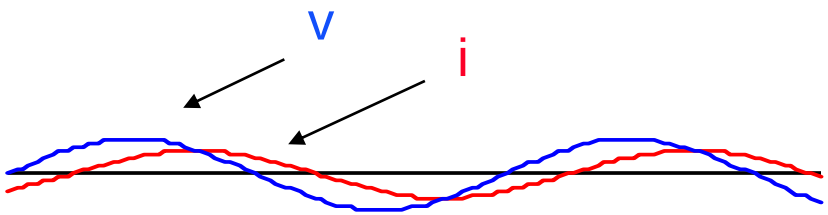
Most common power quality issues (EU)

Companies get sued & people get fired when this stuff happens

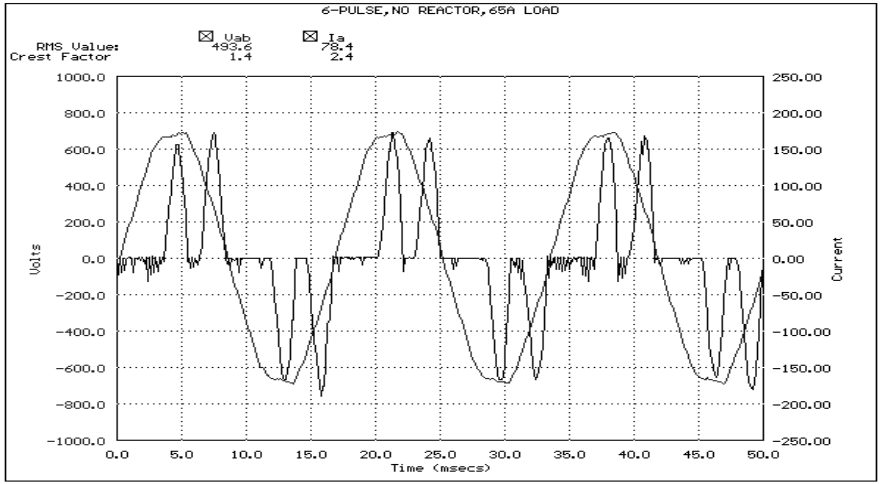
CORRECTING POWER QUALITY ISSUES

Understanding the root of Power Quality problems

Linear Load



Non-Linear Load



Power Quality – A new Problem?

In the past, Power Quality problems were reserved for large industrial users

- Power Quality problems have existed since the early days of the Electrical Power System
- By the mid 20th century, most utilities provided sufficient and stable power and few customers had Power Quality issues.

Today, Power Quality is becoming everyone's problem

- In order to consume less energy, we have developed equipment which draws less energy but draws it in an **intermittent/jerky** manner.
- Today, generating capacity has been outpaced by energy demand and everyone is adding energy efficient devices to the grid
- Renewable Energy is adding to the problem by adding generation with short term variations
- The grid is not necessarily going to collapse, but the power is not always smooth

Should we be concerned about harmonics ?

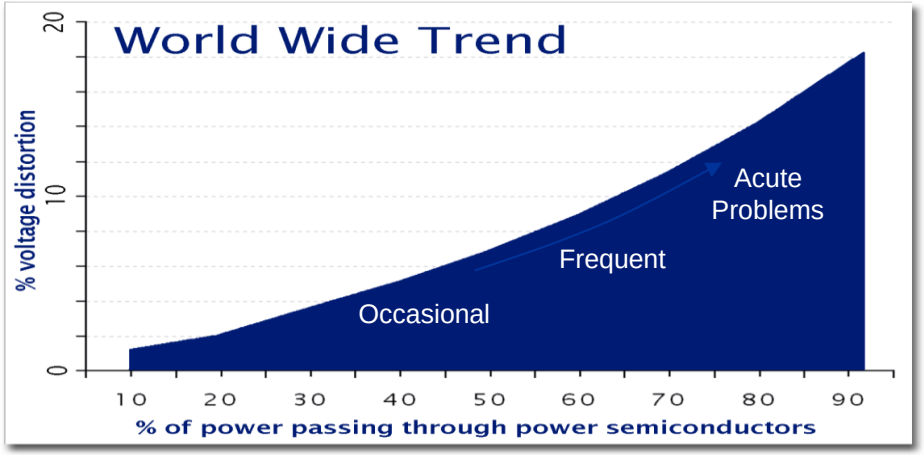
“ We don’t have harmonics in our facility ”

“ Our devices don’t cause harmonics “

“ Harmonics have never been a problem before…”

How common is this power quality problem?

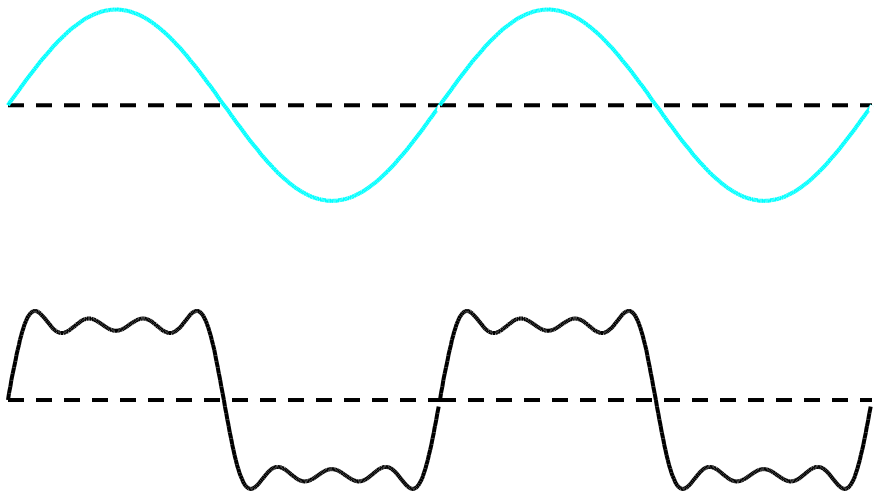
- **Over $20 billion of power semiconductor products installed annually**
  - Computers and peripherals, IT devices, VFD, UPS, and industrial power supplies
- **35 – 40% of all power flows through power semiconductors today**
- **Growth to 70% in the next few years**



Distortion: what is it ?

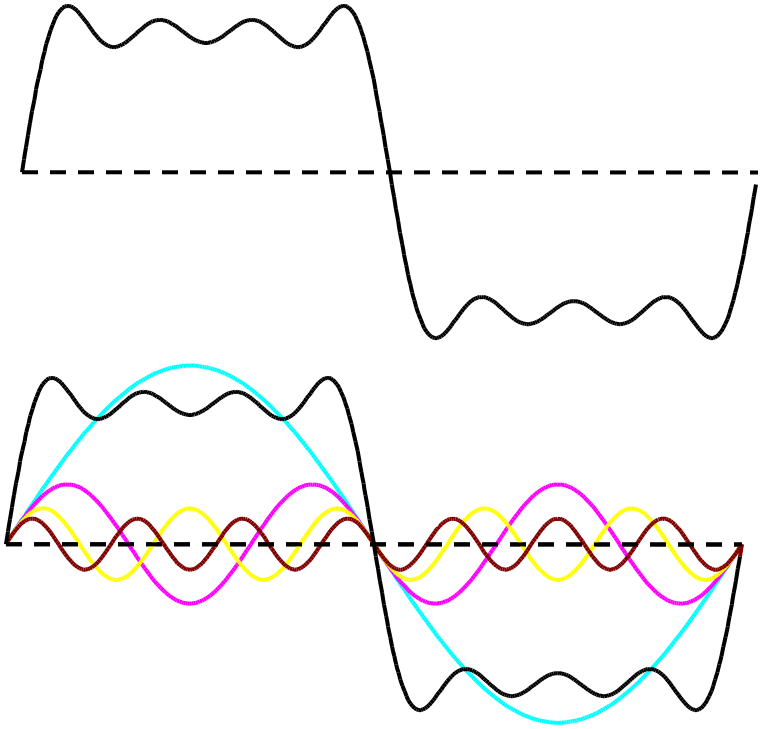
A linear waveform is a *sinusoidal* and *periodic* waveform (current or voltage)

A non-linear (or distorted) waveform is any periodic waveform (current or voltage) which is non-sinusoidal



Distortion and Harmonics

A distorted waveform can be represented as the sum of its Harmonics



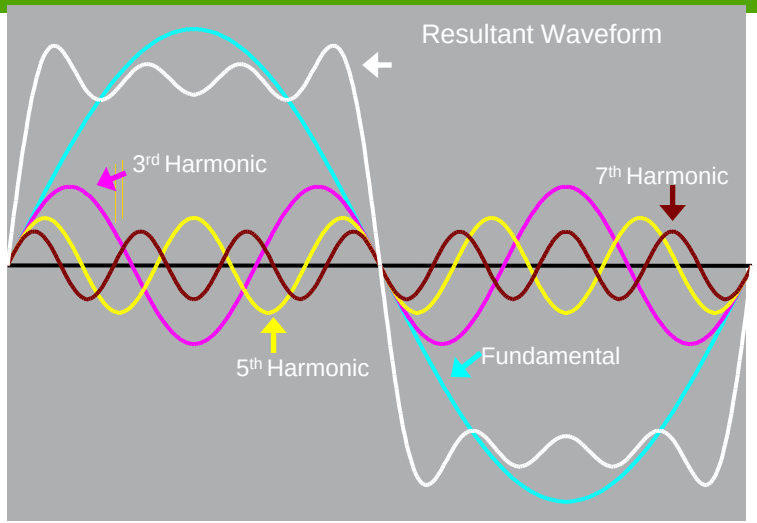
Harmonic basics

What are harmonics?

- A harmonic is a component of a periodic wave having a frequency that is an integer multiple of the fundamental power line frequency
  - 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



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

Multipulse converters

$H_c = np +/- 1$

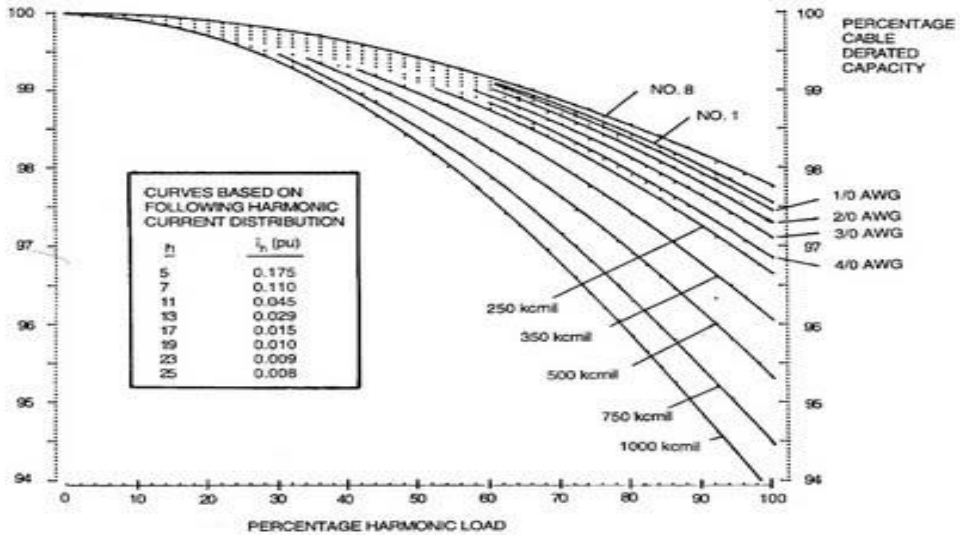
H_c = characteristic harmonic order present

n = an integer

p = number of pulses

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	

Skin Effect



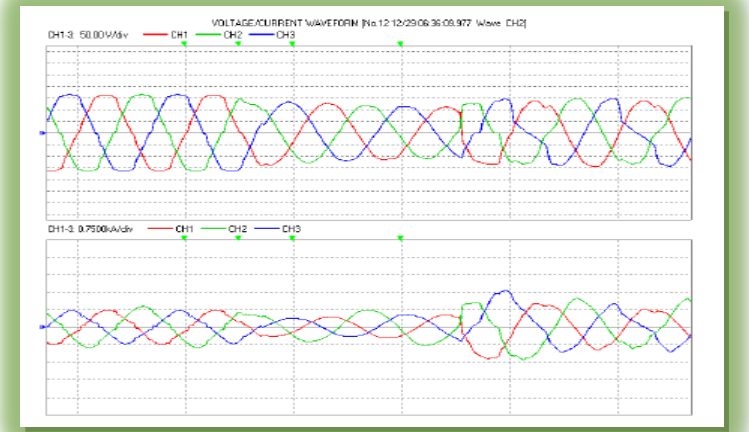
The cables resistance may increase due to skin effect. Skin effect is a case where unequal flux linkages across the cross section of the cable causes the AC current to flow on the outer periphery of the conductor.

What are Harmonics?

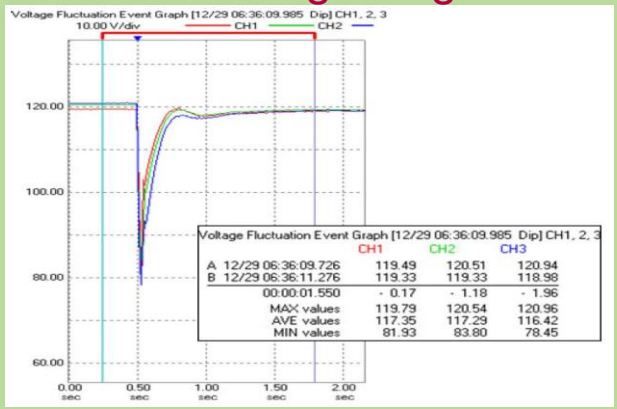
Examples of Voltage anomalies

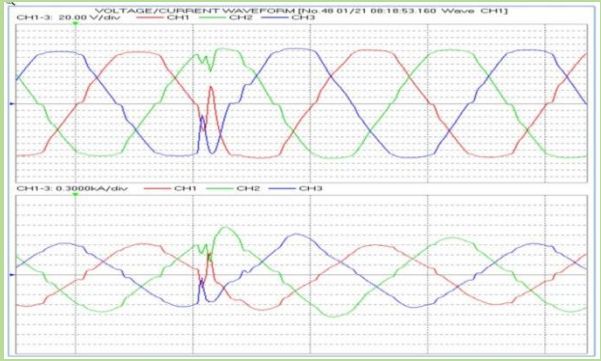
POWER		VOLTAGE		CURRENT	
Freq	59.968 Hz				
P1	0.0728MW	U1	119.09 V	I1	0.6225kA
P2	0.0872MW	U2	120.17 V	I2	0.7303kA
P3	0.0717MW	U3	120.51 V	I3	0.6059kA
Psum	0.2317MW	THD-U1	4.78 %	THD-I1	7.94 %
S1	0.0741MVA	THD-U2	4.72 %	THD-I2	8.86 %
S2	0.0878MVA	THD-U3	4.70 %	THD-I3	8.51 %
S3	0.0730MVA	Upk+1	163.45 V	Ipk+1	0.931kA
Ssum	0.2349MVA	Upk+2	163.81 V	Ipk+2	1.112kA
Q1	0.0139Mvar	Upk+3	164.07 V	Ipk+3	0.939kA
Q2	0.0103Mvar	Upk-1	-162.38 V	Ipk-1	- 0.944kA
Q3	0.0137Mvar	Upk-2	-162.93 V	Ipk-2	- 1.120kA
Qsum	0.0379Mvar	Upk-3	-163.74 V	Ipk-3	- 0.940kA
PF1	0.9824	Uave	119.92 V	KF1	1.53
PF2	0.9930	Uunb	0.30 %	KF2	1.47
PF3	0.9822			KF3	1.59
PFsum	0.9863			Iave	0.6529kA
				Iunb	6.18 %

Voltage Distortion



Voltage Sag





Multiple Zero Crossings

Total power factor

$$TPF = (DPF) \times (\text{Distortion factor})$$

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

$$\text{Distortion factor} = \frac{1}{\sqrt{1 + THD(I)^2}} = \cos \delta$$

TPF = Total or true power factor

DPF = Displacement power factor

Distortion factor = Harmonic power factor

Total power factor example

Variable frequency drive (PWM type)

- DPF = 0.95
- THD(I) = 90%
  - (no DC choke & no input line reactor)
- Distortion factor = $\frac{1}{\sqrt{1 + 0.9^2}} = .7433$

TPF = 0.95 x 0.7433 = 0.7061

- Example: Variable speed drive (6-pulse PWM type)

$$DPF = 0.95$$
$$THDi = 200\%$$
$$DF = \frac{1}{\sqrt{(1+2^2)}} = 0.408$$

$$TPF = 0.95 \times 0.408 = 0.388$$

No DC choke & no input line reactor

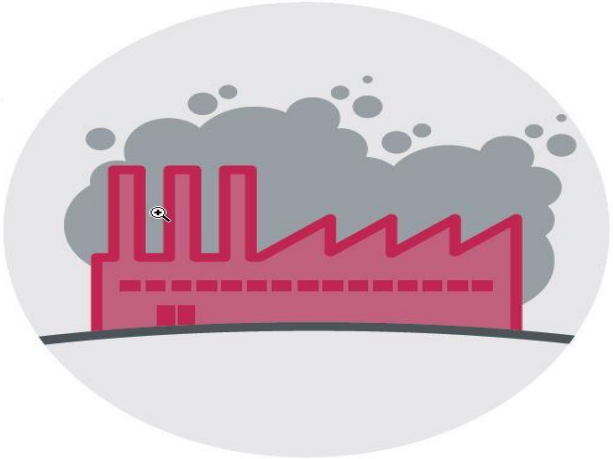
$$DPF = 0.95$$
$$THDi = 40\%$$
$$DF = \frac{1}{\sqrt{(1+.4^2)}} = 0.928$$

$$TPF = 0.95 \times 0.928 = 0.882$$

Other Power Quality Signs

Typical Power Quality Symptoms

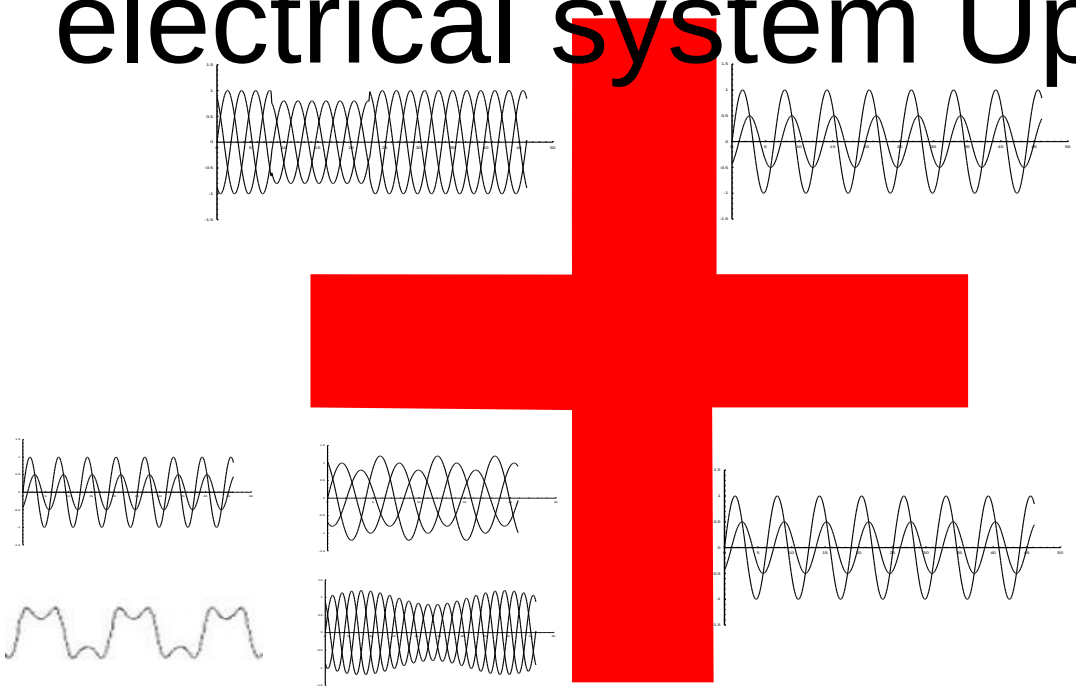
- Flickering and blinking lights
- Transformer issues, such as noise, extra hot, or premature failure
- Panels, neutral wiring, and other distribution equipment running hot
- Printed circuit board failures in drives, PLCs, industrial PC, etc.
- Breaker trip and drive shutdown



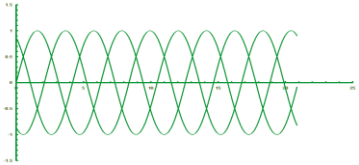
- Premature motor failure and unexpected equipment shutdown
- Contactors dropping out
- Poor network communications
- Higher utility bills
- Poor power factor
- Low system capacity

SOLVING POWER QUALITY ISSUES

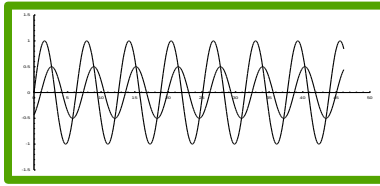
Power Quality – the Key to electrical system Uptime



Power Quality Problems

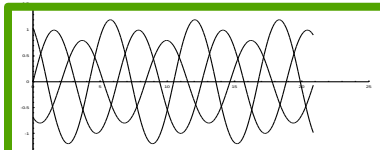


3-phase balanced

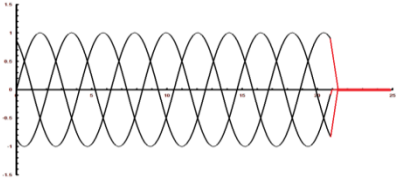


Power Factor

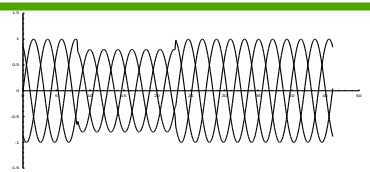
Harmonics



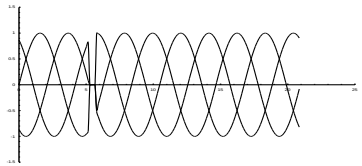
Phase unbalance



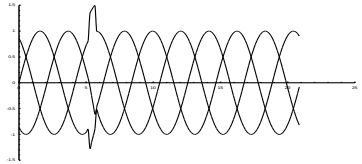
Blackout



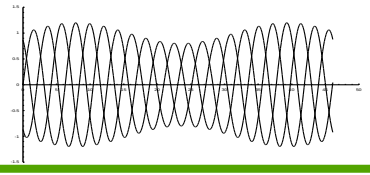
Sags/swells
(usually from the grid)



Notches



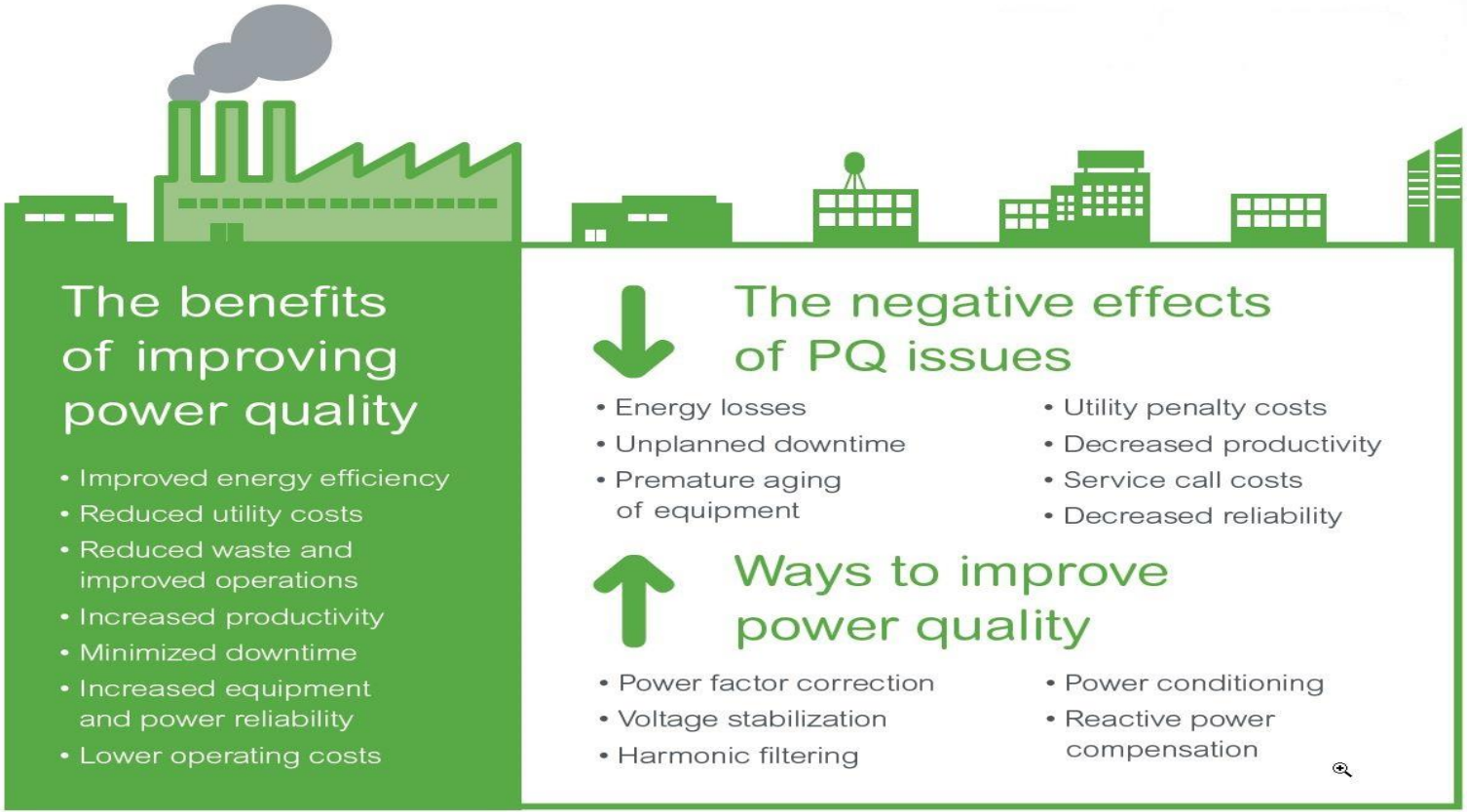
Transient
(Spike)



Flicker
(usually from inside
the facility)

Noise

Benefits of Improving Power Quality Issues



The PTPFC offer in Canada

Mini-EVR
SureVolt
SagFighter

Sags
Swells

Volt. Regulation

LV Cap Banks

VarSet
AV6000
AT6000

LV PFC

Harmonics
Load imbalance
Ficker
PPC

AccuSine PCS+
AccuSine PFV+
AccuSine SWP

Active Harmonic Filtering and VAR Compensation

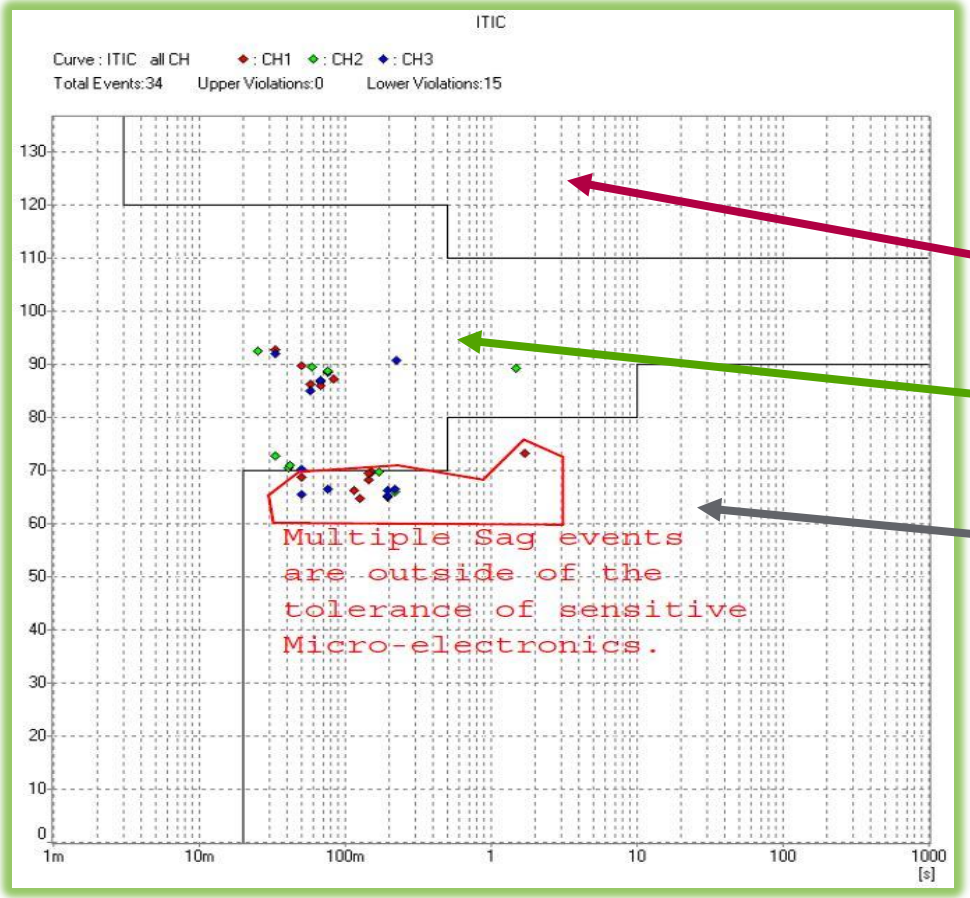
MV Equipment

MV PFC

Capacitors (Propivar NG)
Metal Enclosed Banks

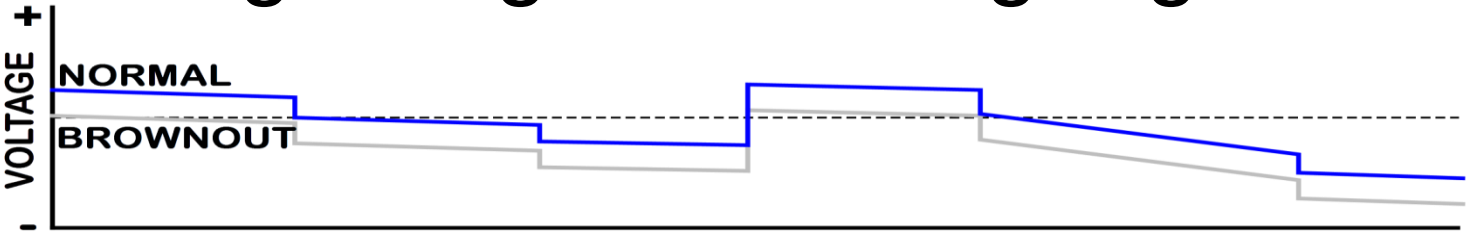
VOLTAGE SAGS AND SWELLS

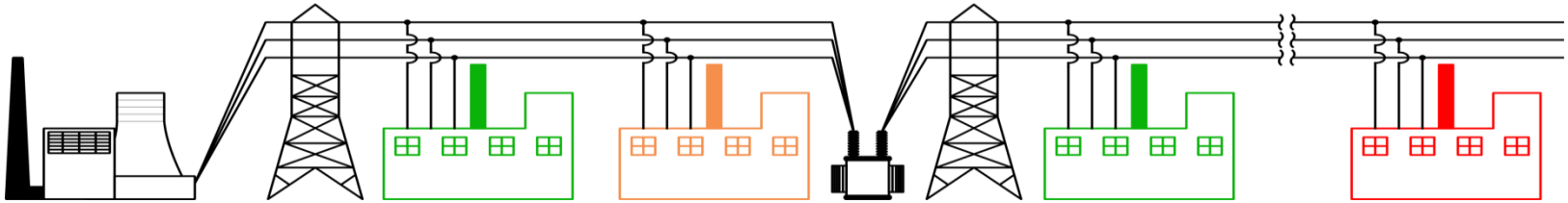
Effect of Sags / Swells on sensitive equipment



- The Information Technology Industry Council (ITIC) curve shows the voltage tolerances which sensitive electronic equipment must withstand
- Voltages above the envelope may damage the equipment
- Voltages within the envelope must permit normal operation of the equipment
- Voltages below the envelope may cause the equipment to malfunction or shutdown

Voltage Regulator / Sag Fighter





External: Line Drops & Brownouts

HARMONIC DISTORSION

Existing harmonic standards

Standards relative to **installations**:

IEC 61000 - a series of standards dealing with power quality issues.

- IEC 61000-2-2 harmonic levels at public low-voltage power supply systems
- IEC 61000-2-4 harmonic levels at LV and MV industrial installations
- IEC 61000-3-6 harmonic levels at MV and HV installations

IEEE 519 – 2014 : requirements on harmonic control in electrical installations (NEMA)

Adjustments at country level may exist (ex. Engineering Recommendation G5/4)

Standards relative to **individual equipment** :

IEC 61000

IEC 61000-3-2	low voltage equipment with rated current under 16A
IEC 61000-3-12	low voltage equipment with rated current higher than 16A and lower than 75A

IEC 61800-3 specific standard for variable speed drives

How much is too much ?

Standards and regulations provide the harmonic limits !!

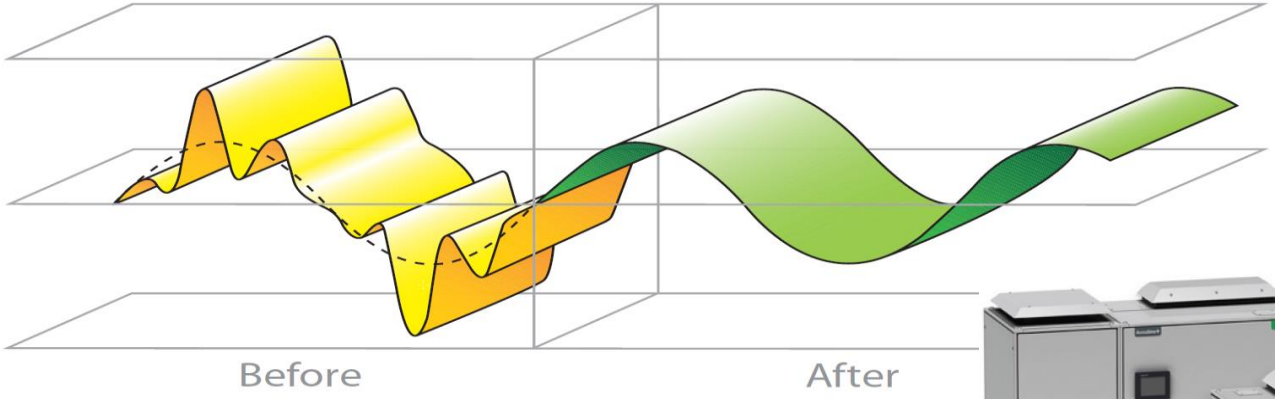
Generally, for THDu :

- under 5% : normal situation, no risk of malfunctions
- 5 to 8% : significant harmonic pollution, some malfunctions are possible
- Higher than 8% : major harmonic pollution, malfunctions are probable

THDi (to be used with caution, as the impact of the THDi depends on the system load)

- under 10% : normal situation, no risk of malfunctions
- 10 to 30% : significant harmonic pollution, some malfunctions are possible
- Higher than 30% : major harmonic pollution, malfunctions are probable

AccuSine PCS+



Example

Drives without line reactors

- Transfo 1000 kVA 600V Z=5.75%

Equipment list for NONLINEAR LOADS

Item	Quantity	Size	Unit of Measure	Type of Equipment	Rectifier pulses	Installed Impedance (%Z)	Maximum Capacity Utilized	Full Load Displacement PF
1	20	10	HP	PWM VFD	6	0.00%	80.0%	0.950
2	10	25	HP	PWM VFD	6	0.00%	80.0%	0.950

AC Motors Operating Direct-on-Line

Item	Quantity	Size	Unit of Measure	Rated Full Load PF (Nameplate)	Maximum Capacity Utilized
11	1	100	KW	1.000	80.0%
12	50	1	HP	0.750	50.0%
13	2	100	HP	0.800	80.0%

Uncorrected System

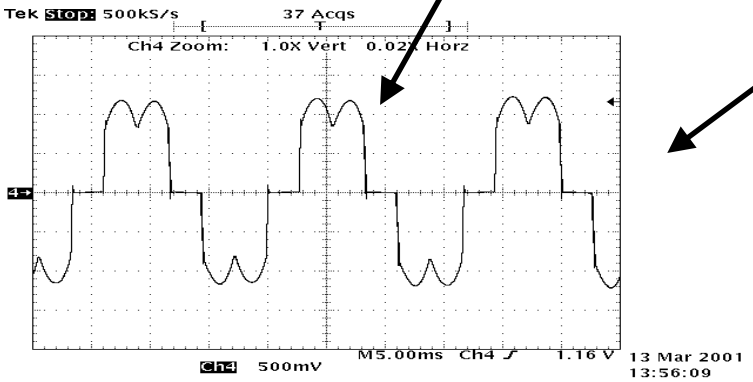
Type of RMS Current	Original System Current Amplitudes & Total Harmoic Current Distortion		Power	
Total I_{rms}	522.5	amps	543.03	KVA
Total I_{fund}	491.6	amps	452.34	KW
Total I_h	177.1	amps	0.9408	Distortion PF
Total $I_{reactive}$	205.5	amps	213.58	KVAR
% THDi	36.04%		0.9043	Cos ϕ
%TDD	36.04%		0.8507	Total PF

- TDD=36%
- Harmonic current= 177A
- IEEE-519 not met. TDD target = 8%
- 130A harmonic filter
- Power Factor= 85%

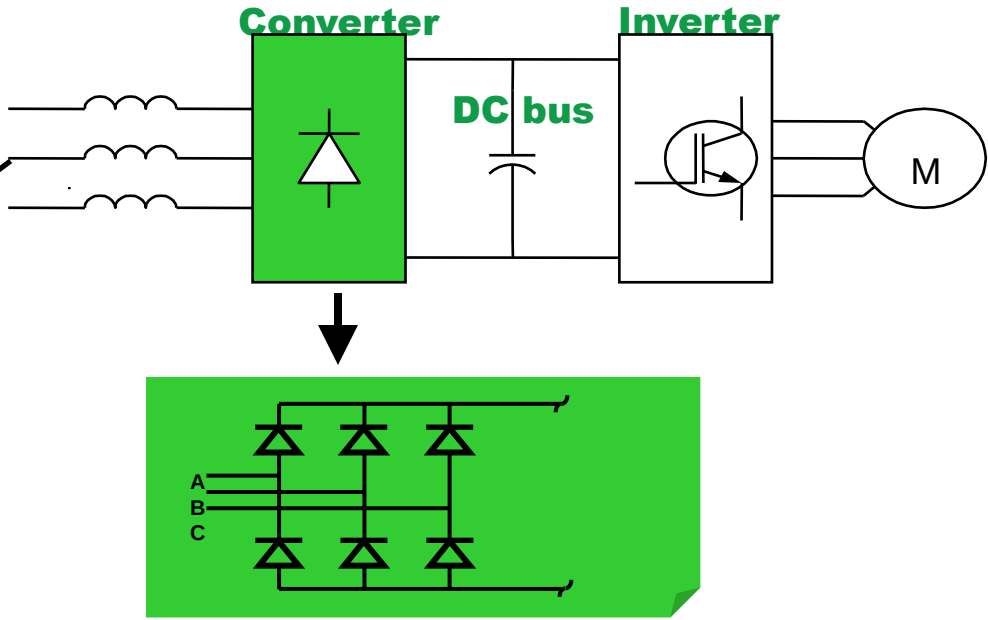
Drive with 3% line reactor(or “DC bus choke”)

Current:

HIGH TDD between 35-40%



Basic PWM VSD



Example

Drives with 3% line reactor

- Transfo 1000 kVA 600V Z=5.75%

Equipment list for NONLINEAR LOADS

Item	Quantity	Size	Unit of Measure	Type of Equipment	Rectifier pulses	Installed Impedance (%Z)	Maximum Capacity Utilized	Full Load Displacement PF
1	20	10	HP	PWM VFD	6	3.00%	80.0%	0.950
2	10	25	HP	PWM VFD	6	3.00%	80.0%	0.950

AC Motors Operating Direct-on-Line

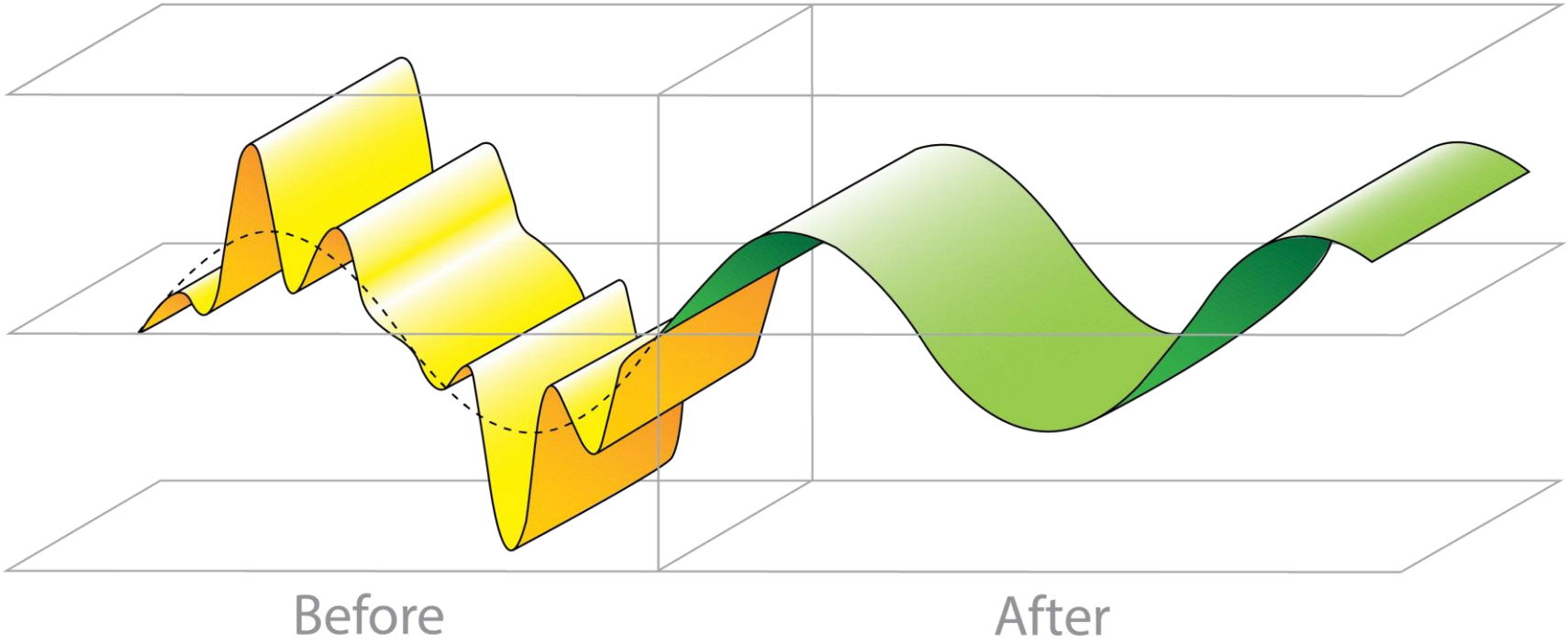
Item	Quantity	Size	Unit of Measure	Rated Full Load PF (Nameplate)	Maximum Capacity Utilized
11	1	100	KW	1.000	80.0%
12	50	1	HP	0.750	50.0%
13	2	100	HP	0.800	80.0%

Uncorrected System

Type of RMS Current	Original System Current Amplitudes & Total Harmoic Current Distortion		Power	
Total I_{rms}	589.0	amps	612.8	KVA
Total I_{fund}	583.8	amps	543.34	KW
Total I_h	78.1	amps	0.9912	Distortion PF
Total $I_{reactive}$	234.3	amps	243.49	KVAR
% THDi	13.39%		0.9126	Cos ϕ
%TDD	13.39%		0.9045	Total PF

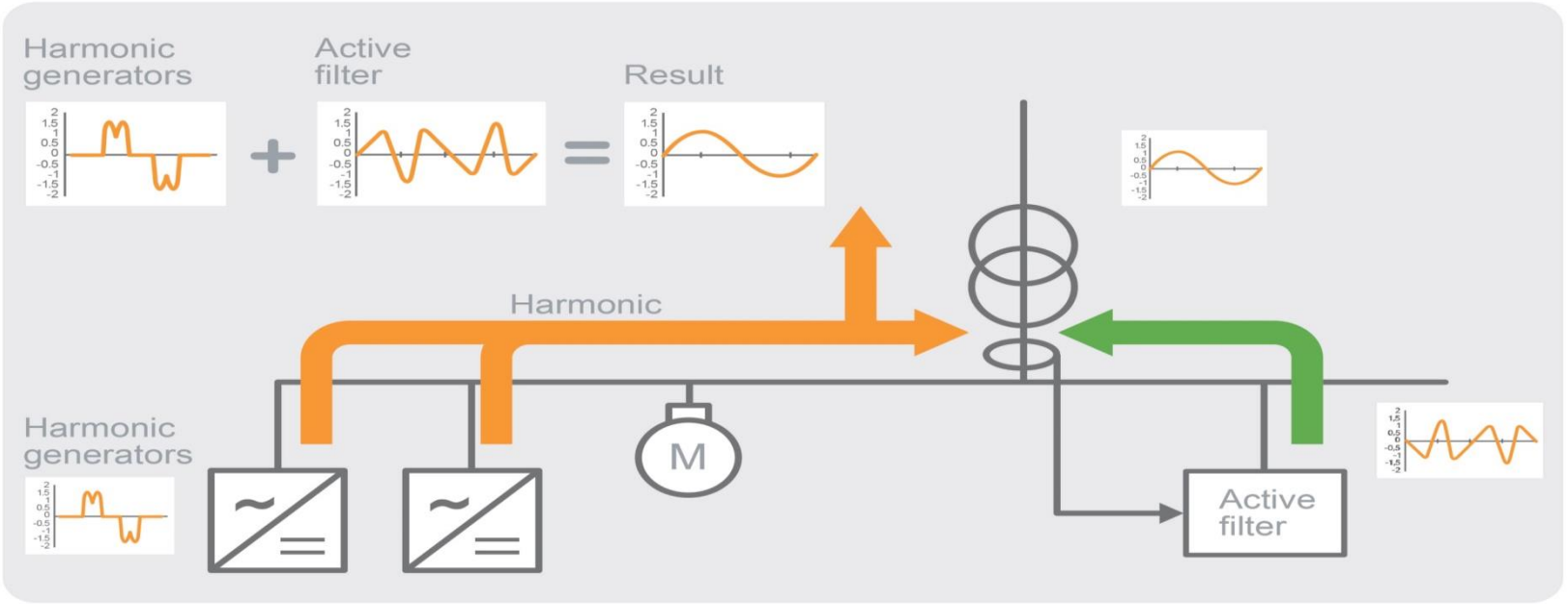
- TDD=13.4%
- Harmonic current= 78A
- IEEE-519 not met. TDD target = 8%
- 48A harmonic filter
- Power Factor= 90.5%
- **The addition of the line reactor has reduced the harmonic current by 99A and corrected the PF**

Filtering harmonic currents with Active Filter

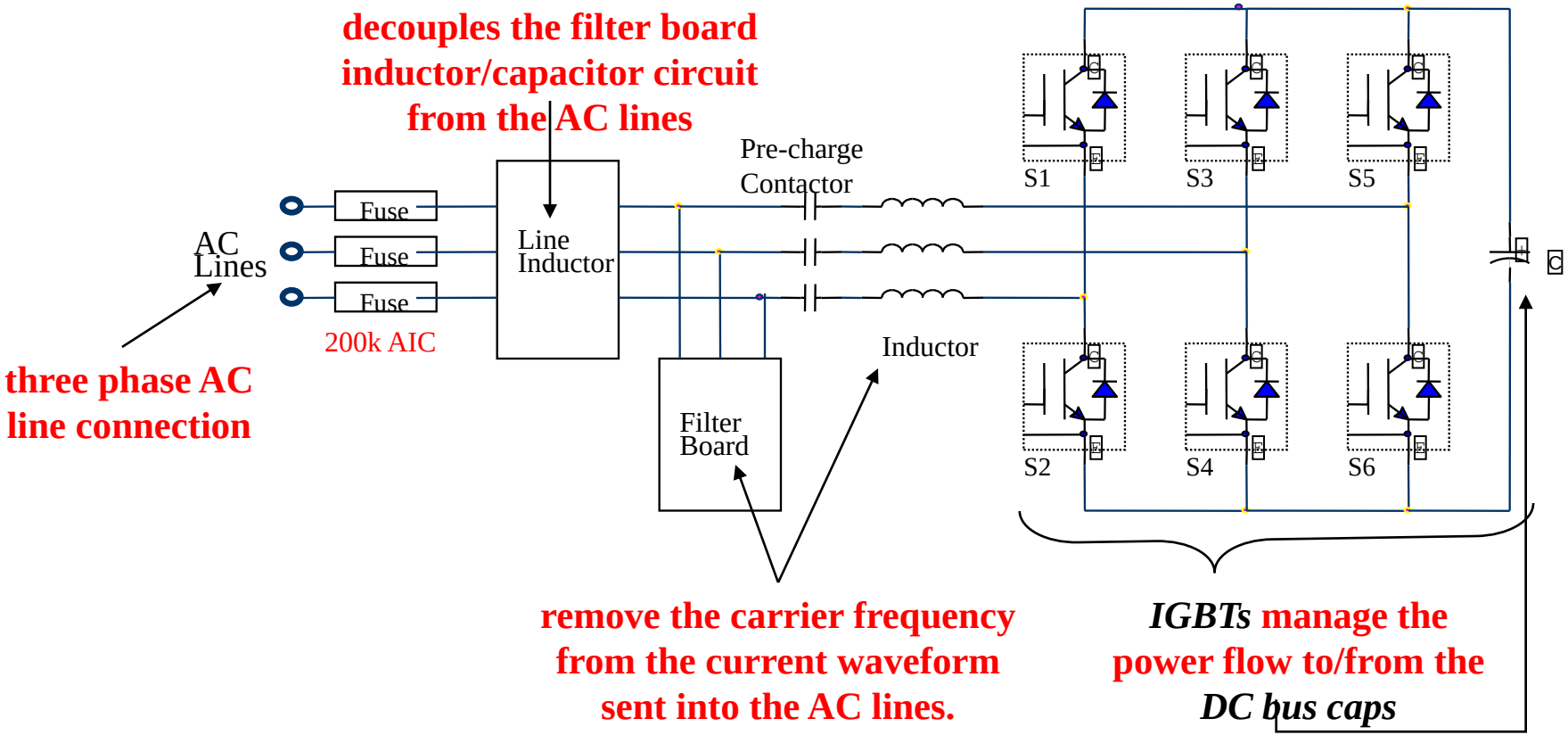


AccuSine PLUS theory of operation

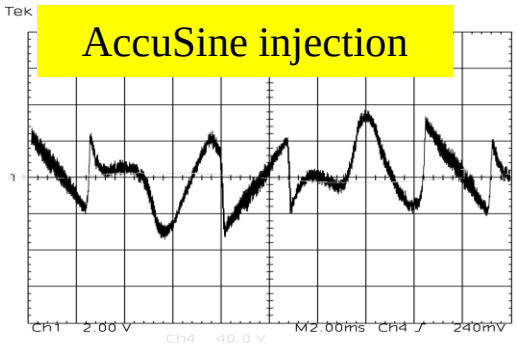
- **AccuSine PLUS is a power electronic converter utilizing digital logic to inject corrective currents into a 3-phase power-source. These injected currents will compensate for existing harmonic currents from the 2nd to the 50th harmonic**

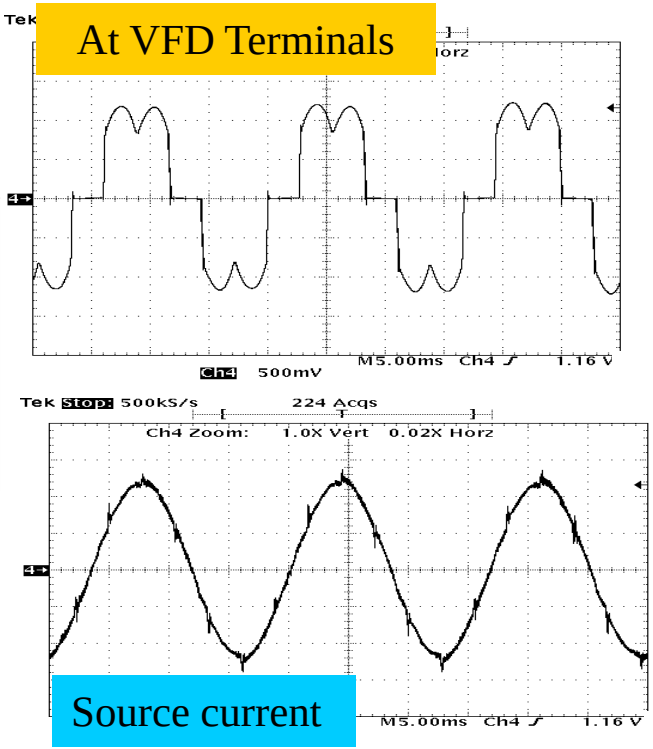


AHF Power Diagram: Example based on AccuSine



Harmonic Mitigation with AccuSine® PCS





Order	AS off % I fund	AS on % 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%

Example
Drives with 3% line reactor and 94A AccuSine PLUS

- Transfo 1000 kVA 600V Z=5.75%

Equipment list for NONLINEAR LOADS

Item	Quantity	Size	Unit of Measure	Type of Equipment	Rectifier pulses	Installed Impedance (%Z)	Maximum Capacity Utilized	Full Load Displacement PF
1	20	10	HP	PWM VFD	6	3.00%	80.0%	0.950
2	10	25	HP	PWM VFD	6	3.00%	80.0%	0.950

AC Motors Operating Direct-on-Line

Item	Quantity	Size	Unit of Measure	Rated Full Load PF (Nameplate)	Maximum Capacity Utilized
11	1	100	KW	1.000	80.0%
12	50	1	HP	0.750	50.0%
13	2	100	HP	0.800	80.0%

Corrected System

Type of RMS Current	Corrected Current Amplitudes & Total Harmoic Current Distortion		Corrected Power	
Total I_{rms}	584.0	amps	606.91	KVA
Total I_{fund}	583.8	amps	543.34	KW
Total I_h	16.4	amps	0.9996	Distortion PF
Total $I_{reactive}$	234.3	amps	243.49	KVAR
% THDi (achieved)	2.82%		0.9126	Cos ϕ
% TDD (achieved)	2.82%		0.9122	Total PF

- TDD=2.8%
- Harmonic current= 16.4A
- IEEE-519 met . TDD target = 8%
- Power Factor= 91.2%

- **Adding the Active Harmonic Filter exceeds IEEE standard**

Evaluating Severity of Harmonics

- **Total Harmonic Distortion: Current**
  - A measure of the amount by which a composite current waveform deviates from an ideal sine wave
  - Caused by the manner in which electronic loads draw current for only a part of a complete sine wave
  - Measured as THD:

Causes additional heating in conductors and transformers, and leads to Voltage Distortion

- **Expressed as a %, THD is of little value**
- **Total Demand Distortion is becoming accepted**

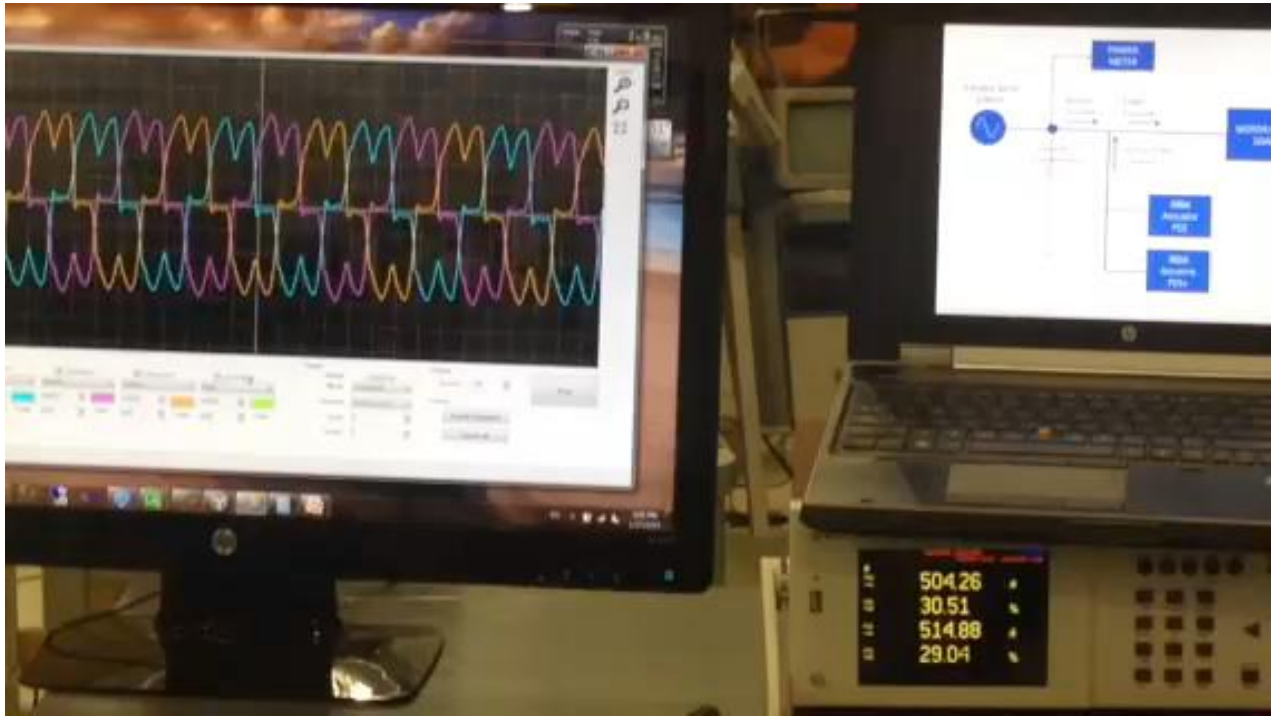
$$\Rightarrow \quad I_{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots}}{I_1} \times 100 \ \% = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100 \ \%$$

IEEE 519

- TDD and THD(I) are not the same except at 100% load
- As load decreases, TDD decreases while THD(I) increases
- Example:

	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%

AccuSine PCS+ Performance



Thank You

Any Questions?