EPCOS - Power Quality Solutions

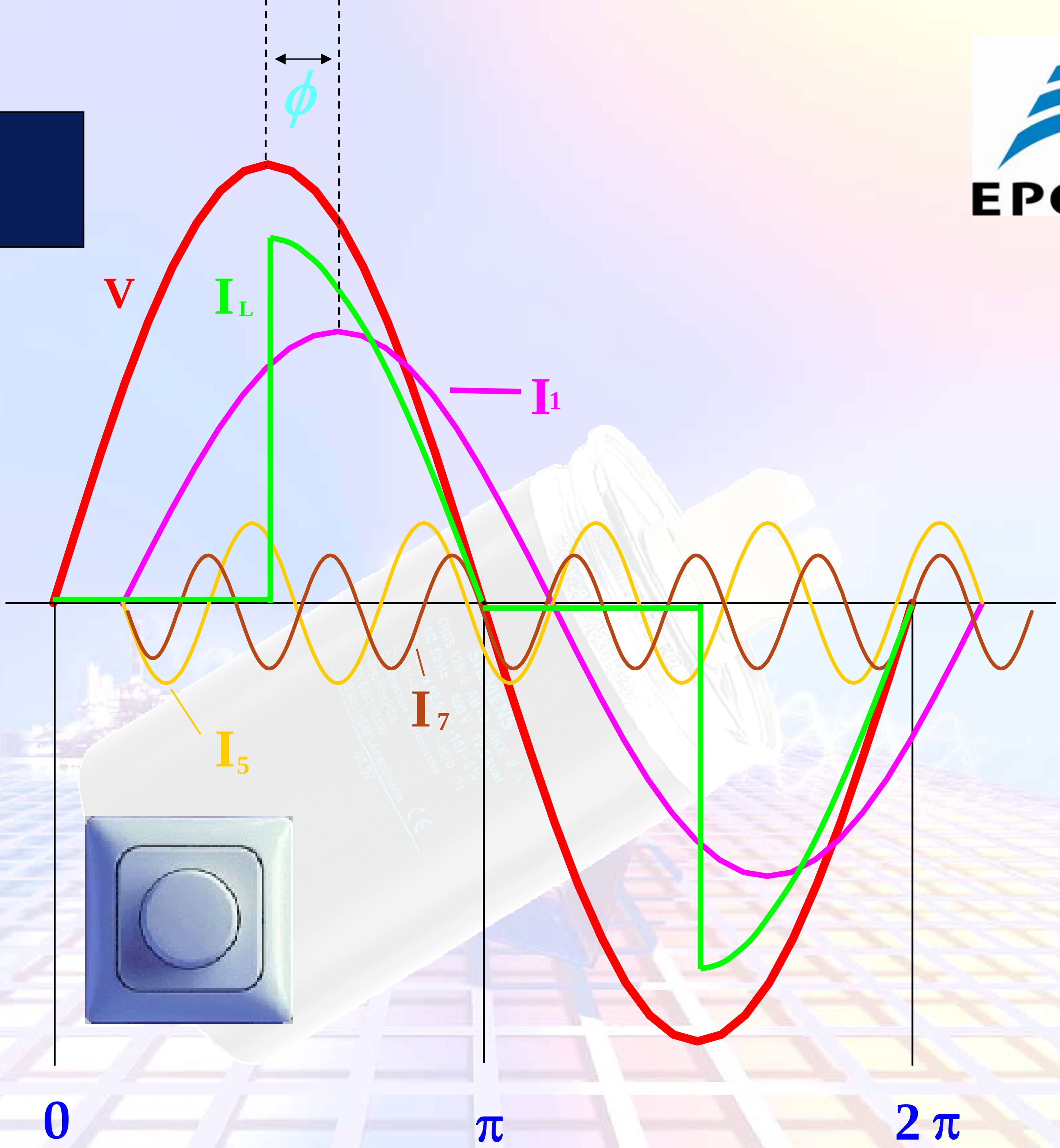
Power Factor Correction & Harmonic Filter

EPCOS

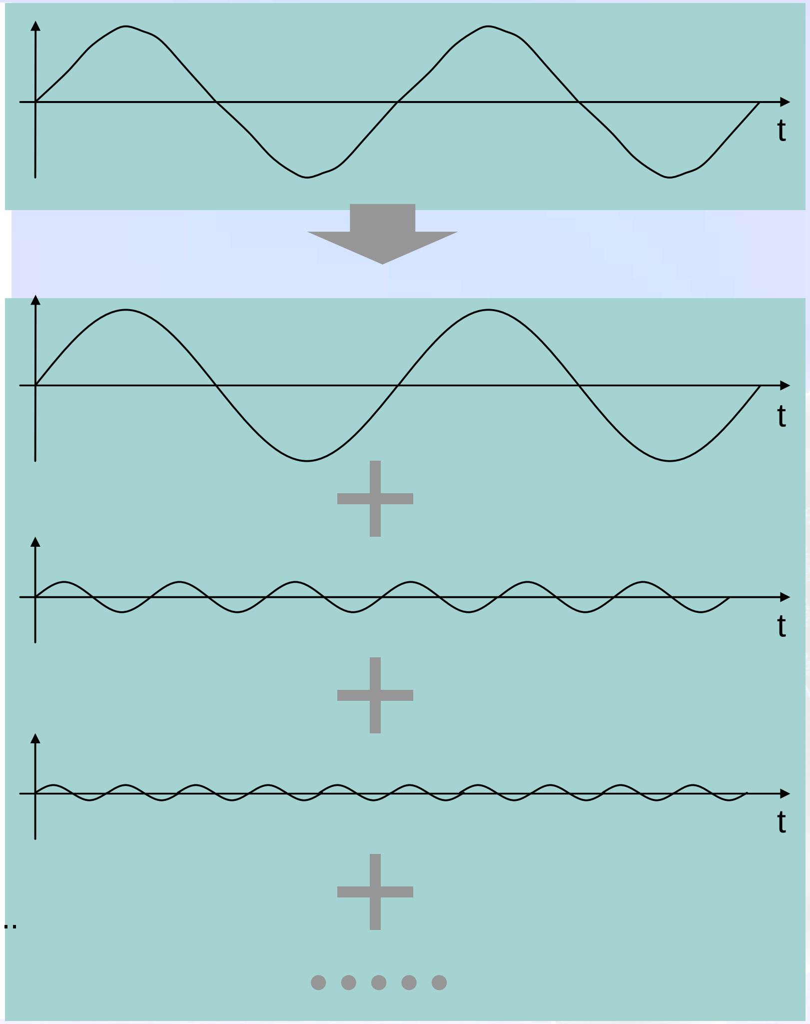
Loads create disturbances

Harmonics
Reactive power
Unsymmetrical load
Flicker

Non linear load



Modern drives a main source for harmonics



Distorted sinusoidal oscillation

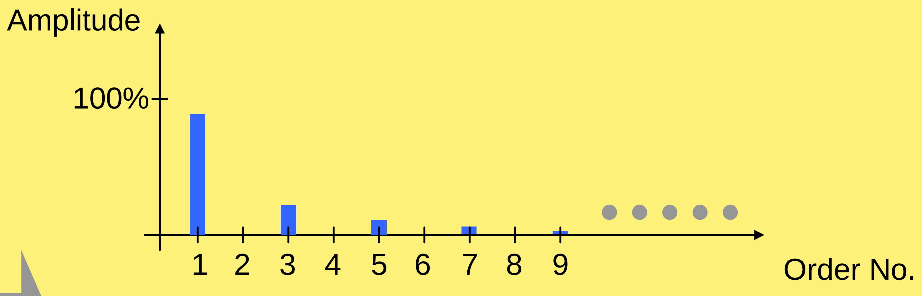
Basic fundamental

3rd order harmonic

5th order harmonic

Harmonics 7th, 9th, 11th, ... order

Representation of the harmonic contents in the diagram:



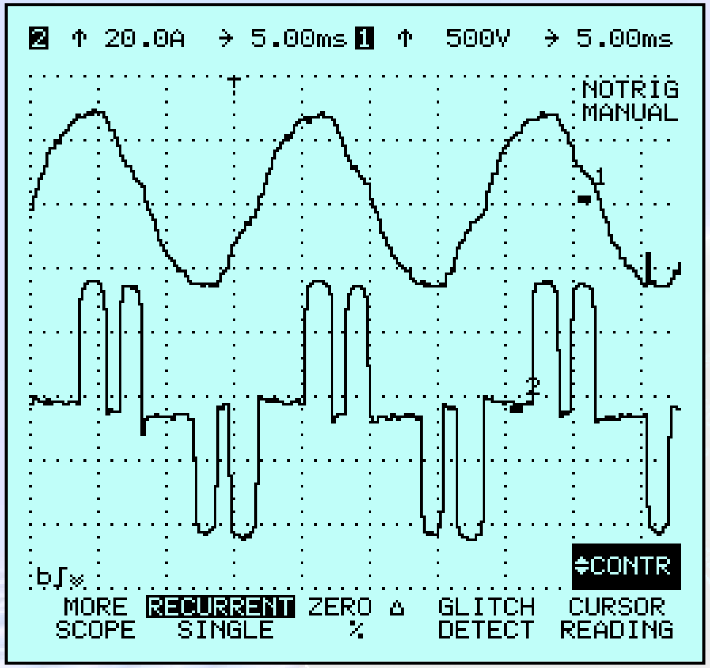
Relative harmonic distortion (Distortion factor D.F.):

$$D.F.=\frac{\sqrt{3\cdot\left(U_3^2+U_5^2+U_7^2+...\right)}}{U_1}\cdot 100\%$$

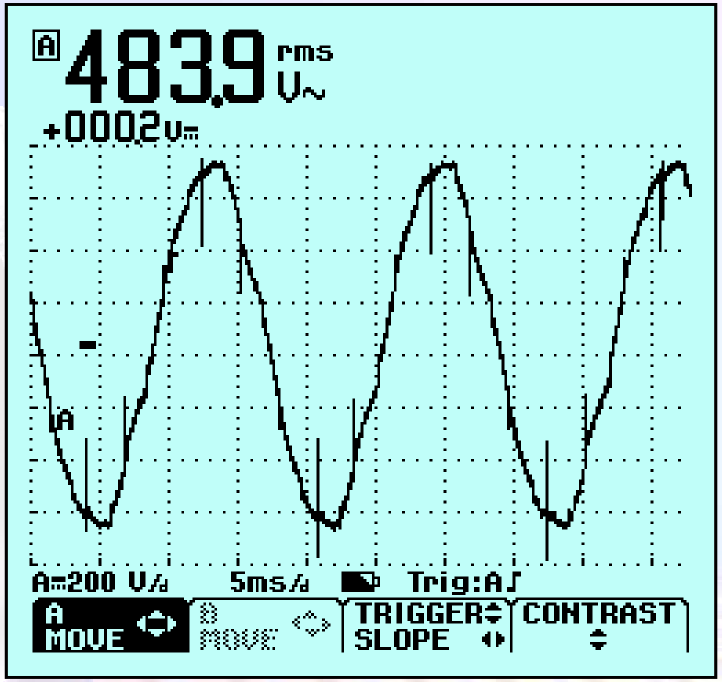
Harmonic order	F	3rd	5th	7th
Frequency	50	150	250	350

Examples for poor power quality

Adjustable Speed Drives

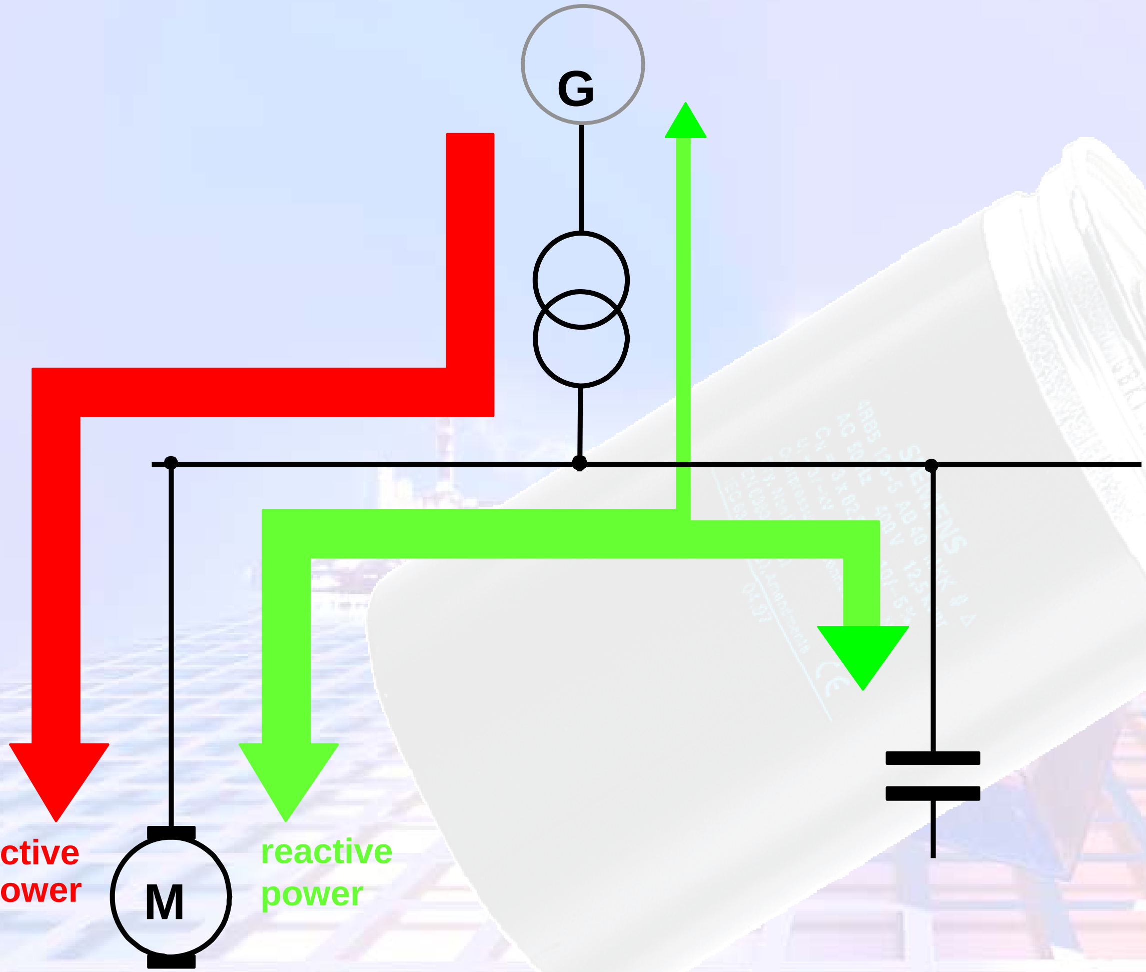


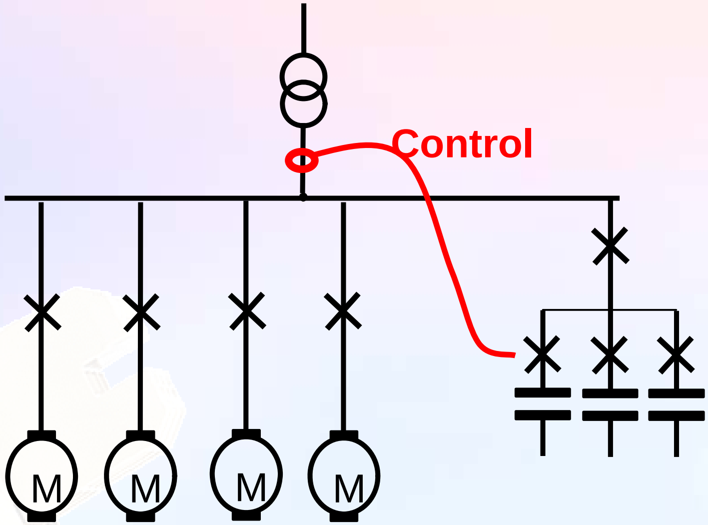
Flat topping of Drive input voltage, heavily distorted current

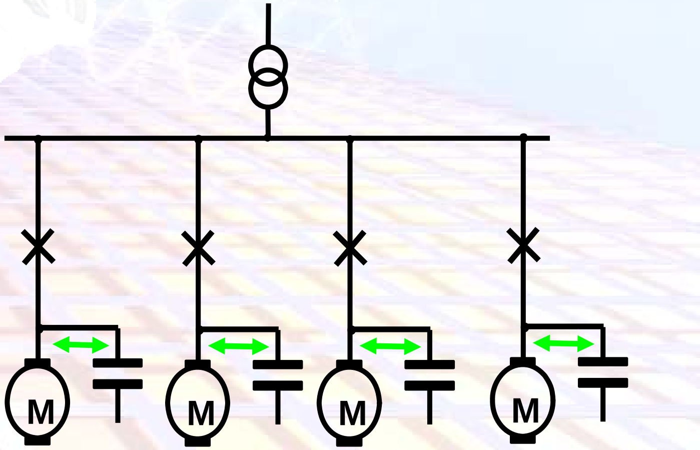


Notching on the input can interfere with other loads on the same branch circuit

Compensated System







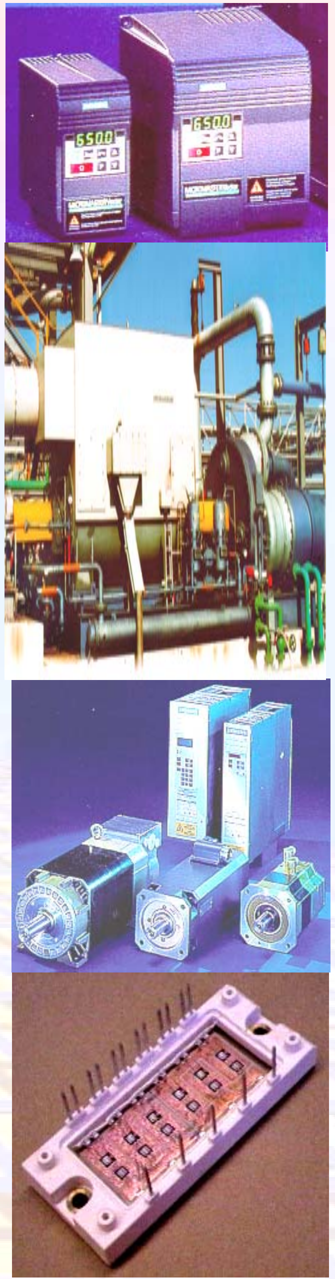
Changing load structure

<u>Past - load:</u> most loads were “linear”

- **Induction-motors, heating, bulbs**
- **voltage was followed by current - only a few problems**

Features	Customer benefits
• Simple and rugged design	– High reliability – Long lifetime – Favourably-priced
• No commutator	– Unrestricted operation for partial- and overload conditions – Low maintenance (only the bearings)
• High degree of protection	– Can be universally used

Changing load structure



<u>Today's - loads:</u> most loads act "non linear"

Loads having non linear voltage-current characteristics are called non linear loads. When connected to a sinusoidal voltage, these loads produce non sinusoidal currents.

Non linear devices can be classified into <u>three major categories</u>:

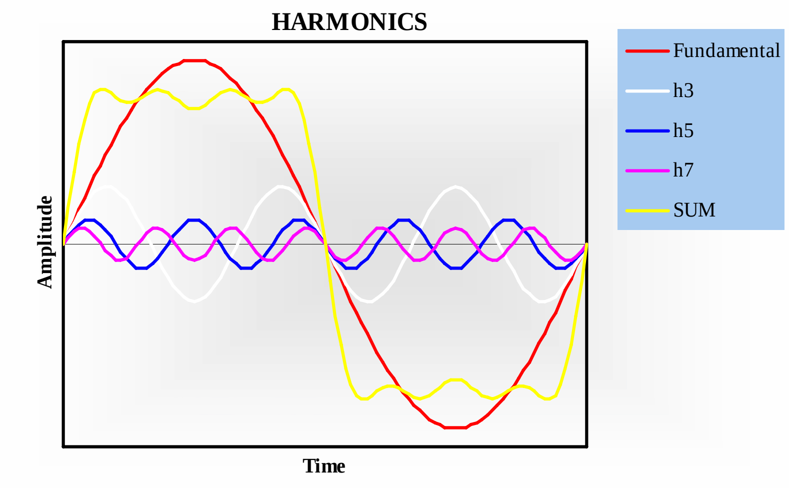
1. Power Electronics: e.g. rectifiers, variable speed drives, UPS, ...

2. Ferromagnetic devices: (non linear magnetizing characteristics)

3. Arcing devices: Arcing devices, e.g. arc furnace equipment, generate harmonics due to the non linear characteristics of the arc itself.

Problems caused by HARMONICS

- Overheating of transformers (K-Factor), and rotating equipment
- Neutral overloading / unacceptable neutral-to-ground voltages
- Failed capacitor banks
- Breakers and fuse tripping
- Unreliable operation of electronic equipment, and generators
- Erroneous register of electric meters
- Wasted energy / higher electric bills - KWD & KWH
- Wasted capacity - Inefficient distribution of power
- Increased maintenance cost of equipment and machinery



Problems caused by harmonics

Standards, e.g. EN50160

Harmonic voltage

The THD of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8%.

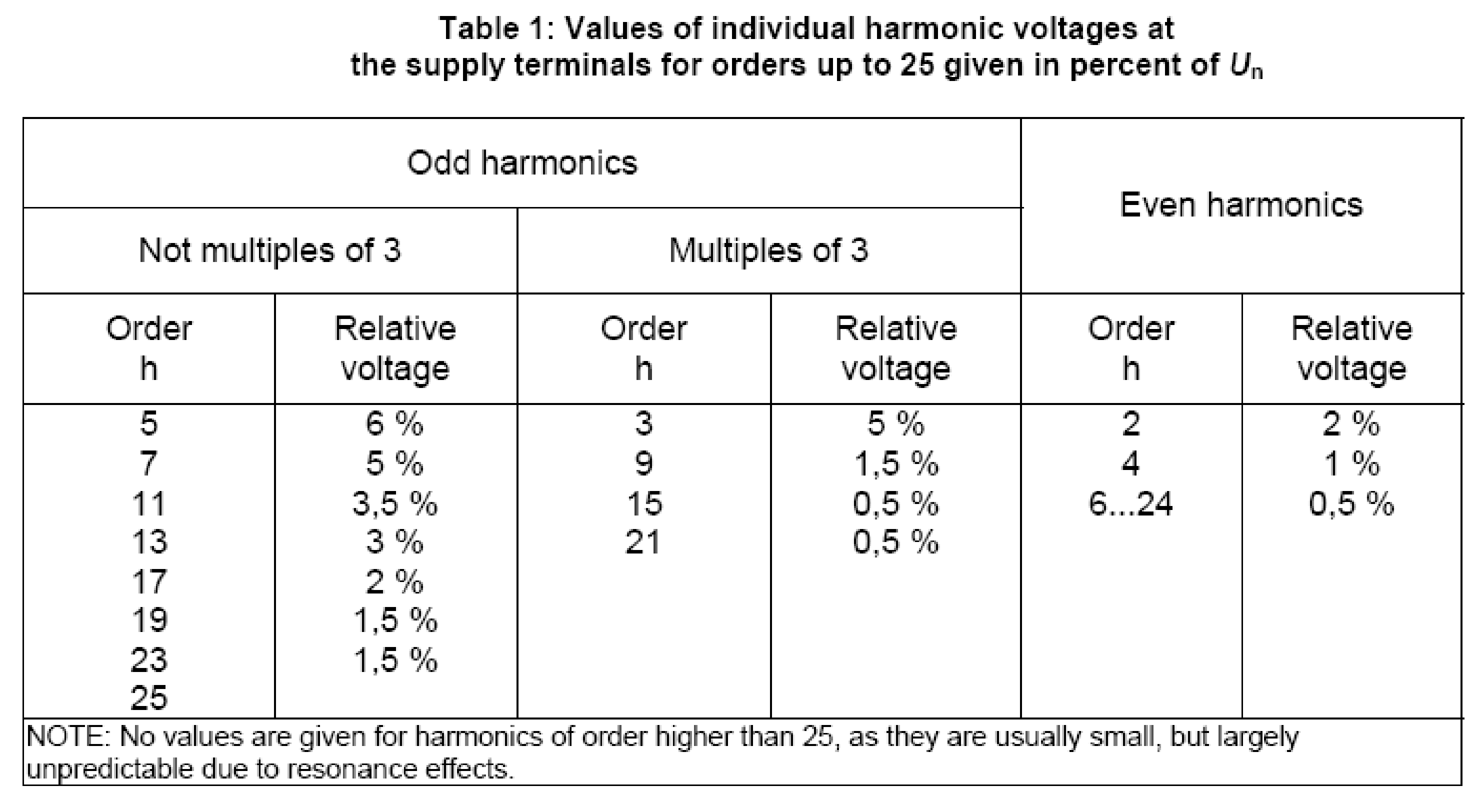


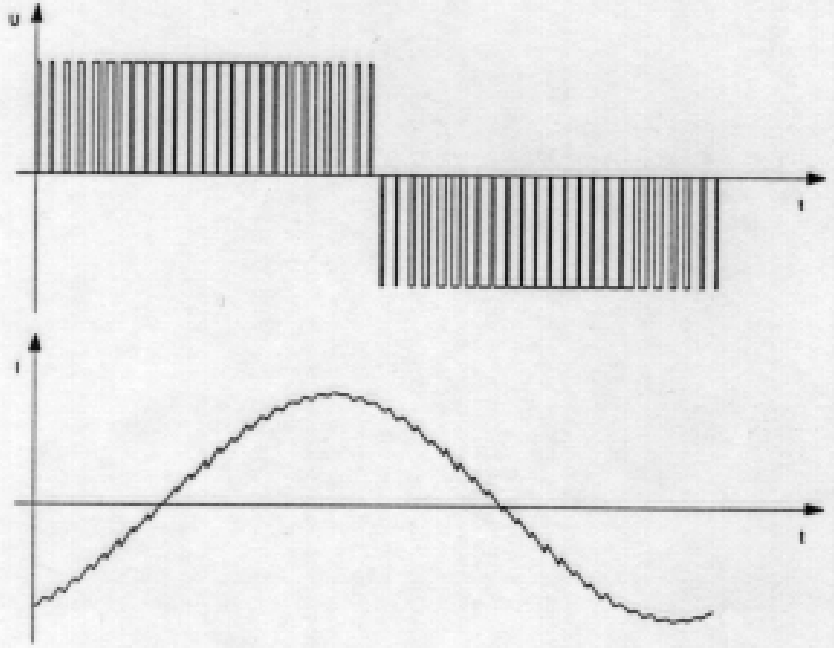
Table 1: Values of individual harmonic voltages at the supply terminals for orders up to 25 given in percent of U_n

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative voltage	Order h	Relative voltage	Order h	Relative voltage
5	6 %	3	5 %	2	2 %
7	5 %	9	1,5 %	4	1 %
11	3,5 %	15	0,5 %	6...24	0,5 %
13	3 %	21	0,5 %		
17	2 %				
19	1,5 %				
23	1,5 %				
25					

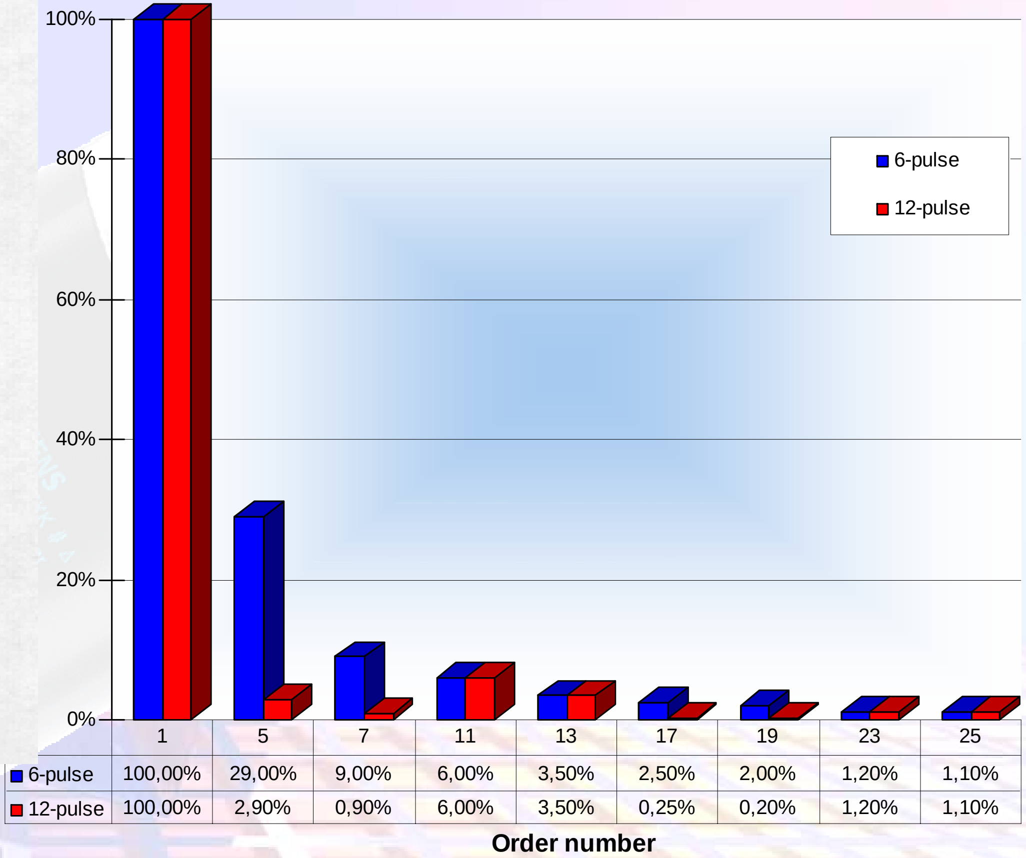
NOTE: No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.

HARMONICS fed back by 6/12 pulse rectifier

Voltage characteristic at the drive converter output (PWM)



Current characteristic at the drive converter output

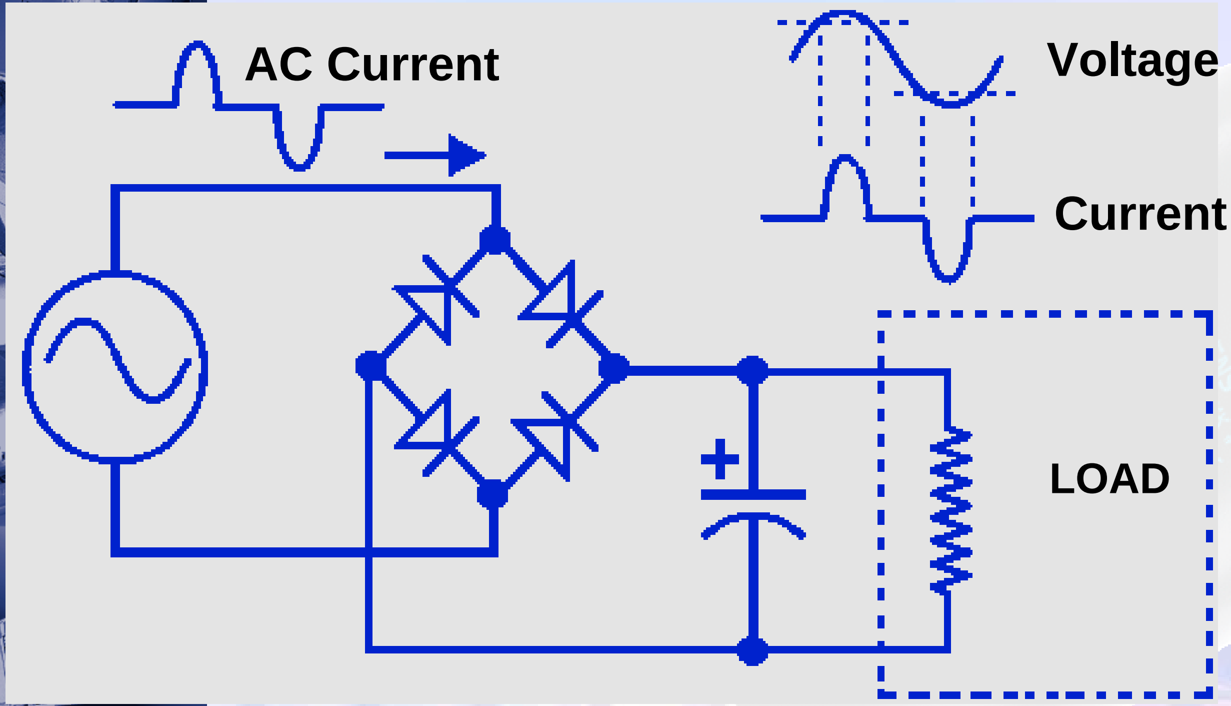


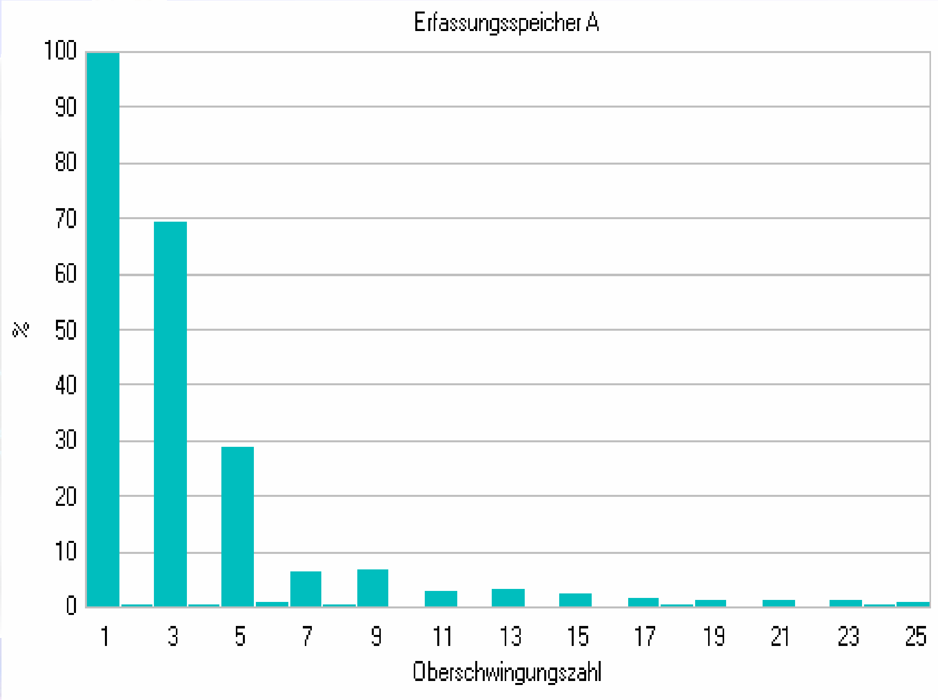
	1	5	7	11	13	17	19	23	25
🟦 6-pulse	100,00%	29,00%	9,00%	6,00%	3,50%	2,50%	2,00%	1,20%	1,10%
🟥 12-pulse	100,00%	2,90%	0,90%	6,00%	3,50%	0,25%	0,20%	1,20%	1,10%

Order number

Example for single phase Non-Linear load

Example of a non-linear load: Switched mode power supply

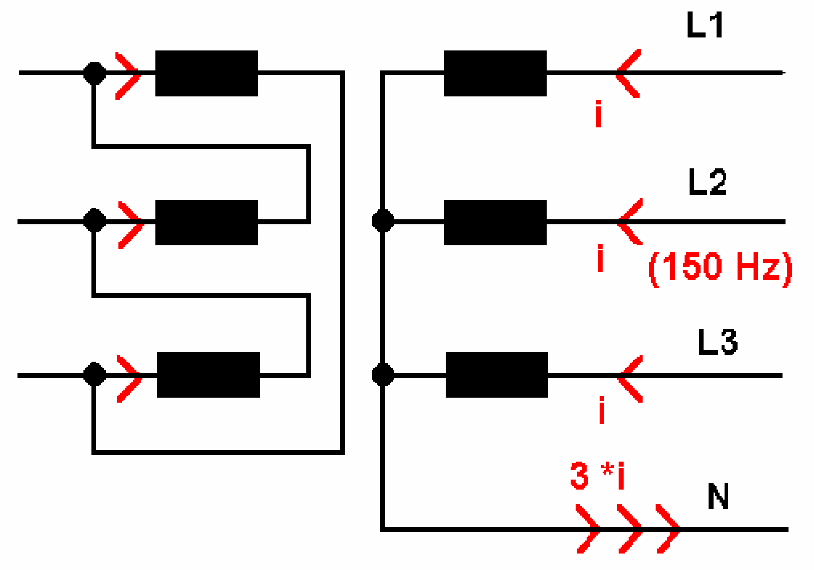


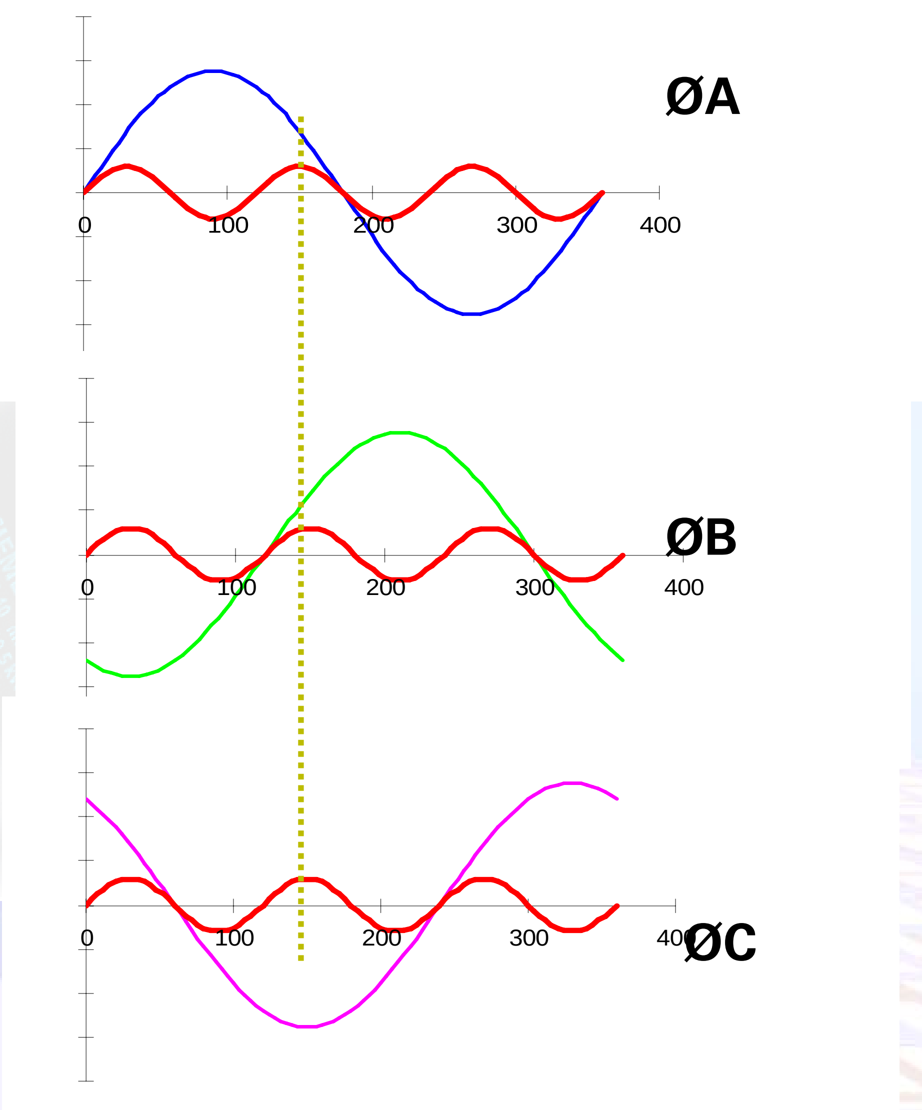


3rd harmonic in the neutral conductor

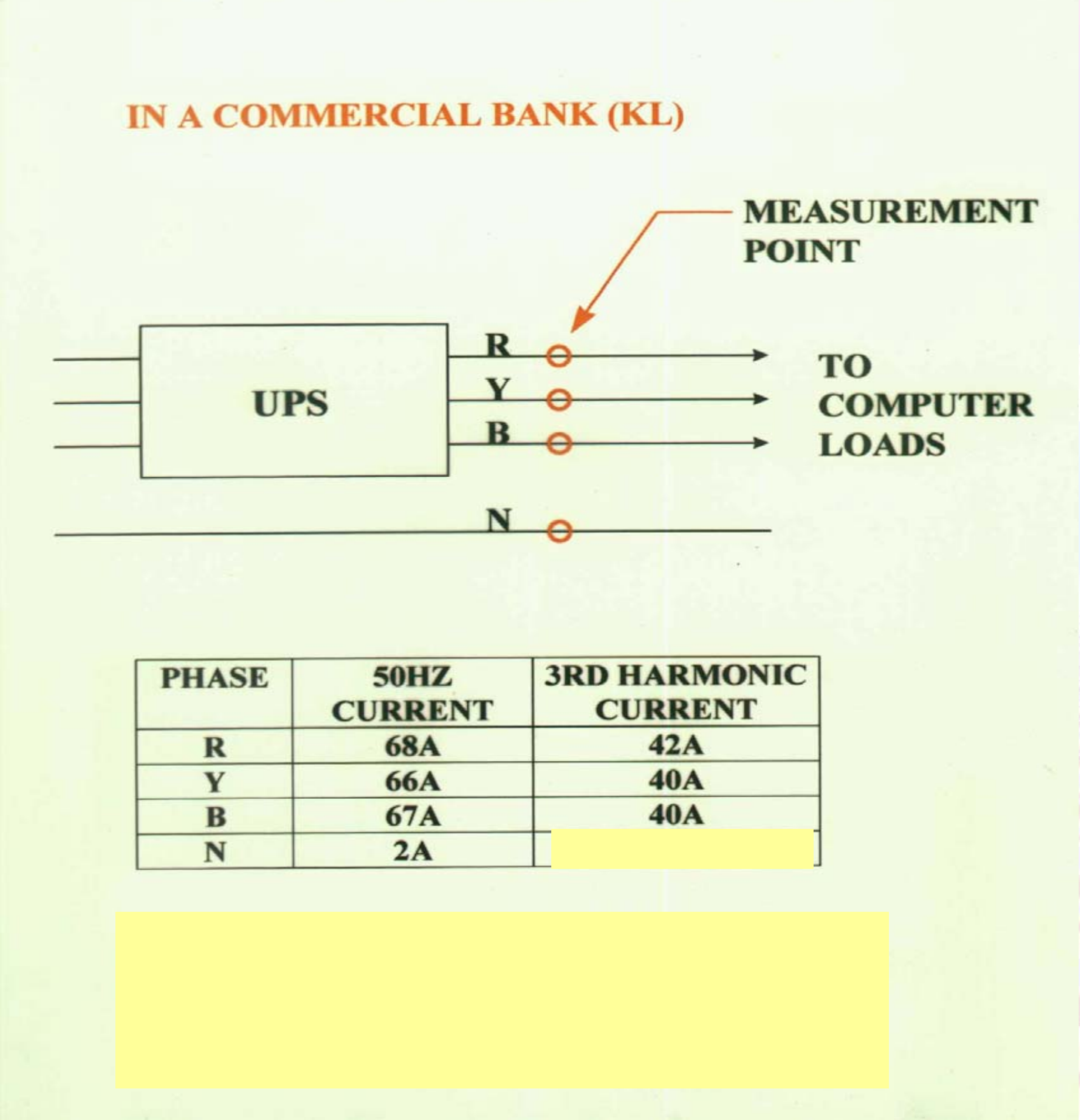
In a 3-phase-system with neutral conductor, 3rd harmonics will sum up in the neutral conductor..

Harmonics of 3rd order of each conductor are in phase.





3rd harmonic in the neutral conductor



IN A COMMERCIAL BANK (KL)

MEASUREMENT POINT

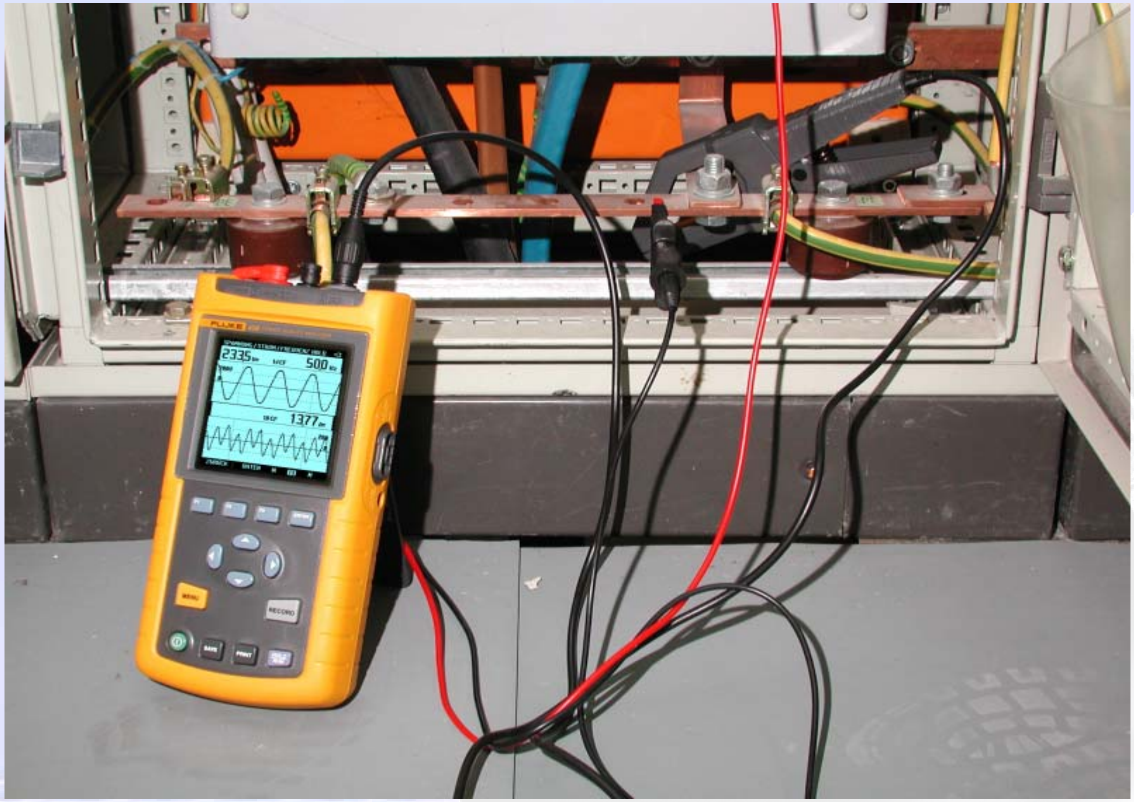
UPS

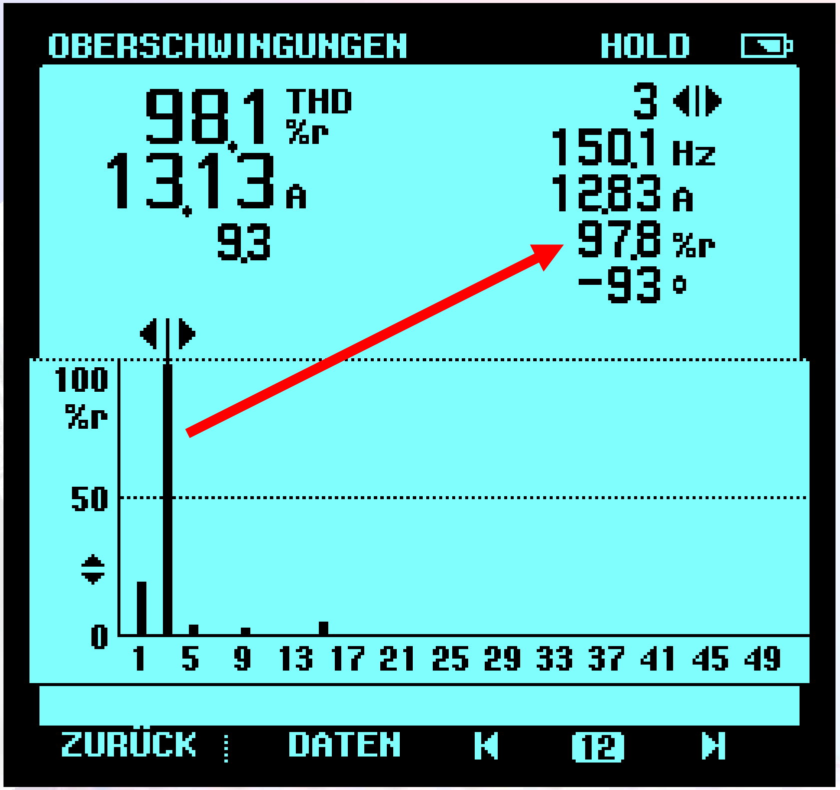
R
Y
B
N

TO COMPUTER LOADS

PHASE	50HZ CURRENT	3RD HARMONIC CURRENT
R	68A	42A
Y	66A	40A
B	67A	40A
N	2A	

3rd harmonic in the neutral conductor





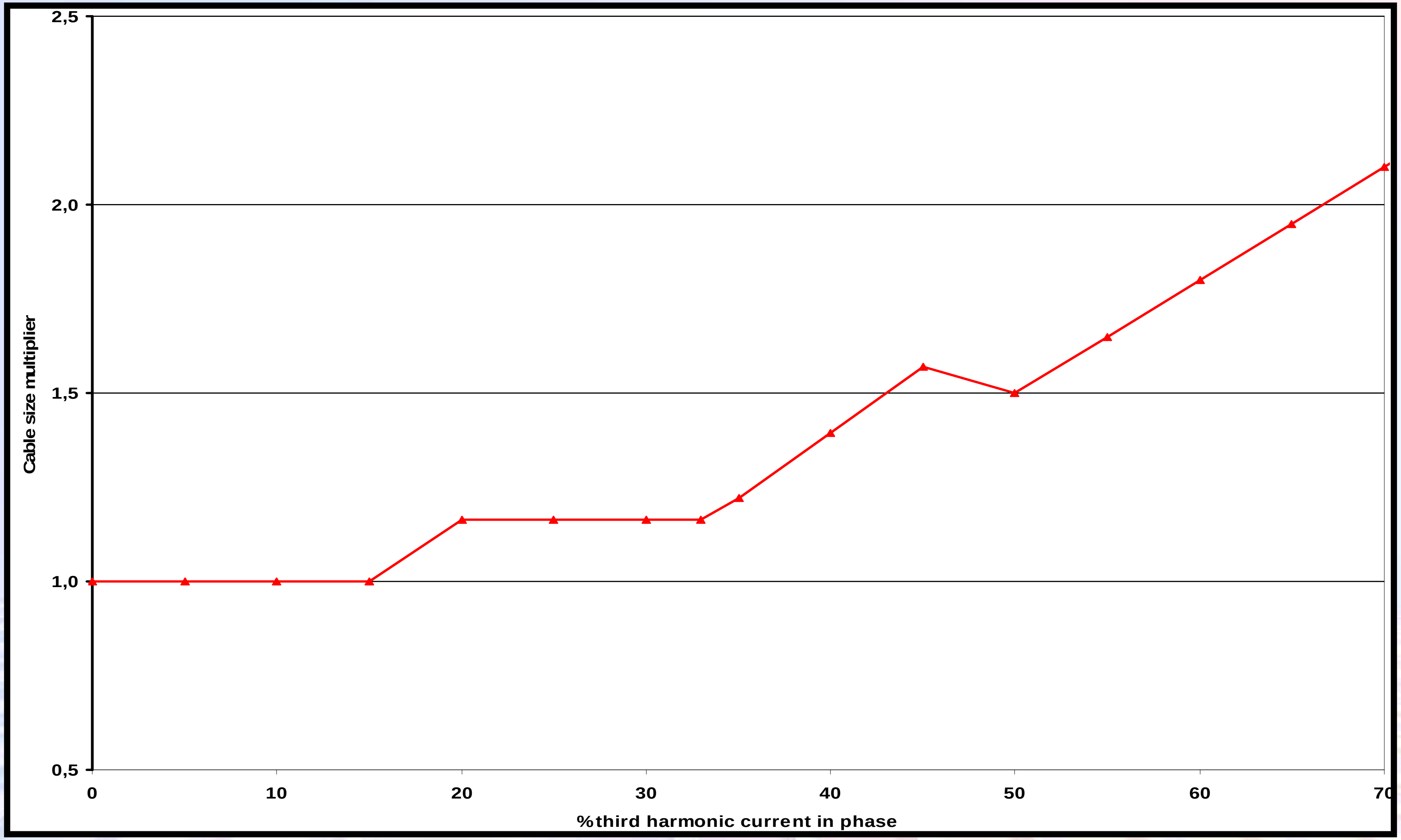
OBERSCHWINGUNGEN HOLD

98.1 THD %r
13.13 A
9.3

3
150.1 Hz
12.83 A
97.8 %r
-93 °

Measuring at feed-in:
4 Phases needed

Neutral conductor sizing IEC standard 60364-52



COST caused by HARMONICS

- Additional investment due to faster equipment derating
- Higher energy consumption
- Higher downtime of production equipment
  - Higher maintenance and repair cost
  - Reduced product quality
  - Reduced production output
- Investment for stronger equipments/components

or

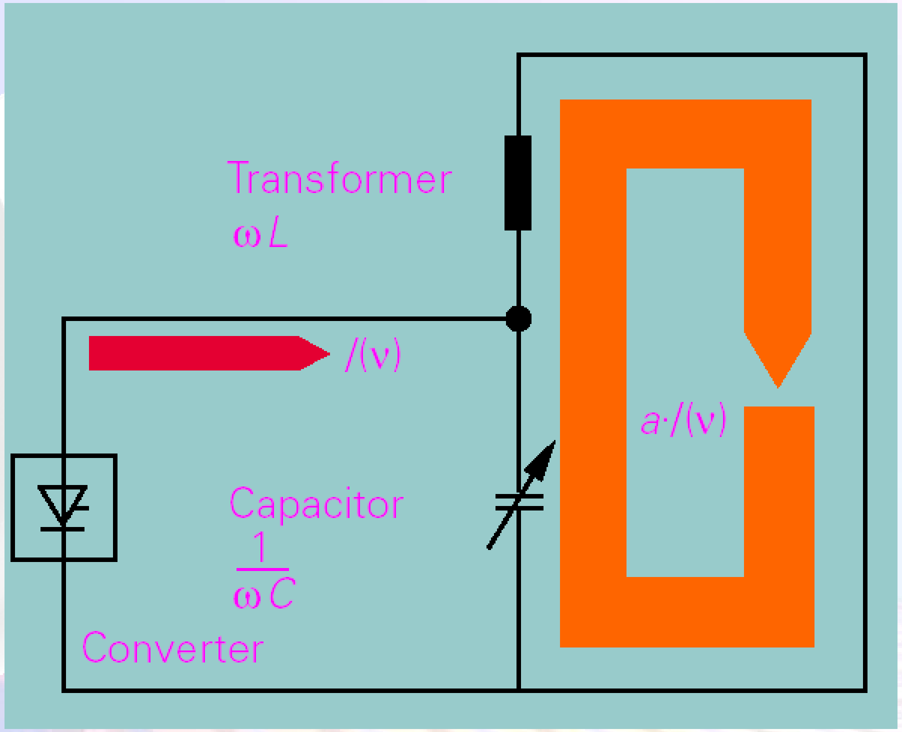
- **Solution: One time investment for harmonic filter**

Summary

- Consumer structure has changed from linear to non linear loads
- Harmonics in the net are increasing
- Increasing unknown energy losses
- Unknown overloads
- Problems in the net become more complex
- Beside convent. PFC, filters become more and more important
- De-tuned filters for most applications
- Active filters for a niche market

Resonance

Most critical are applications in which the application configuration (PFC capacitor and transformer) form a resonance circuit with a frequency close to existing harmonic frequencies. In such a case harmonic currents stimulate the resonance circuit and create resonance amplification with harmful over voltages and over currents.

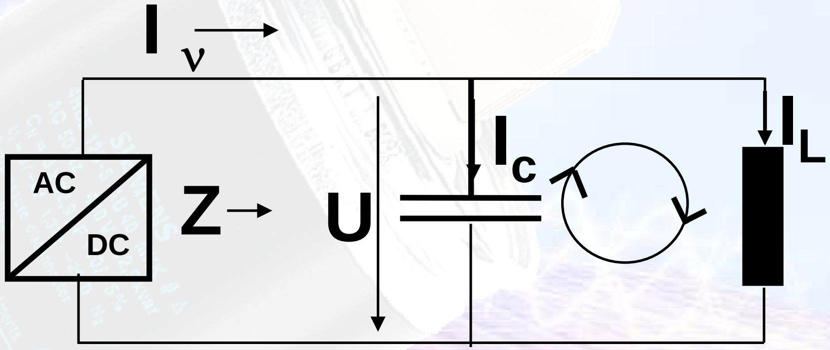


Parallel resonance

What happens in case of parallel resonance?

1) I_ν is constant and imprinted

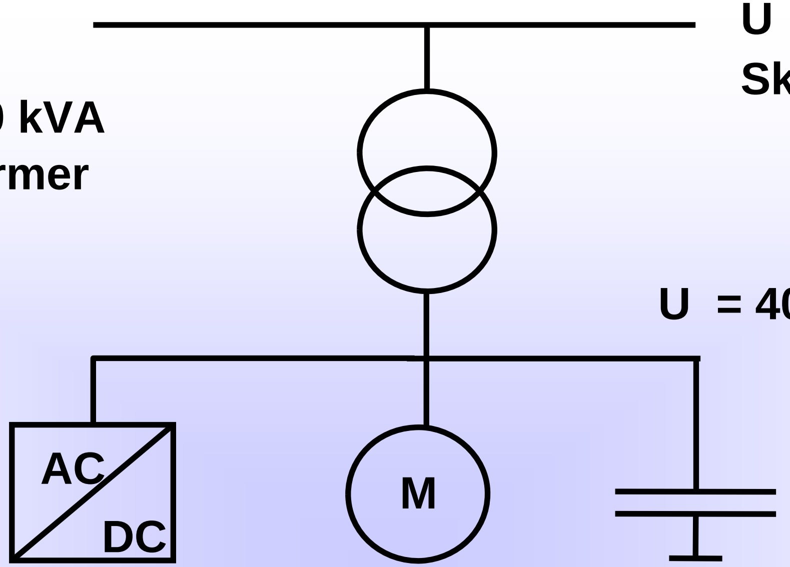
2) Impedance $Z \rightarrow \infty$



1) + 2) $\Rightarrow$ voltage $U \rightarrow \infty$ (ohmic law)

3) With $U \rightarrow \infty \Rightarrow I_c = I_L \rightarrow \infty$

Parallel resonance: example



U = 20 KV
Sk = 500 MVA

S = 1000 kVA
Transformer
uk = 6%

U = 400 V

Qc = 400kvar

P = 100 KW

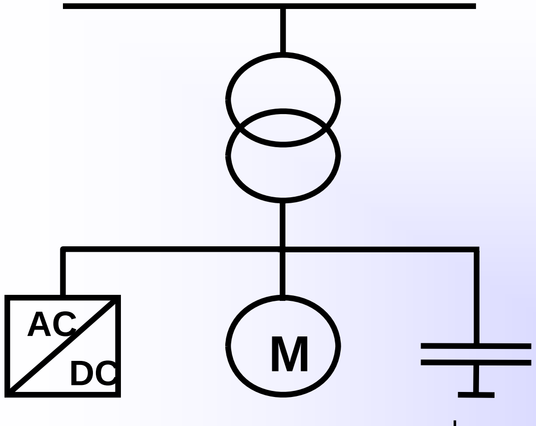
<u>**P = 500 KW, 6-pulse**</u>

I_{50} Hz = 720A
I_{250} Hz = 144A
I_{350} Hz = 103A
I_{550} Hz = 65A
I_{650} Hz = 55A
I_{850} Hz = 42A
I_{950} Hz = 38A

$$I_{350}\,\text{Hz} = \frac{720}{7}\,\text{A}$$

Parallel resonance: example

$$f_R = 50 \cdot \sqrt{\frac{S_T \cdot 100}{Q_C \cdot u_K}}$$



$$S_{KLV} = \frac{S_{Tr}}{u_k} \cdot 100 \rightarrow$$

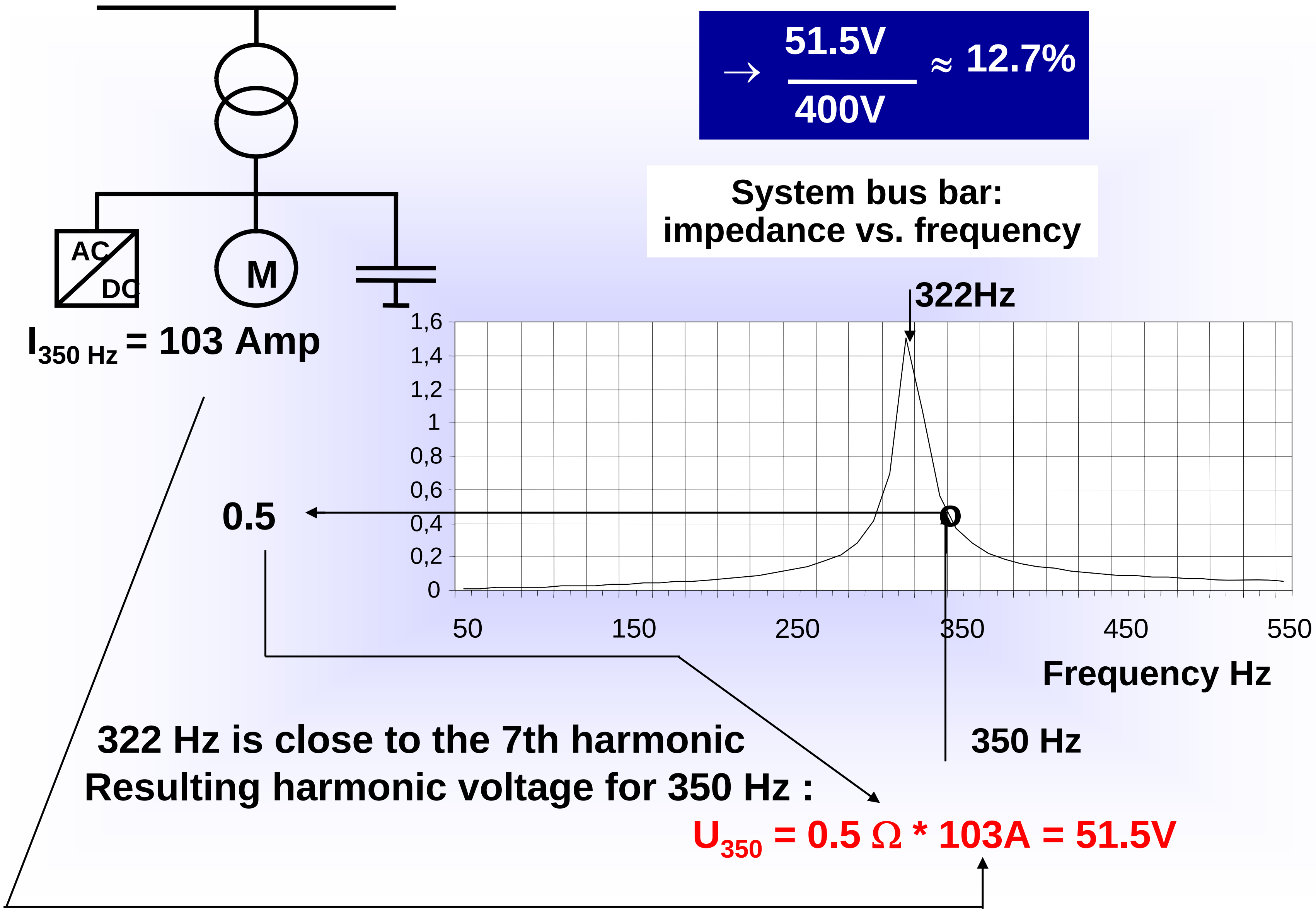
$$S_{KLV} = \frac{1000 \text{ kVA}}{6} \cdot 100 = 16.67\text{MVA}$$

$$f_{rp} = 50\text{Hz} \cdot \sqrt{\frac{S_{KLV}}{Q_c}}$$

$$\rightarrow \quad f_{rp} = 50 \text{ Hz} \cdot \sqrt{\frac{16.67 \text{ MVA}}{0.4 \text{ Mvar}}} = 322 \text{ Hz}$$

Attention: close to the 7th harmonic!

Parallel resonance: example



$$\rightarrow \frac{51.5V}{400V} \approx 12.7\%$$

System bus bar: impedance vs. frequency

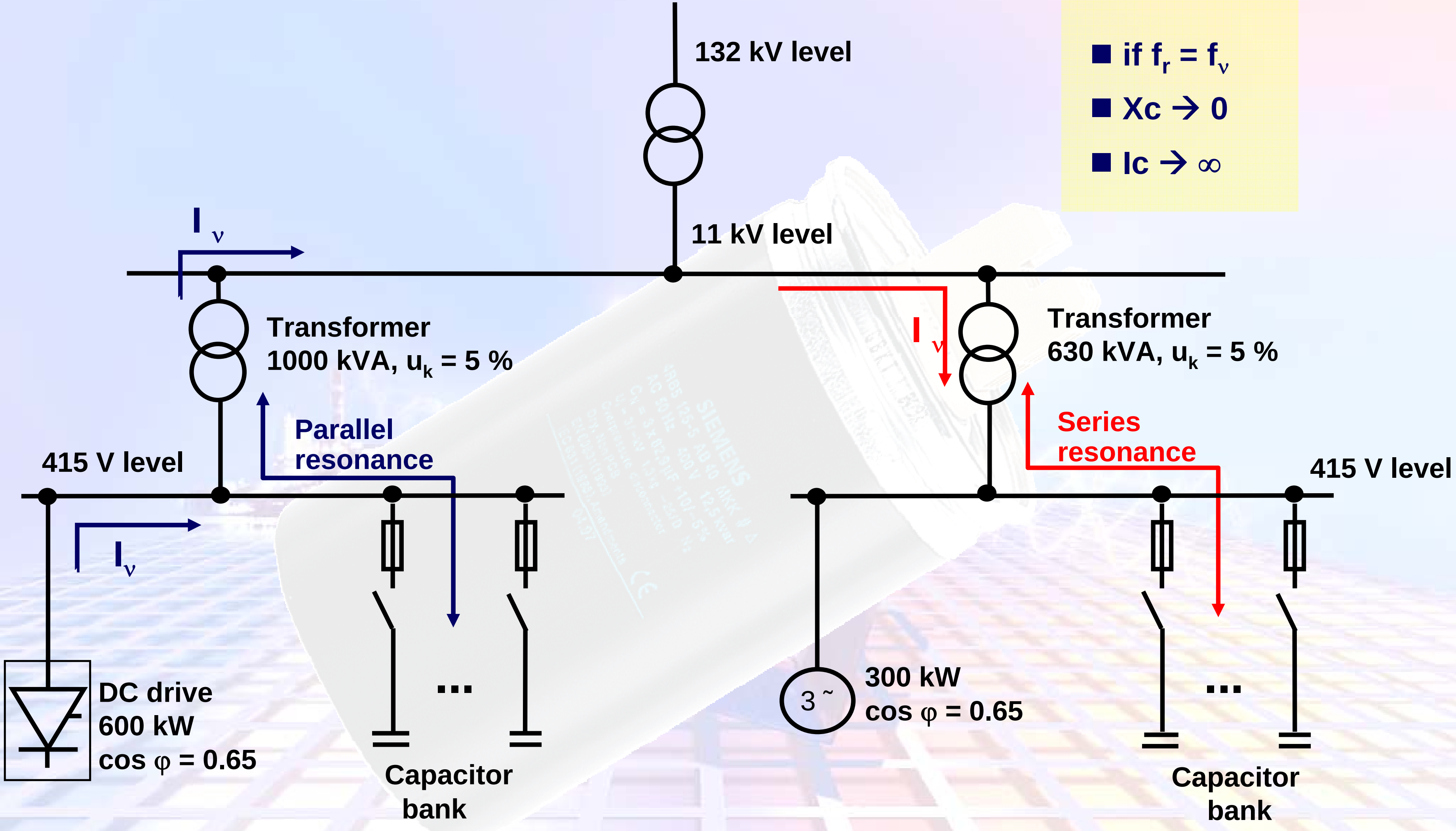
$I_{350\ Hz} = 103\ Amp$

322 Hz is close to the 7th harmonic
Resulting harmonic voltage for 350 Hz :

$$U_{350} = 0.5\ \Omega * 103A = 51.5V$$

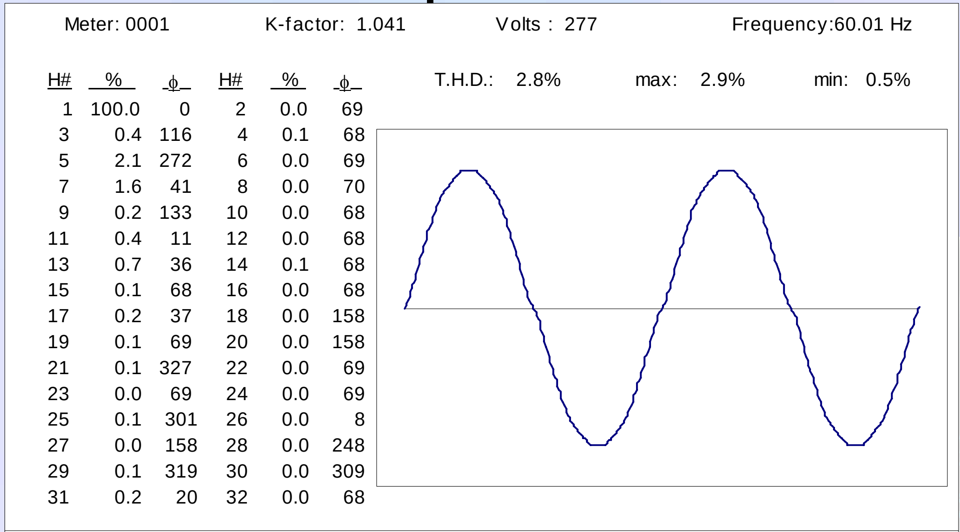
Resonance?

- if $f_r = f_\nu$
- Xc → 0
- Ic → ∞



Harmonics MAGNIFICATION

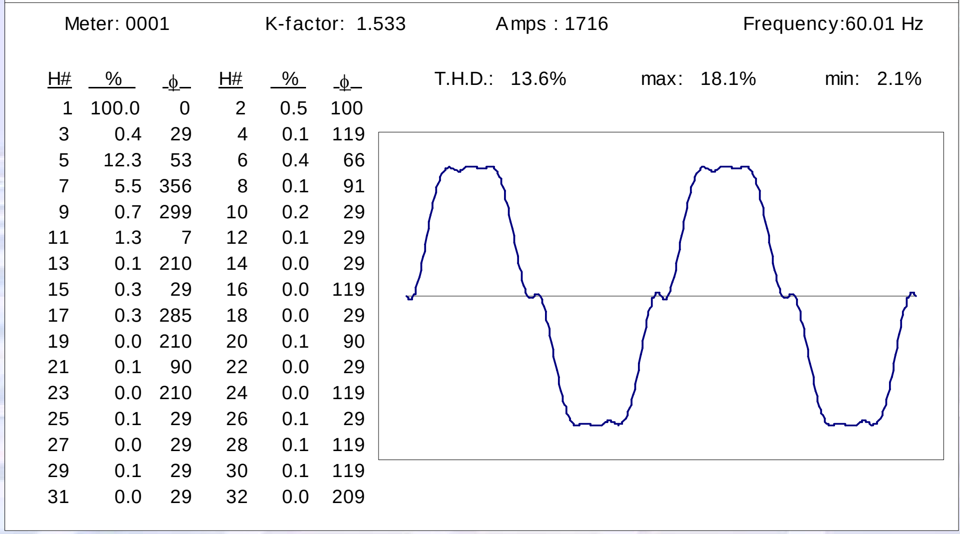
No PFC capacitors



Meter: 0001 K-factor: 1.041 Volts : 277 Frequency:60.01 Hz

T.H.D.: 2.8% max: 2.9% min: 0.5%

H#	%	ϕ	H#	%	ϕ
1	100.0	0	2	0.0	69
3	0.4	116	4	0.1	68
5	2.1	272	6	0.0	69
7	1.6	41	8	0.0	70
9	0.2	133	10	0.0	68
11	0.4	11	12	0.0	68
13	0.7	36	14	0.1	68
15	0.1	68	16	0.0	68
17	0.2	37	18	0.0	158
19	0.1	69	20	0.0	158
21	0.1	327	22	0.0	69
23	0.0	69	24	0.0	69
25	0.1	301	26	0.0	8
27	0.0	158	28	0.0	248
29	0.1	319	30	0.0	309
31	0.2	20	32	0.0	68

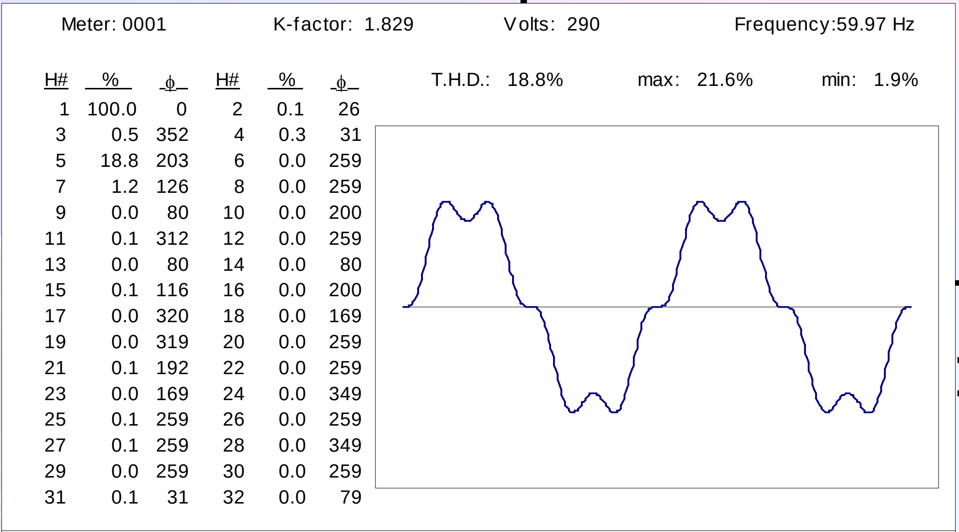


Meter: 0001 K-factor: 1.533 Amps : 1716 Frequency:60.01 Hz

T.H.D.: 13.6% max: 18.1% min: 2.1%

H#	%	ϕ	H#	%	ϕ
1	100.0	0	2	0.5	100
3	0.4	29	4	0.1	119
5	12.3	53	6	0.4	66
7	5.5	356	8	0.1	91
9	0.7	299	10	0.2	29
11	1.3	7	12	0.1	29
13	0.1	210	14	0.0	29
15	0.3	29	16	0.0	119
17	0.3	285	18	0.0	29
19	0.0	210	20	0.1	90
21	0.1	90	22	0.0	29
23	0.0	210	24	0.0	119
25	0.1	29	26	0.1	29
27	0.0	29	28	0.1	119
29	0.1	29	30	0.1	119
31	0.0	29	32	0.0	209

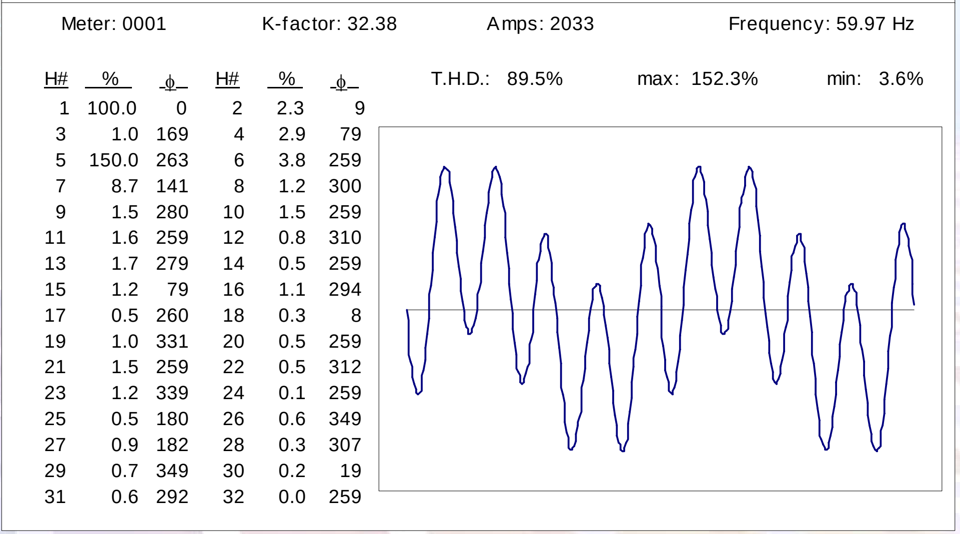
With PFC capacitors



Meter: 0001 K-factor: 1.829 Volts: 290 Frequency:59.97 Hz

T.H.D.: 18.8% max: 21.6% min: 1.9%

H#	%	ϕ	H#	%	ϕ
1	100.0	0	2	0.1	26
3	0.5	352	4	0.3	31
5	18.8	203	6	0.0	259
7	1.2	126	8	0.0	259
9	0.0	80	10	0.0	200
11	0.1	312	12	0.0	259
13	0.0	80	14	0.0	80
15	0.1	116	16	0.0	200
17	0.0	320	18	0.0	169
19	0.0	319	20	0.0	259
21	0.1	192	22	0.0	259
23	0.0	169	24	0.0	349
25	0.1	259	26	0.0	259
27	0.1	259	28	0.0	349
29	0.0	259	30	0.0	259
31	0.1	31	32	0.0	79



Meter: 0001 K-factor: 32.38 Amps: 2033 Frequency: 59.97 Hz

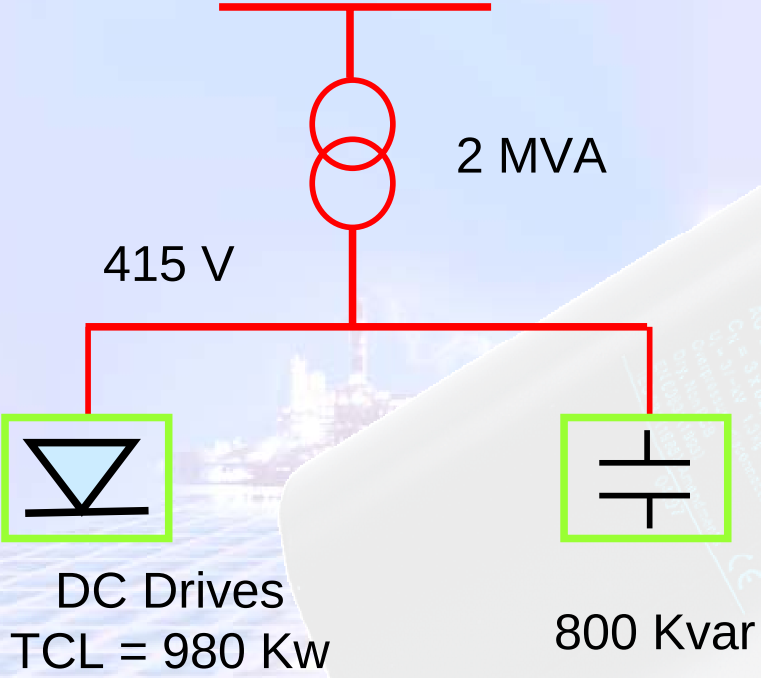
T.H.D.: 89.5% max: 152.3% min: 3.6%

H#	%	ϕ	H#	%	ϕ
1	100.0	0	2	2.3	9
3	1.0	169	4	2.9	79
5	150.0	263	6	3.8	259
7	8.7	141	8	1.2	300
9	1.5	280	10	1.5	259
11	1.6	259	12	0.8	310
13	1.7	279	14	0.5	259
15	1.2	79	16	1.1	294
17	0.5	260	18	0.3	8
19	1.0	331	20	0.5	259
21	1.5	259	22	0.5	312
23	1.2	339	24	0.1	259
25	0.5	180	26	0.6	349
27	0.9	182	28	0.3	307
29	0.7	349	30	0.2	19
31	0.6	292	32	0.0	259

Voltage

Current

Real case of parallel resonance in KL/Malaysia

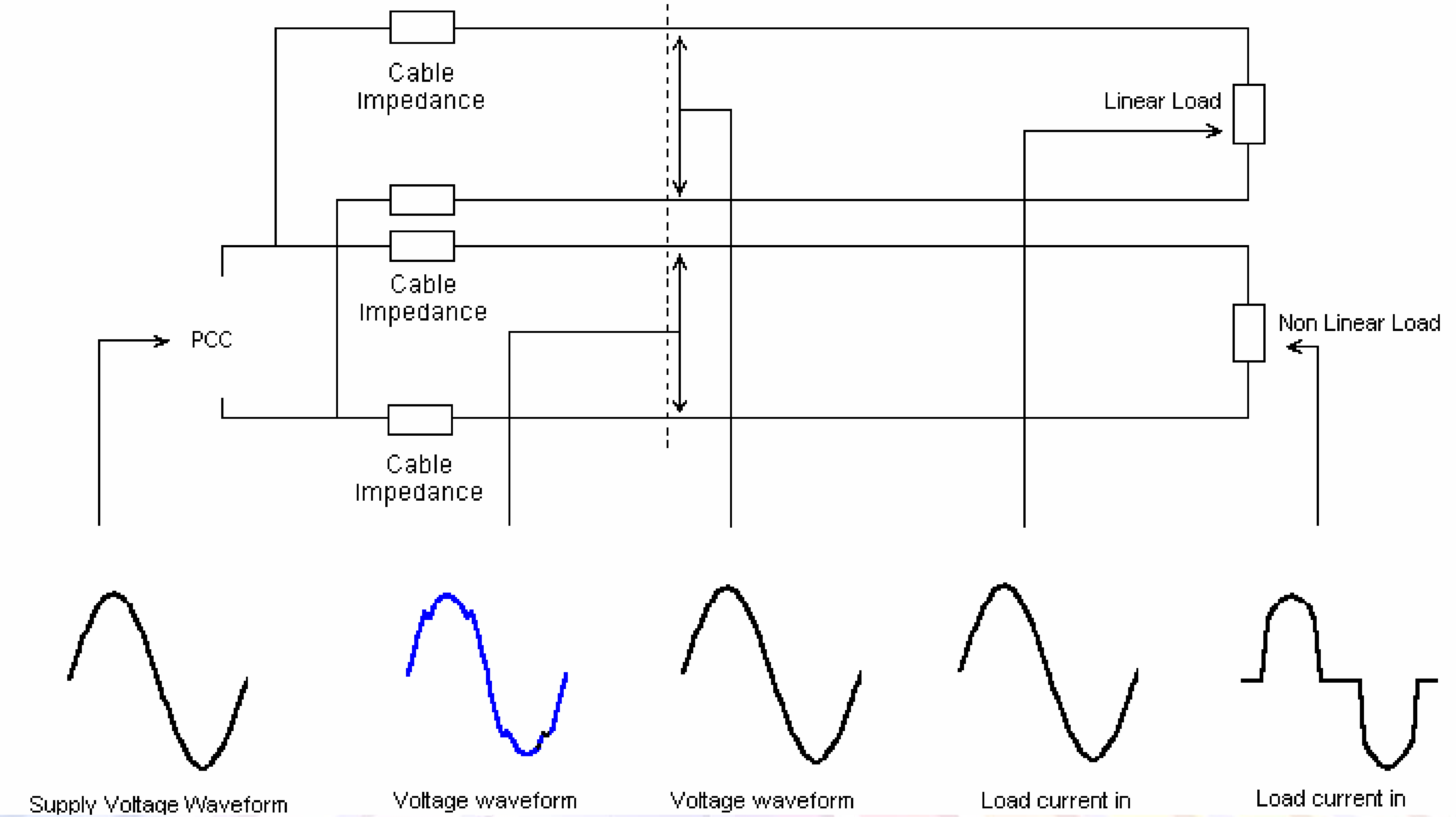


Harmonic Current	Without Capacitor	With Capacitor	After Filter
1	1200 A		
5	265 A		
7	70 A		
11	50 A		
VTHD	5.12 %		
PF	0.617 %		

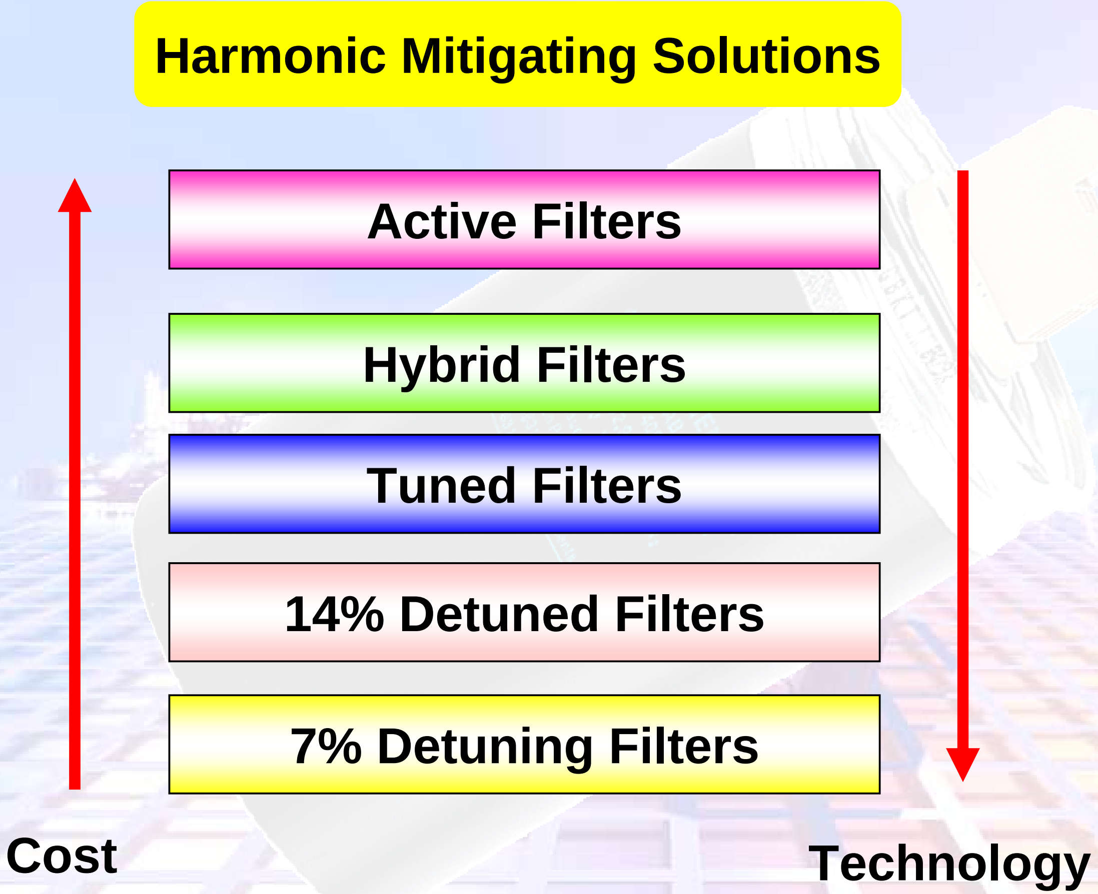
Remedial measures

- Increase fault level (reduction of impedances)
- Limiting total output of harmonic sources
- Limit number of simultaneously operating harmonic sources
- Balanced connection of 1-phase loads to the 3-phases
- Pull in extra neutral wires
- Isolated ground separated from the safety ground
- Using equipment with higher pulse number
- **De-tuned HARMONIC filters**
- Tuned filter circuits
- Active harmonic filter

Reducing Voltage Distortion by Circuit Separation



Harmonic filter circuits



Harmonic Mitigating Solutions

Active Filters

Hybrid Filters

Tuned Filters

14% Detuned Filters

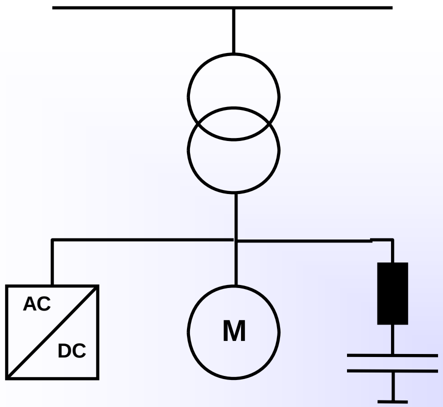
7% Detuning Filters

Cost

Technology

De-tuned harmonic filter

EPCOS



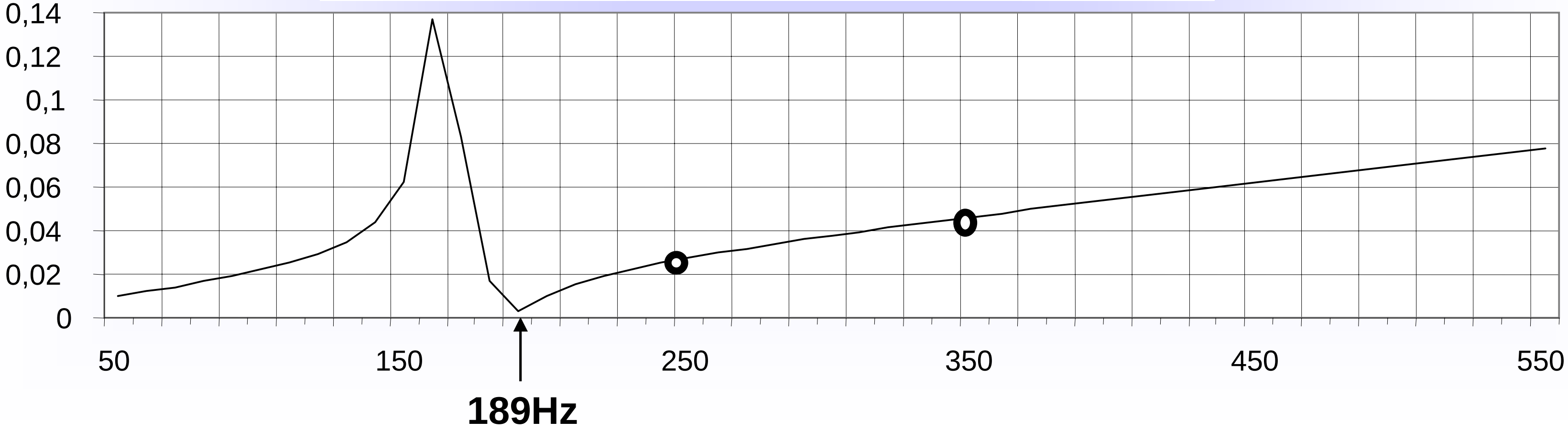
Kvar: 400

Previous Example, now for 7%-detuned filter

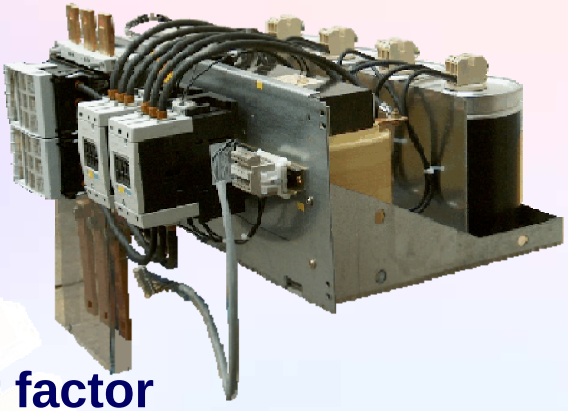
Resulting harmonic voltage e.g. :

7th (350Hz):
0.045 Ohm · 103A = 4.6V ➔ 1.1%

System busbar: impedance vs. frequency

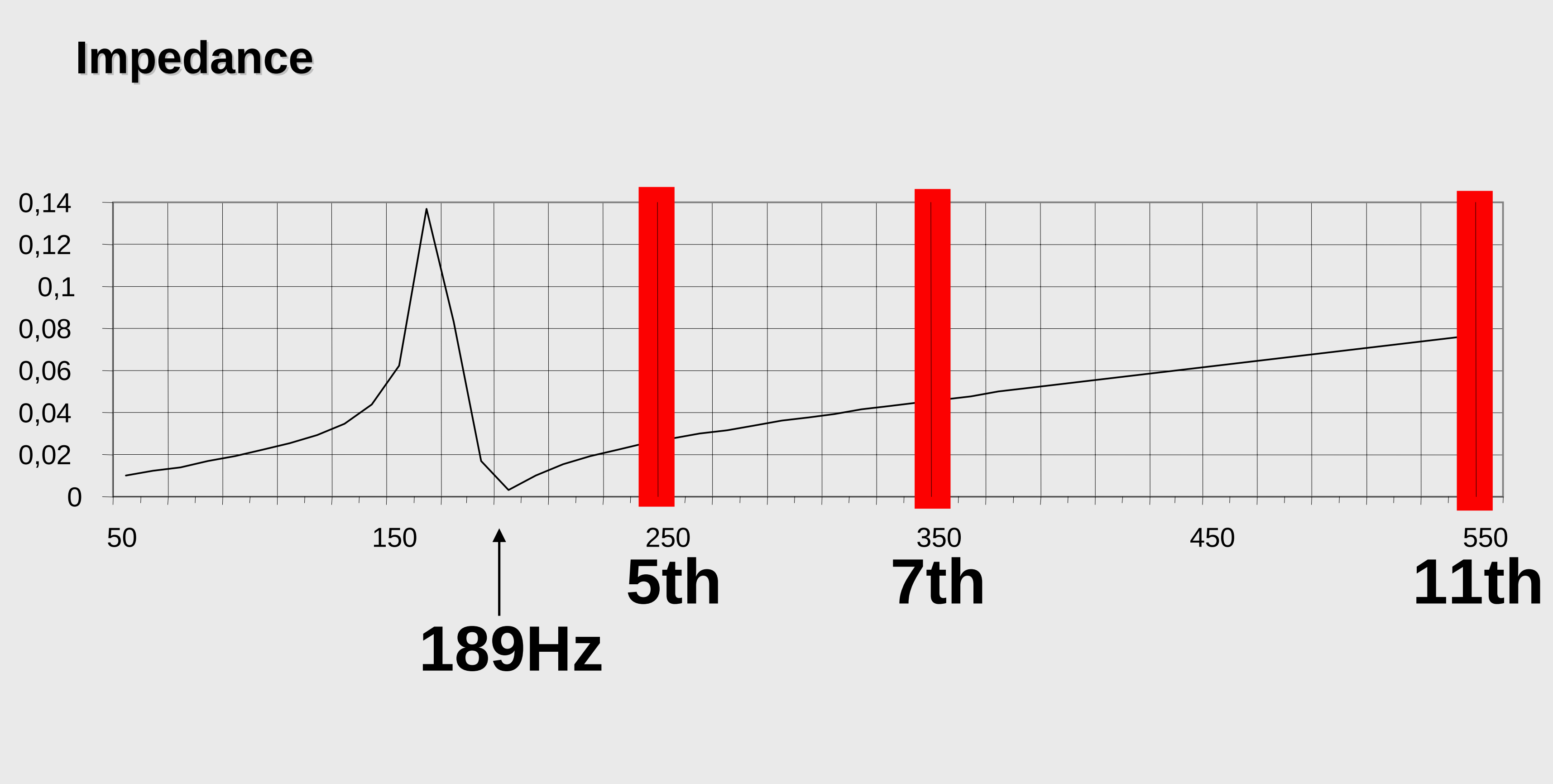


Customer benefits of detuned filters

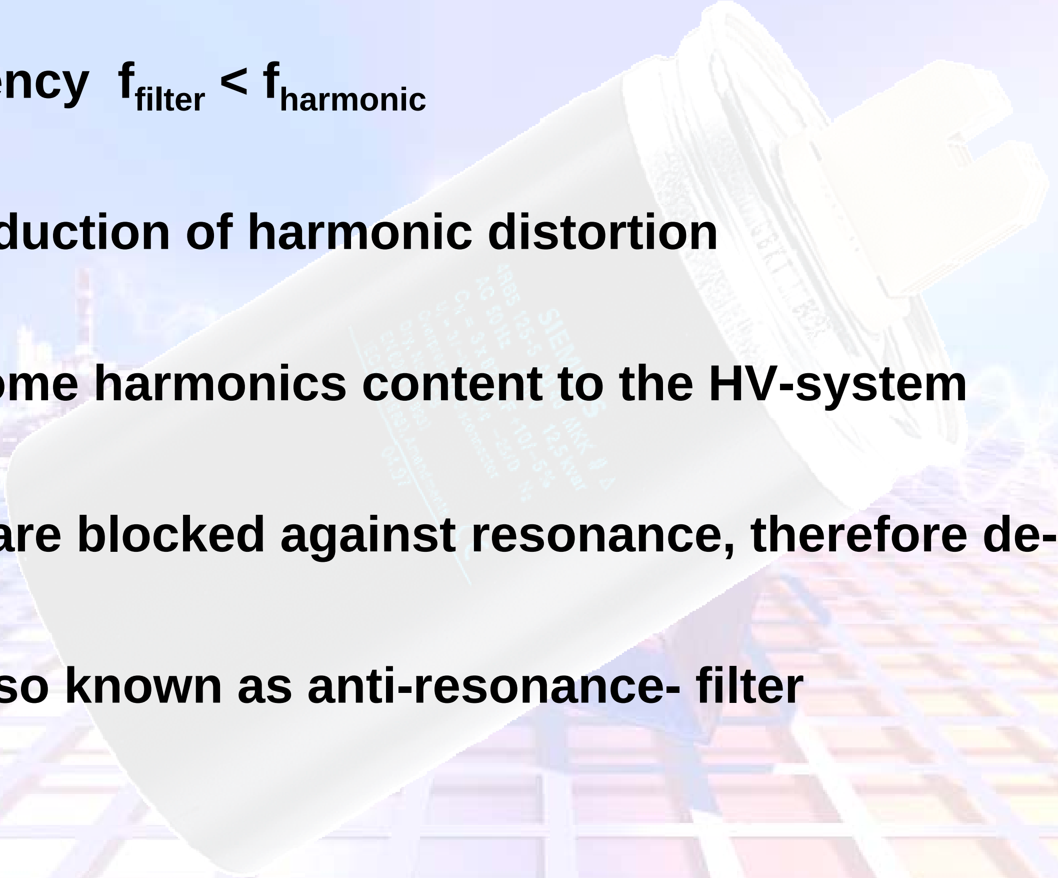


- **Improvement of Power Factor**
- **Reduction of harmonics**
- **Reduction of ohmic losses, real kW energy savings**
- **Elimination of power utilities penalties on low power factor**
- **Power Quality improvement**
- **Climatic protection, reduction of greenhouse gas emissions**
- **Reduction of new investment for distribution equipment (transformers, LV switchgear)**
- **Reduction of equipment maintenance cost and down time of production equipment**
- **Improvement of production process stability**

Summary: detuned filter



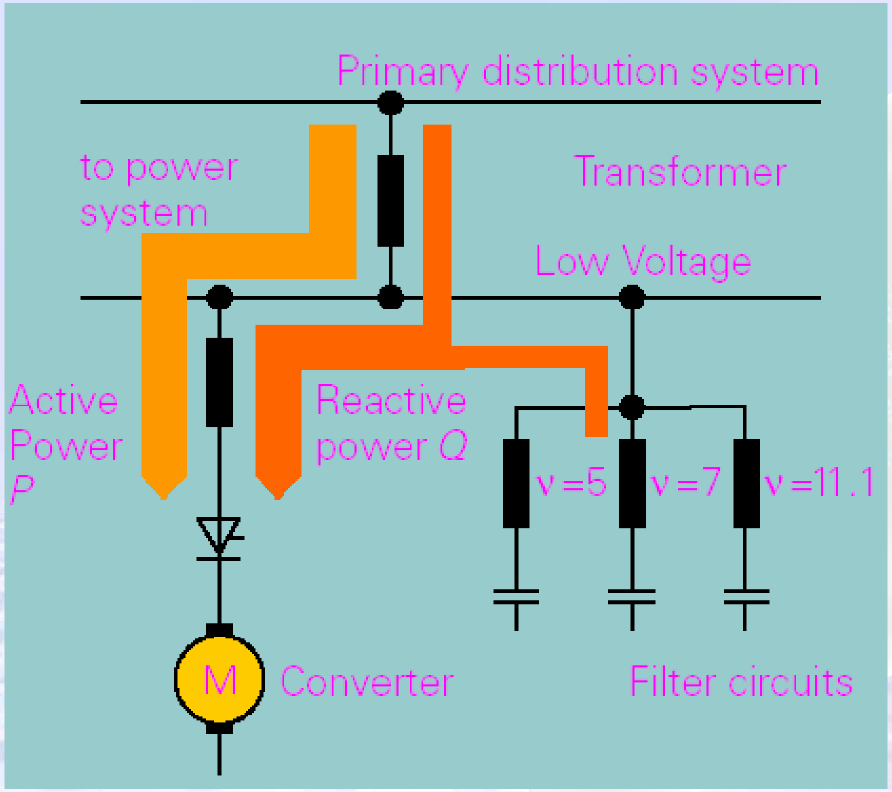
Summary: detuned filter

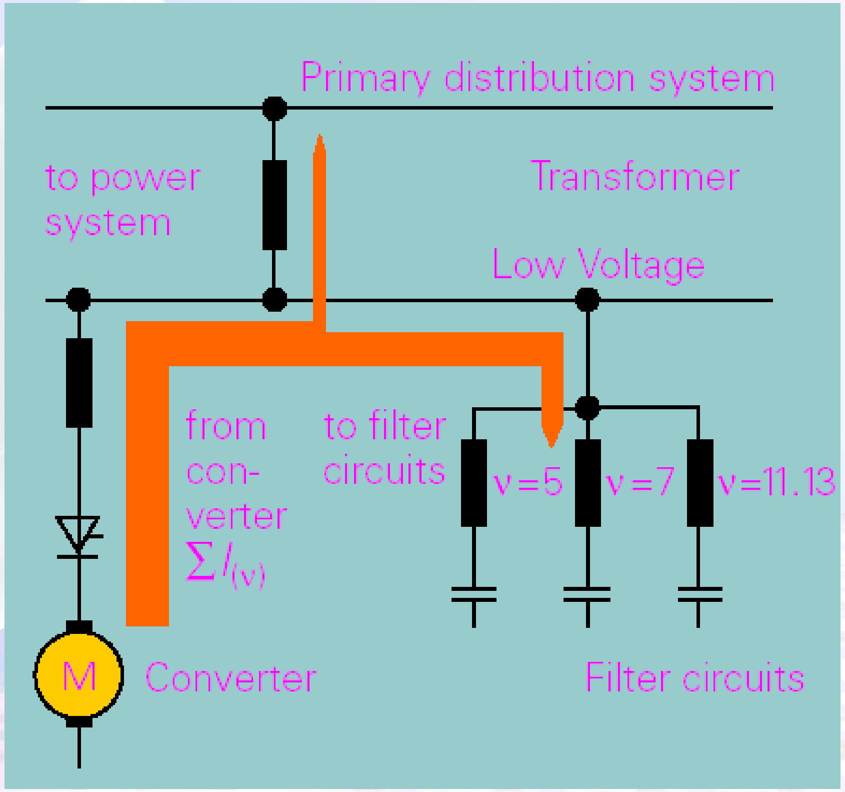


- Resonance frequency not close to any harmonic
- Filter frequency $f_{filter} < f_{harmonic}$
- A certain reduction of harmonic distortion
- Export of some harmonics content to the HV-system
- Capacitors are blocked against resonance, therefore de-tuned filters are also known as anti-resonance- filter

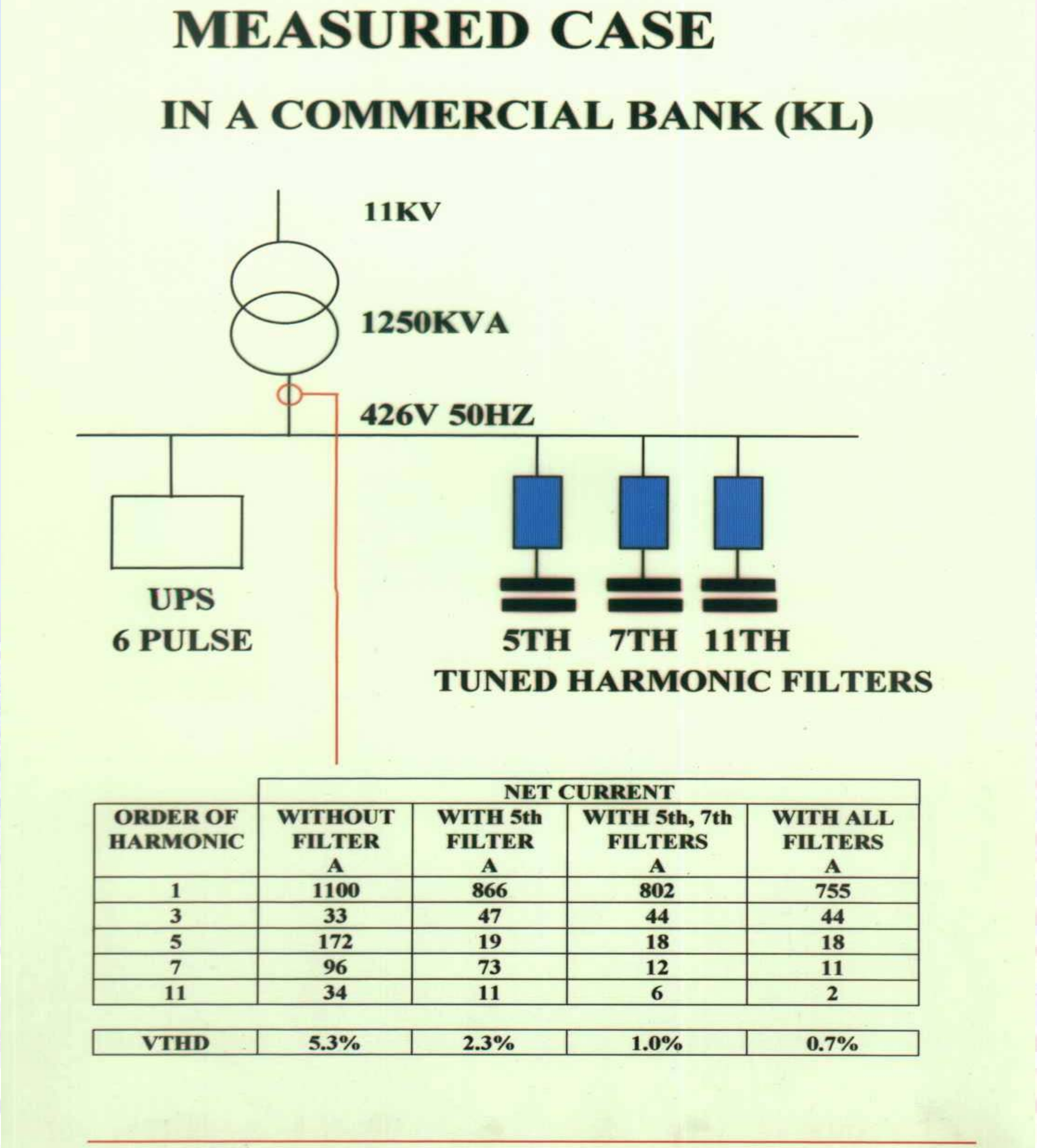
Tuned harmonic filter

Power factor correction & Filtering harmonics (cleaning the grid)





Tuned harmonic filter

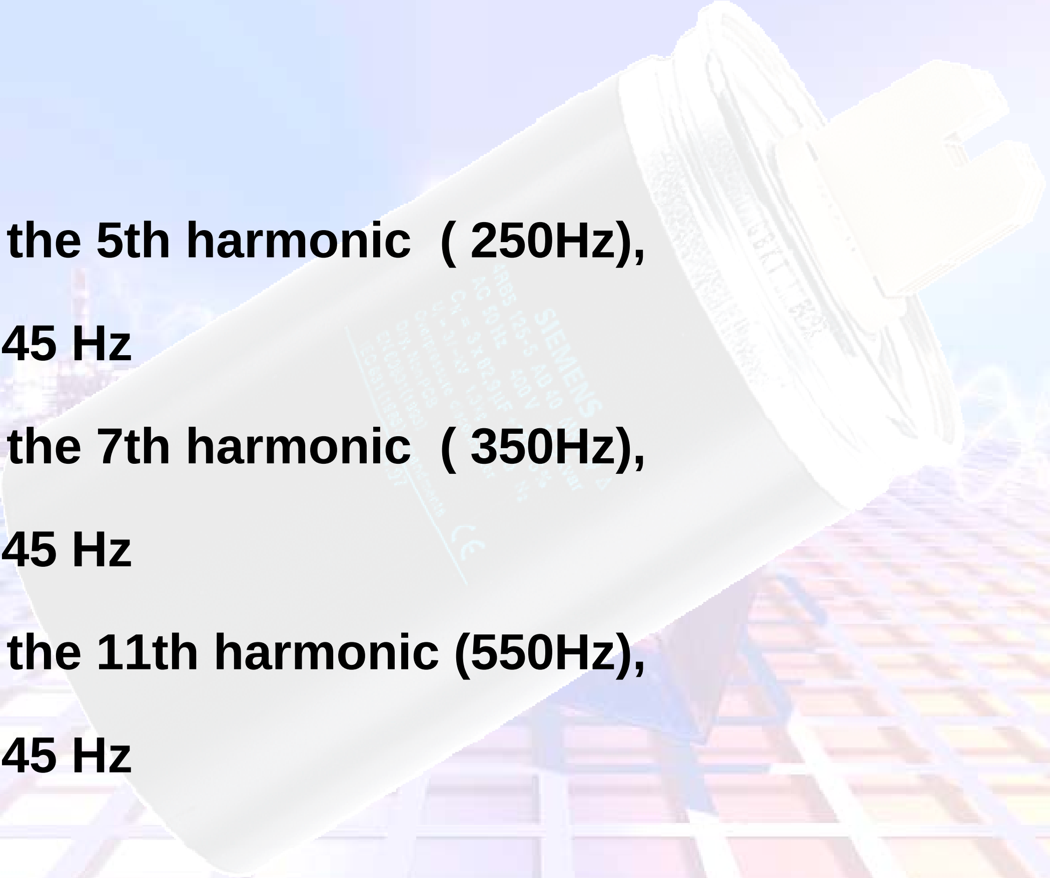


MEASURED CASE

IN A COMMERCIAL BANK (KL)

ORDER OF HARMONIC	NET CURRENT WITHOUT FILTER A	WITH 5th FILTER A	WITH 5th, 7th FILTERS A	WITH ALL FILTERS A
1	1100	866	802	755
3	33	47	44	44
5	172	19	18	18
7	96	73	12	11
11	34	11	6	2
VTHD	5.3%	2.3%	1.0%	0.7%

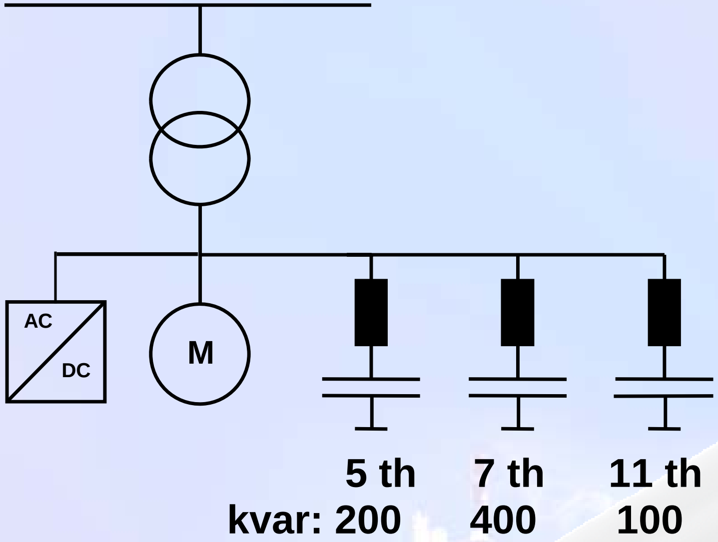
Tuned harmonic filter



A typical tuned filter bank at 50Hz fundamental frequency consists of :

- 1 filter for the 5th harmonic (250Hz), tuned to 245 Hz
- 1 filter for the 7th harmonic (350Hz), tuned to 345 Hz
- 1 filter for the 11th harmonic (550Hz), tuned to 545 Hz

Tuned harmonic filter



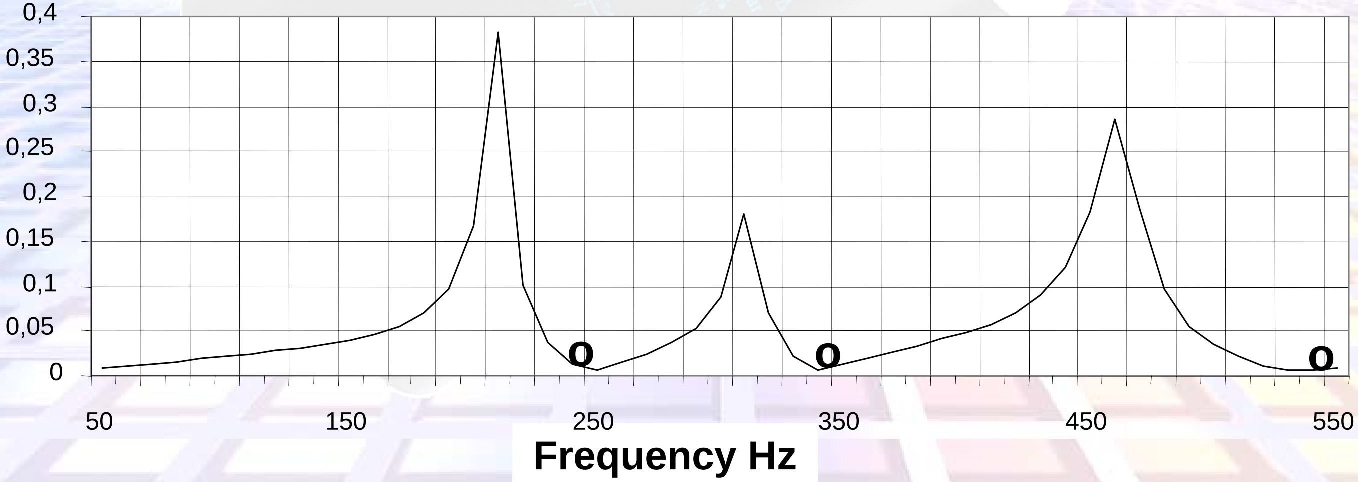
Previous Example, now for a TUNED FILTER

Resulting harmonic voltage e.g.:

5th (250Hz): 0.01 Ohm ·144 A = 1.4V ➔ 0.4%

7th (350Hz): 0.01 Ohm ·103 A = 1.0V ➔ 0.2%

System bus bar: impedance vs. frequency

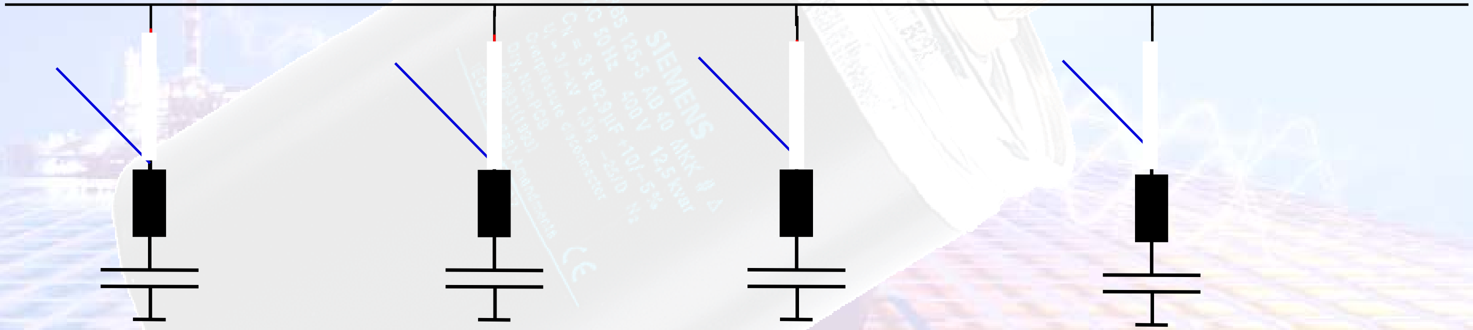


Tuned harmonic filter

Switching sequence of tuned filter: LIFO

Switching in:

→ 3rd → 5th → 7th → 11th



Switching out:

← 3rd ← 5th ← 7th ← 11th

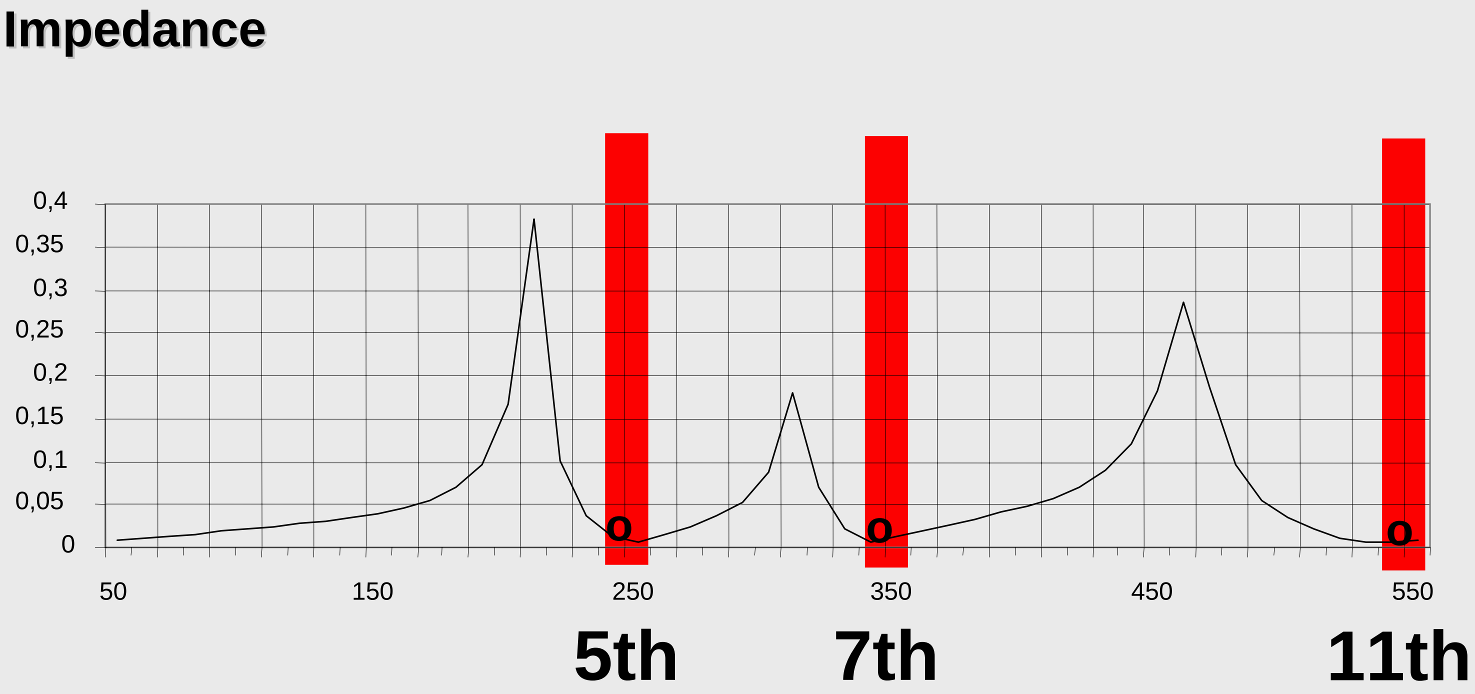
Summary: tuned filter

- Resonance frequencies of the series filter circuits are very close to existing harmonics
- Excellent reduction of harmonics on the bus bars
- Capacitors are charged with high harmonic currents

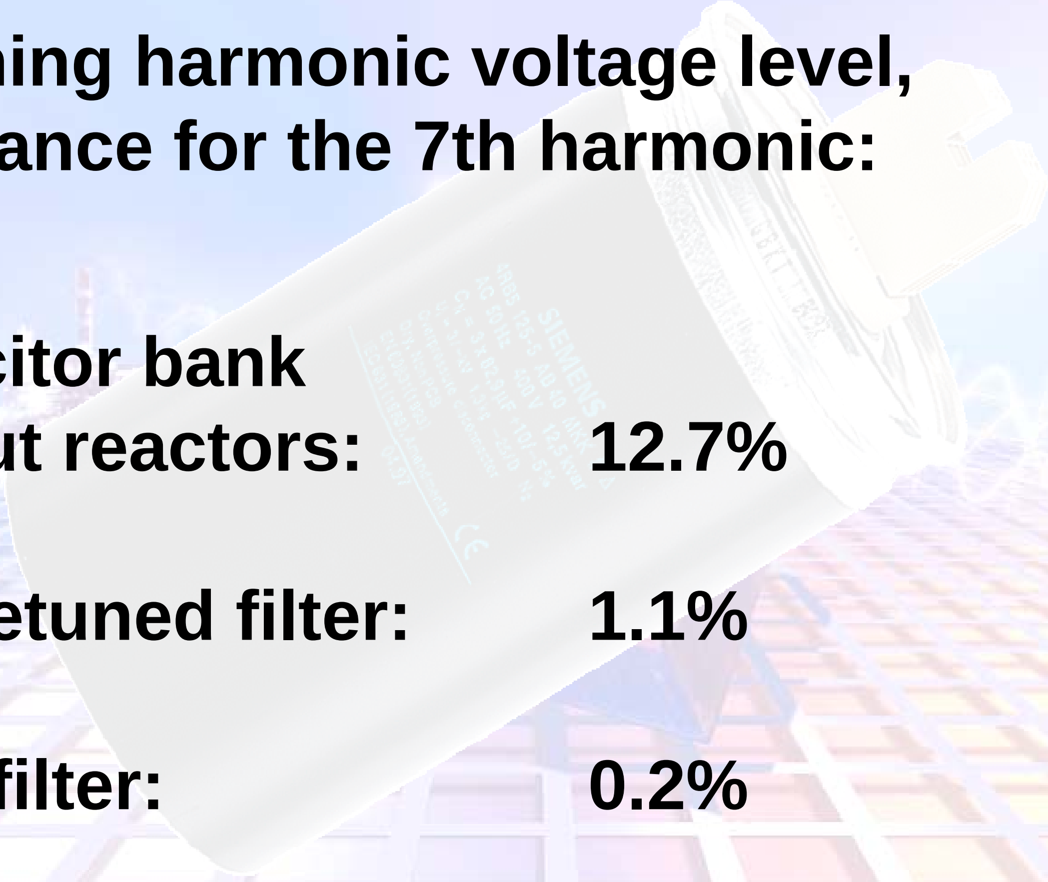
  ➔ „cleaning“ of the network
- No export of additional harmonic load to the HV-system

  ➔ „torture“ for the capacitors, if they are not rated for this high effective current
- Risk of sucking-off harmonic currents from HV side!!

Summary: tuned filter



Harmonic filters



FINAL COMPARISON:

Remaining harmonic voltage level, for instance for the 7th harmonic:

• **Capacitor bank without reactors:**	**12.7%**
• **7% - detuned filter:**	**1.1%**
• **tuned filter:**	**0.2%**

Questionnaire form

Please fill-in:				
A) Required capacitor bank data:				
rated voltage		VAC		
frequency		Hz		
rated output		kvar		
output divided into *		x		kvar
+		x		kvar
+		x		kvar
+		x		kvar
detuning factor p		%		
or resonance frequency fres		Hz		
cable support from the bottom („X“)				
or cable support from the top („X“)				
Protection class, INDOOR Standard: IP31, except all parts for ventilation	IP			

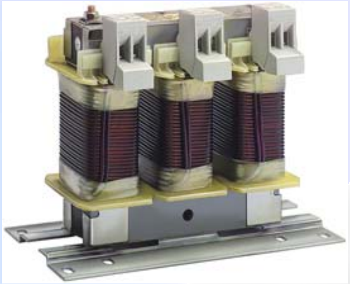
Filter circuit reactors

EPCOS

Technical features

Standard-Series

- Effective filter output
  5 kVar ... 100 kVA
- Filtering factor
  5,67 % - 7 % -14 %
- Rated voltage
  3AC 400 V
- Approvals
  c UL us



Advantages at a glance

Highest Linearity

Inductively designed for I eff,
thermally permanent with 1,05 x I_{eff}
overload-proved

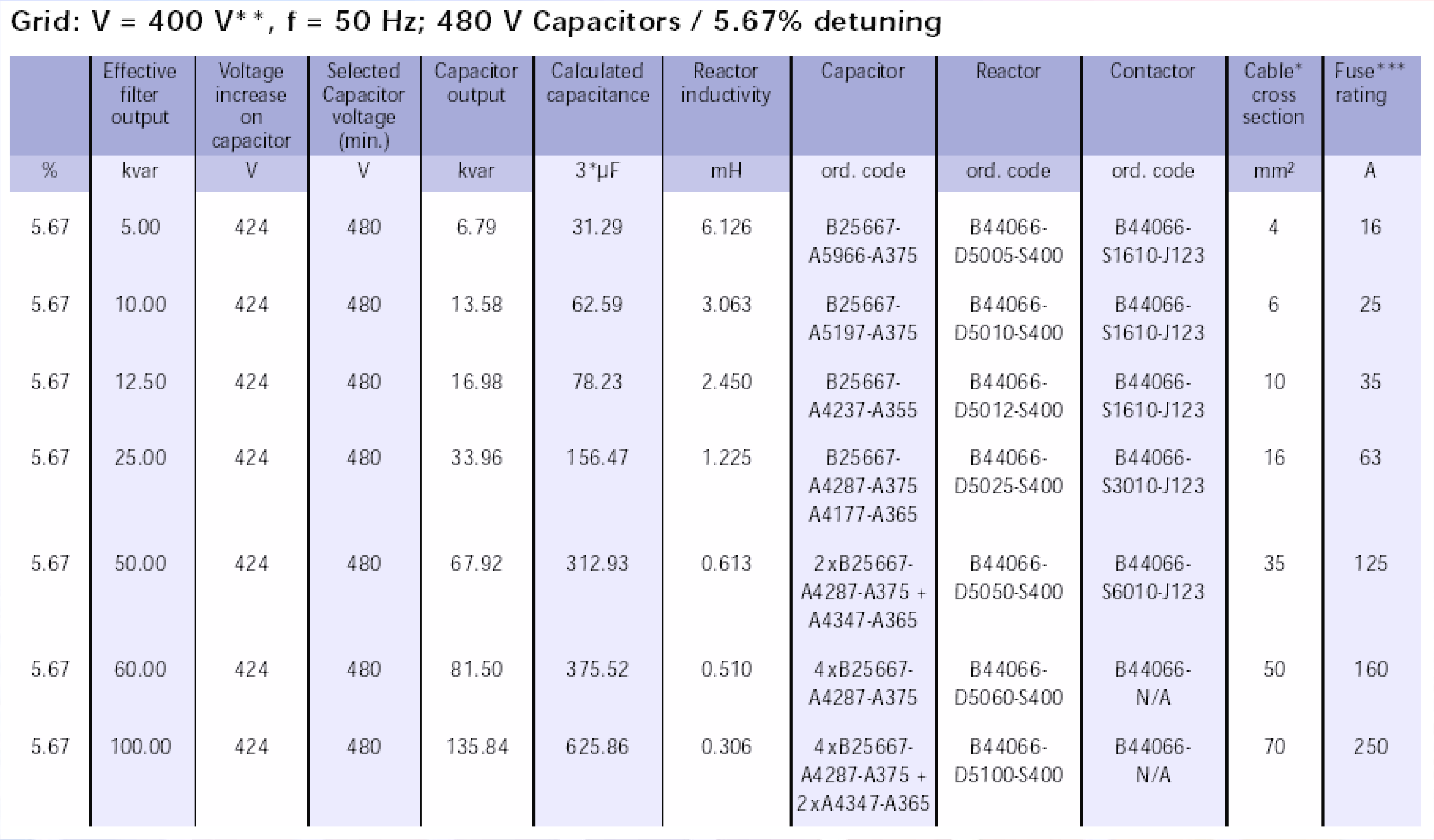
Temperature switch in standard-series

With mounting plate
according to EN 60852, for use
of electrical screwdrivers

International approvals

Highest life time by high quality
materials

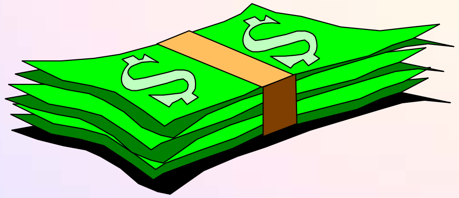
Component selection chart

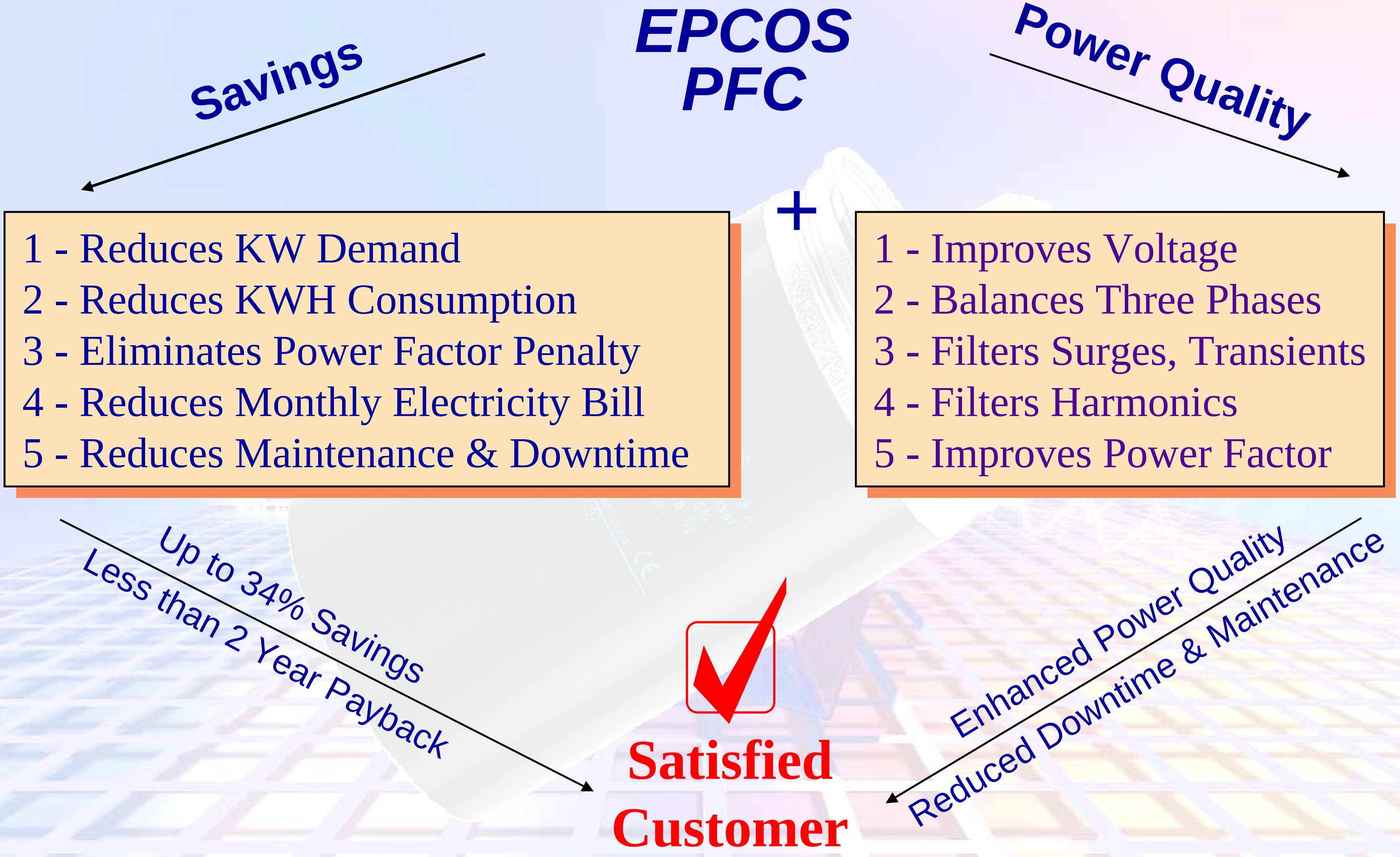


Grid: V = 400 V**, f = 50 Hz; 480 V Capacitors / 5.67% detuning

	Effective filter output	Voltage increase on capacitor	Selected Capacitor voltage (min.)	Capacitor output	Calculated capacitance	Reactor inductivity	Capacitor	Reactor	Contactor	Cable* cross section	Fuse*** rating
%	kvar	V	V	kvar	3*µF	mH	ord. code	ord. code	ord. code	mm²	A
5.67	5.00	424	480	6.79	31.29	6.126	B25667-A5966-A375	B44066-D5005-S400	B44066-S1610-J123	4	16
5.67	10.00	424	480	13.58	62.59	3.063	B25667-A5197-A375	B44066-D5010-S400	B44066-S1610-J123	6	25
5.67	12.50	424	480	16.98	78.23	2.450	B25667-A4237-A355	B44066-D5012-S400	B44066-S1610-J123	10	35
5.67	25.00	424	480	33.96	156.47	1.225	B25667-A4287-A375 A4177-A365	B44066-D5025-S400	B44066-S3010-J123	16	63
5.67	50.00	424	480	67.92	312.93	0.613	2xB25667-A4287-A375 + A4347-A365	B44066-D5050-S400	B44066-S6010-J123	35	125
5.67	60.00	424	480	81.50	375.52	0.510	4xB25667-A4287-A375	B44066-D5060-S400	B44066-N/A	50	160
5.67	100.00	424	480	135.84	625.86	0.306	4xB25667-A4287-A375 + 2xA4347-A365	B44066-D5100-S400	B44066-N/A	70	250

Return on Investment





EPCOS PFC

Savings

Power Quality

1 - Reduces KW Demand
2 - Reduces KWH Consumption
3 - Eliminates Power Factor Penalty
4 - Reduces Monthly Electricity Bill
5 - Reduces Maintenance & Downtime

+

1 - Improves Voltage
2 - Balances Three Phases
3 - Filters Surges, Transients
4 - Filters Harmonics
5 - Improves Power Factor

Up to 34% Savings
Less than 2 Year Payback

Enhanced Power Quality
Reduced Downtime & Maintenance

Satisfied Customer