CERN Accelerator School

Electrical Network and Power Converters

Hans Ulrich Boksberger
Paul Scherrer Institute
5232 Villigen PSI
Switzerland

Outline

- Utility Standards
- Definitions
- Short Circuit
  - Point of Reference
  - Capacity
  - Impedance
  - Transformers
  - Feeders
- Voltage Variations
  - Standard Voltage
  - Flicker
  - Surges
- Electro Magnetic Interference
  - Harmonics compatibility levels
  - Harmonics current emission limits
- Power Converters
  - 6 pulse rectifiers
  - 12 pulse rectifiers
- Compensation/Filtering
  - Impedance from load
  - Impedance from source
  - Analysis
  - Active circuits

Utility Standards

EN 50160	Voltage characteristics of electricity supplied by public distribution systems
IEC 61000	*Electromagnetic compatibility:*
IEC 61000-2-2	Compatibility levels for low frequency conducted disturbances and signalling in public low voltage (LV) power supply systems
IEC 61000-2-4	Compatibility levels in industrial plants for low-frequency conducted disturbances
IEC 61000-2-12	Compatibility levels for low frequency conducted disturbances and signalling in public medium voltage (MV) power supply systems
IEC 61000-3-4	Limitations of emissions of harmonic currents in LV power supply systems for equipment rated > 16A
IEC 61000-3-6	Assessment of emission limits for distorting loads in MV and HV power systems
IEC 61000-4-7	General guide on harmonics and interharmonics measurements .... for power supply systems and equipment connected thereto

Definitions

PCC	point of common coupling (on a public power supply network)
IPC	in-plant point of coupling (inside a system – not necessarily public)
U_n	Nominal voltage, i.e. reference voltage level of a supply system
U_c	Declared voltage, i.e. contractual r.m.s. value (at an IPC)
Low Voltage LV	Nominal voltages ≤ 1000 V r.m.s.
Medium Voltage MV	Nominal voltages between 1 kV and 35 kV r.m.s.
High Voltage HV	Nominal voltages > 35 kV r.m.s.
S_{sc}	short circuit power ($\sqrt{3}$ * nominal voltage (U_n)* short circuit phase current) at the PCC [MVA]
S_{equ}	rated apparent power of the equipment
Voltage Dip	supply voltage drop below 90% U_c and of a duration from 10 ms to 60 sec
Short Interruption	Any voltage value drop below 1% Uc and of a duration of less than 3 min is considered a *short supply interruption* (EN 50160)
Long Interruption	Any voltage value drop below 1% Uc and of a duration of more than 3 min is considered a *long supply interruption* (EN 50160)
Inrush Current I_a	measured 10 ms r.m.s. value

Short Circuit

Capacity

S_{sc} short circuit power

$$S_{sc} = \frac{U_p^2}{Z}$$

U_p line – line voltage

Z Impedance at the PCC

PSI 50 kV High voltage:

Beznau	*Umiken*
970 MVA	413 MVA
11.2 kA	4.8 kA
0.7 +j2.5 Ω	*2.5 + j5.5 Ω*

Impedance

Note: resistive part $R_{kv} \sim 0$
reactive part $X_{kv} \approx Z$

Transformers

Definitions:
u_r: resistive short circuit voltage [%]
u_x: reactive short circuit voltage [%]
u_k: total short circuit voltage [%]
S_{rT}: apparent, nominal power [VA]
U_{rT}: rated transformer voltage

Figures of merit:

S_{rT} [MVA]	voltage level	u_k [%]	u_r [%]
0.63 – 2.5	MV/LV	4 – 6	< 1
2 – 10	MV/MV	6 – 8	< 1
2 – 10	HV/MV	8 – 17	< 1

$$R_T = \frac{U_{rT}^2}{S_{rT}} * \frac{u_r}{100} \qquad X_T = \frac{U_{rT}^2}{S_{rT}} * \frac{u_x}{100} \qquad u_x = \sqrt{(u_k^2 - u_r^2)}$$

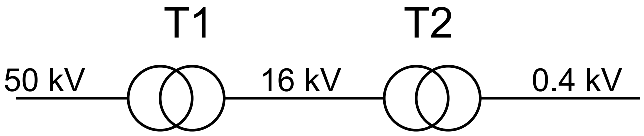
Feeders

Feeder impedances for estimates:
(figures of merit)

ρ Specific resistance [Ωmm²/km] at 20°C
(*19 Ωmm²/km for copper*)
q cross section [mm²]

	r_L [Ω/km]	x_L [Ω/km]
open feeder	ρ/q	0.3 – 0.4
cables	ρ/q	0.08 – 0.12

Example PSI (feeder lengths neglected)



S_{rT1} 10 MVA
u_k 5.6%

S_{rT2} 1.6 MVA
u_k 6%

NOTE: Short circuit power is dominated by the last transformer

$$S_{k50Kv} \text{ from utility} = 413 \text{ MVA}$$

$$S_{scT1} = \frac{S_{rT1}}{u_k} = 179 \text{ MVA}$$

$$S_{scT2} = \quad = 26 \text{ MVA}$$

$$\frac{1}{S_{sc0.4}} = \frac{1}{S_{sc50kV}} + \frac{1}{S_{scT1}} + \frac{1}{S_{scT2}} = $$

$$= \frac{1}{413} + \frac{1}{179} + \frac{1}{26} = \frac{1}{21.5}$$

Voltage Standards

The standard EN 50160 specifies the nominal voltages for Europe and is not an EMC standard; however, it describes the maximum values or variations of the voltage characteristics under normal operating conditions.

Nominal Voltage
Un = 230/400 V r.m.s.

Slow voltage changes
Un ± 10% (for 95% of 10 min periods)

Rapid voltage changes (t > 1 s)
Un ± 5% (LV level)
Un ± 4% (MV level)

Supply voltage dips (indicative)
U < 0.9 Un (10 ms – 60s; up to 1000 dips per year have to be expected)

Short interruptions (indicative)
U < 1% Un (t < 180 s)

Long interruptions (indicative)
U < 1% Un (t > 180 s)

Temporary and transient overvoltages (indicative)
U < 1.5 kV (LV distributions)
U < 3 * Un (MV distributions)

Long duration surges: > 100 µs
- due to fuse operation 1 – 2 kV unidirectional waveform
- due to power factor correction capacitors < 3*Un oscillatory waveforms up to kHz

Medium duration surges: 1 to 100 µs
- due to lighting strikes up to 20 kV

Short duration surges: < 1 µs
- due to local load switching

Flicker

Load changes will inevitably cause voltage variations.
The rate of changes for flicker purposes is

defined as: $r = \frac{N}{T} = \frac{\text{number of changes}}{\text{per minute}}$

relative voltage change $d = \Delta U / U_n$

Symmetrical 3 phase load can be assumed for power Converters:

$$d = \Delta U / U_n = \Delta S_{equ} / S_{sc} = \Delta P_{equ} / S_{sc}$$

For the **PSI** - SLS booster
with a repetition rate of 3 Hz

$$r = \frac{N}{T} = \frac{180}{1}$$

Single phase loads show
significantly larger magnitudes:

$d = \mathbf{6} * \Delta S_{equ} / S_{sc}$

Standard IEC 61000 tolerates a limit depending on r with a maximum d = 3%

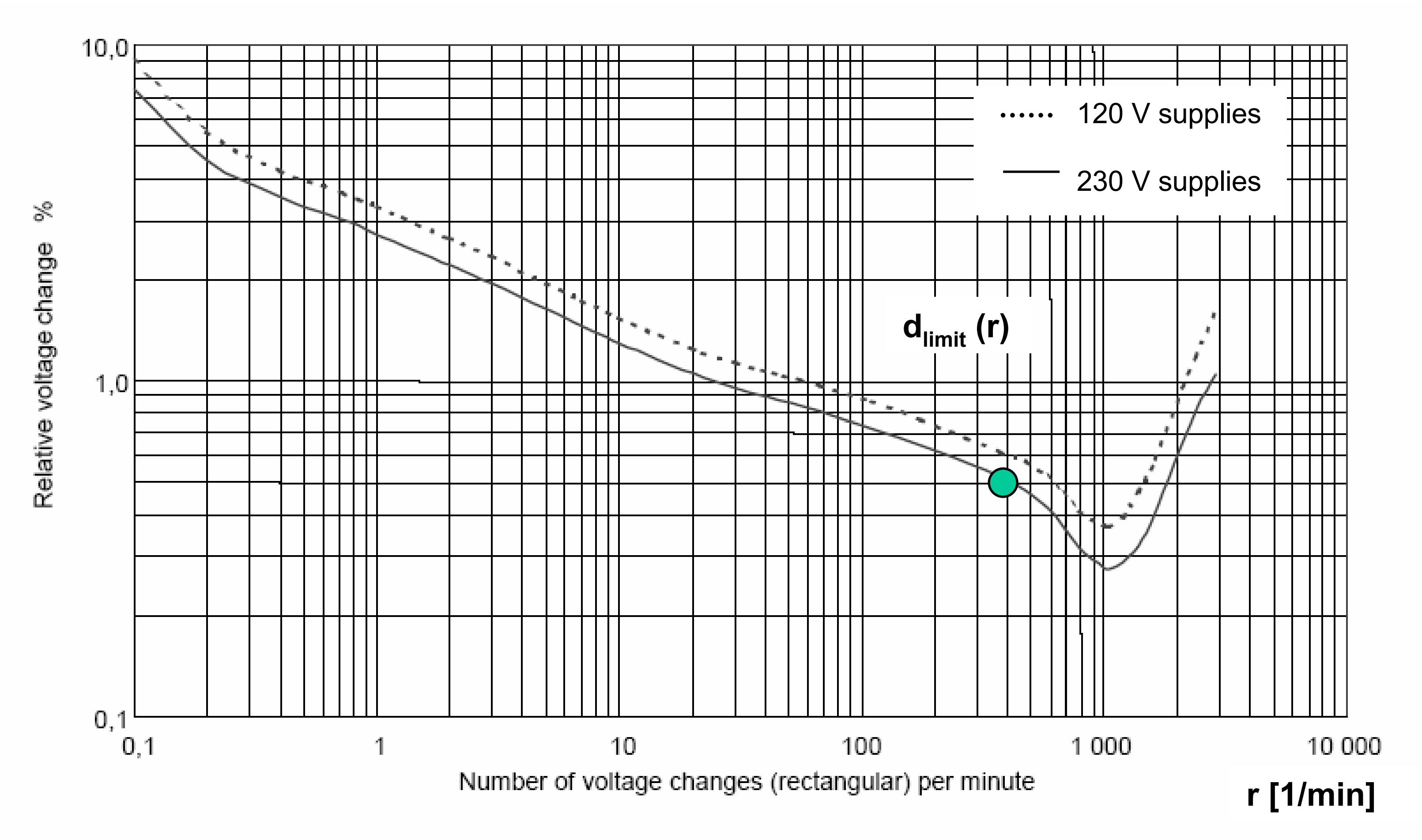
Example: PSI – SLS booster power converter:

Limit = 0.5 % for r = 180 (3 Hz)
S_{sc} = 21.5 MVA
S_{equ} = 1 MVA (1000V, 1000A)
$d = \Delta S_{unit} / S_{sc} = 1 / 21.5 = 4.6\ \% > 0.5\%!$

The maximal tolerable power swing would be:
S_{sc} = 21.5 MVA
d = 0.5 %
$\Delta S_{equ} = d * S_{sc} = 0.5\% * 21.5 = 107$ kVA

Flicker compatibility

Curve of equal severity (P_{st}=1) for rectangular voltage changes on LV power supply systems d_{limit} IEC 61000-2-2



Harmonics (public)

Voltage characteristics I ≤ 16A/ph
compatibility levels for odd order harmonics,
IEC 61000-2-2 for public LV networks

non-multiples of 3		multiples of 3	
harmonic order v	u_v/u_1 [%]	harmonic order v	u_v/u_1 [%]
5	6.0	3	5.0
7	5.0	9	1.5
11	3.5	15	0.3
13	3.0	>15	0.2
17	2.0		
19	1.7		
23	1.4		
25	1.3		

Overall requirement: *THDu* ≤ 8 %

Emission limits

$$\frac{I_v}{I_{equ}} = \frac{p_v}{1000} * \frac{\sqrt{S_{sc}}}{\sqrt{S_{equ}}}$$

Currents of the respective harmonic v must remain below I_v in order to fulfil the emission limits.

V	3	5	7	11	13	17	19	>19
p_v	6 (18)*	15	10	5	4	2	1.5	1

Note: * supplies with a neutral show 3rd harmonics nearly in phase for all three phases which add arithmetically in the neutral (→ 18)

Figures of merit:

No further investigations are required if

- LV supply systems: $S_{sc} / S_{equ} \geq 150$
- MV supply systems: $S_{sc} / S_{equ} \geq 300$

Harmonics (industrial)

Voltage characteristics
compatibility levels IEC 61000-2-4
industrial LV power supply systems

IEC defines three classes of electromagnetic environments in the cited standard:

Class 1	Compatibility level lower than public (laboratory instrumentation, some protection equipment, etc.)
Class 2	Compatibility level equal to public (any equipment designed for supply from public networks)
Class 3	Compatibility level higher than public (equipment in the presence of welding machines, rapidly varying loads, large converters etc.)

Compatibility levels for **harmonics** (excerpt only) however, for very short term (< 3 s) the values may exceed the given ones by a factor of up to 1.5

non-multiples of three			
harmonic order v	Class 1	Class 2	Class 3
harmonic order n	u_v / u_1 [%]	u_v / u_1 [%]	u_v / u_1 [%]
5	3	6	8
7	3	5	7
11	3	3.5	5
13	3	3	4.5
17	2	2	4

Compatibility levels for **total harmonic distortion**

	Class 1	Class 2	Class 3
THDu	5%	8%	10%

Harmonics

Current emission limits
I > 16A/ph based on IEC 61000-3-4

The standard gives guidance on required short circuit power for harmonics emitting equipment intended to be connected to public LV networks.

Definitions:

S_{sc} = three-phase short-circuit power
R_{sce} = short-circuit ratio of an equipment
$R_{sce} = S_{sc} / (3 S_{equ})$ for single-phase equipment
$R_{sce} = S_{sc} / (2 S_{equ})$ for interphase equipment
$R_{sce} = S_{sc} / S_{equ}$ for all three-phase equipment

Connection procedures

Stage 1	Simplified connection and $R_{sce} \geq 33$
Stage 2	Connection based on network and equipment data and $R_{sce} > 33$ depending on R_{sce}
Stage 3	Connection based on .. agreed power and equipment > 75A per phase

Admissible current emission values for simplified connection (Stage 1)

non-multiples of 3		multiples of 3	
harmonic order v	I_v / I_1 [%]	harmonic order v	I_v / I_1 [%]
5	10.7	3	21.6
7	7.2	9	3.8
11	3.1	15	0.7
13	2.0	21	0.6
17	1.2		
19	1.1		
23	0.9		
25	0.8		

Note: The manufacturer has to state in his documentation compliance to IEC 61000-3-4 based on an R_{sce} – value.

Harmonics

Current emission limits in LV supplies I > 16A/ph based on IEC 61000-3-4

Connection procedures for stage 2 and stage 3 depend very much on the R_{sce} – value and may be subject to local specifications or agreements.

A thorough analysis will be required in order to evaluate the admissible harmonic current distortion factors as well as individual harmonic currents. A general statement shall therefore not be made.

Current emission limits in MV supplies based on IEC 61000-3-6

IEC 61000-3-6 outlines the principles for determining the requirements to connect large distorted loads to public power systems. Note that the compatibility levels correspond roughly to the ones stated for LV networks.
The final decision regarding the connection always rests with the utility.

Power Factor Compensation

Power factor compensations are often installed at each power converter unit.

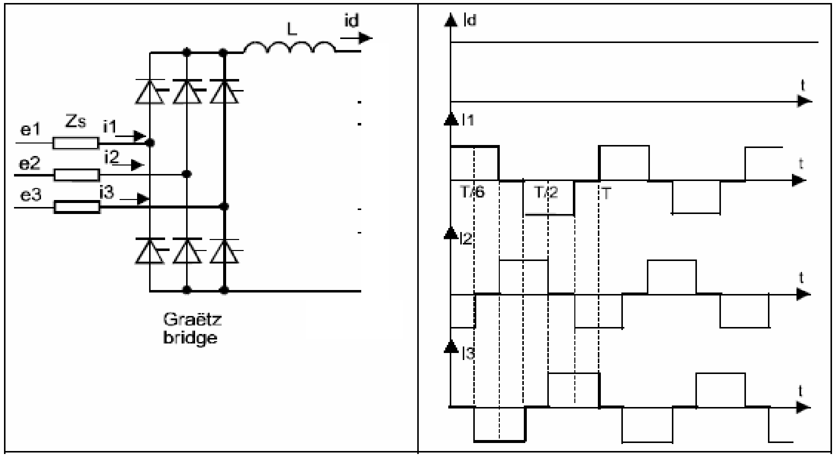
The compensations form resonant circuits with the upstream supply impedances. Its resonance frequency is mainly determined by the ratio of the short circuit power at the IPC and the power of the compensation:

$$f_{res} \approx 50 * \sqrt{(S_{sc} / Q_c)}$$

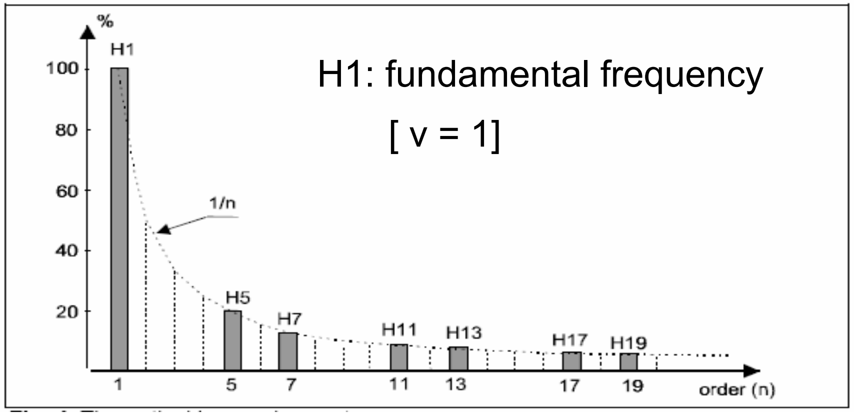
The operation of the compensations is often directly linked to the associated unit and is prone to unexpected resonance effects.
Today power factor compensations are mostly integrated in the filtering circuit for the harmonics produced by the unit.

Power Converters

Standard 6-pulse rectifier



Ideal system with zero-source impedance and infinite filtering choke L and its harmonic current content.



H1: fundamental frequency

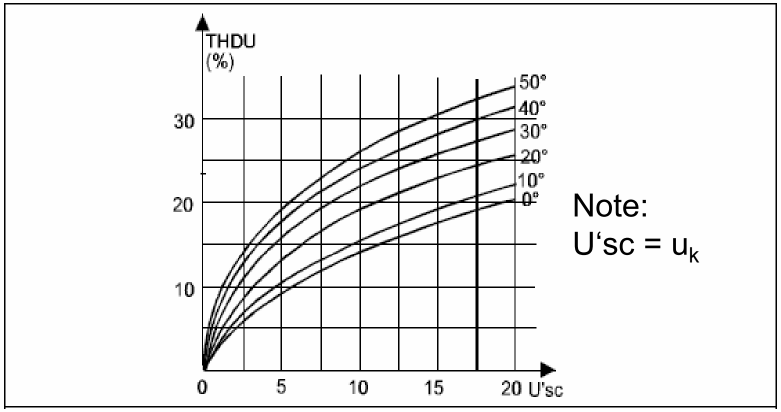
[v = 1]

Real circuits

The real systems have limited filtering chokes and current variations are not instantaneous.

	ideal	real
Harmonic order v	I_v / I_1 [%]	I_v / I_1 [%]
3	0	1
5	20	32
7	14	5
9	0	1
11	9	8
13	8	4

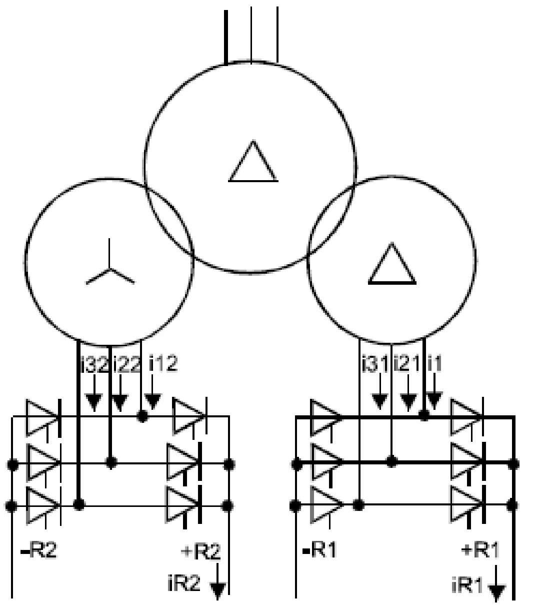
Furthermore, non-zero-source impedances lead to voltage distortions (THDu) shown as a function of the SCR delay angle α.



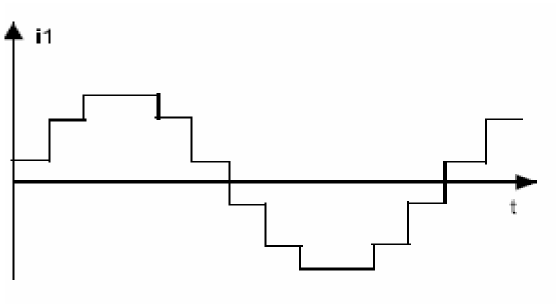
Note:
$U'_{sc} = u_k$

Power Converters

Standard 12-pulse rectifier



Ideal system with zero-source impedance and infinite filtering choke L will show the following current waveform for i1.



The comparison between ideal circuit with a real show the differences; however, neither of the two really fulfils the IEC 61000-3-4 requirement for stage 1 nor stage 2.

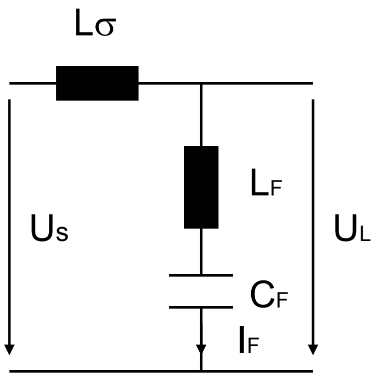
	ideal	real
harmonic order v	I_v / I_1 [%]	I_v / I_1 [%]
3		
5		2.8
7		1.5
9		
11	9.1	9.1
13	7.7	4.7
17		1
19		0.7

THDi	13.6 %	12.9 %

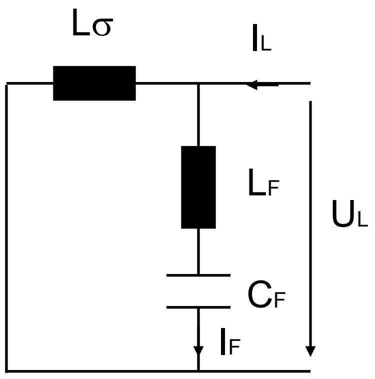
Compensation / Filtering

Today, the most common approach to reduce the emitted harmonic currents into the network is filtering.
Two aspects have to be considered:

- harmonics from the network, i.e. source
- harmonics from the load side



Feeding from the network



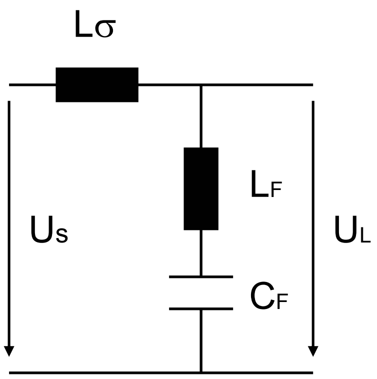
Feeding from the load

$$\frac{U_L}{U_S} = \frac{s^2 L_F C_F + 1}{s^2 (L_F + L_\sigma) C_F + 1}$$

$$\frac{U_L}{I_L} = \frac{s^3 L_\sigma L_F C_F + s L_\sigma}{s^2 (L_F + L_\sigma) C_F + 1}$$

Example: PSI Assembly Hall (WMHA) supply

Transformer	$S_n = 1$ MVA
	$u_k = 5$ %
resulting stray inductance	$L_\sigma = 25\ \mu$H
existing PF compensation	$C_F = 1000\ \mu$F



Without L_F:

$$f_{res} = \frac{1}{2\Pi (L_\sigma C_F)^{1/2}}$$

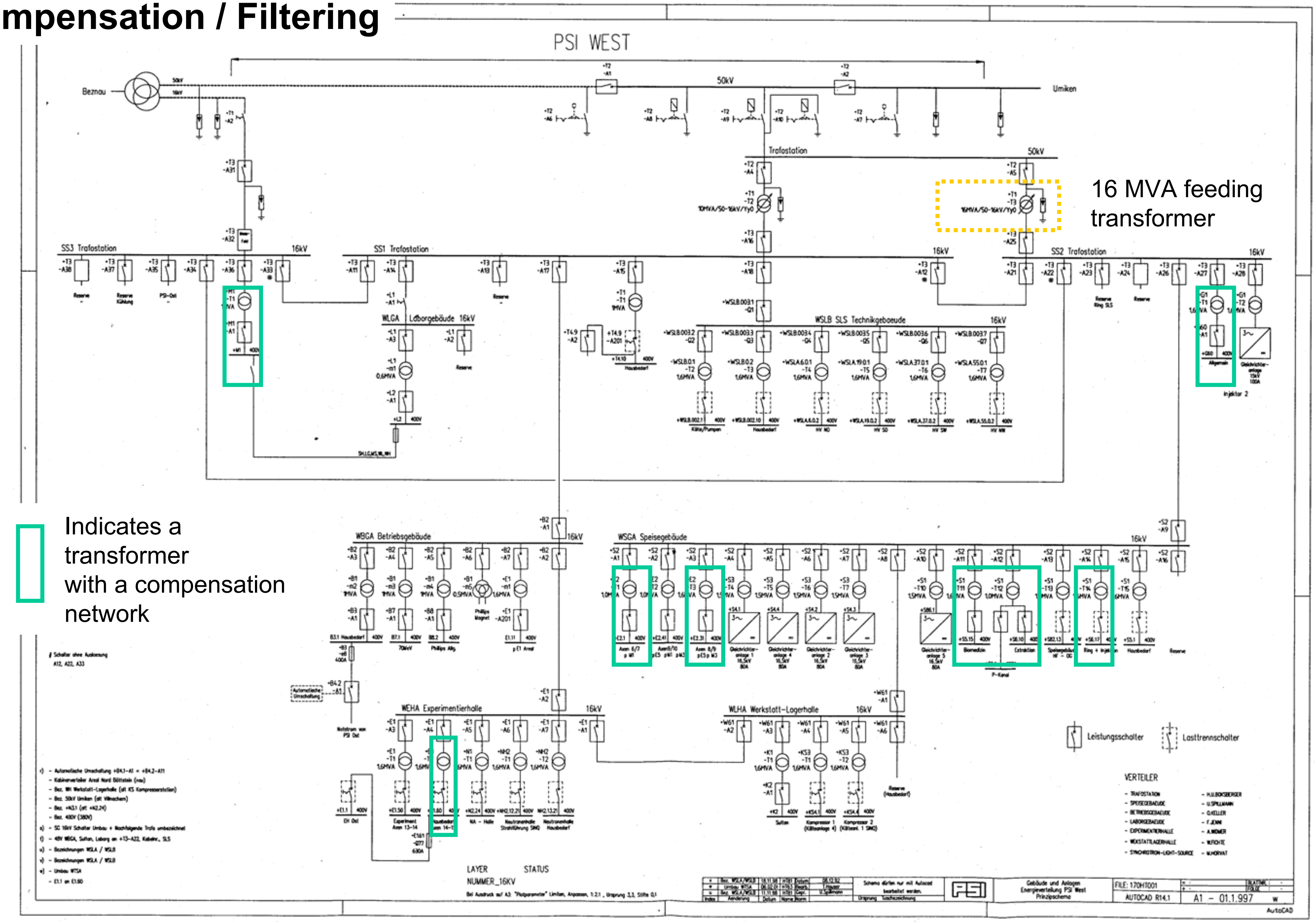
$$= 1007 \text{ Hz}$$

If the goal is to filter above the 11th harmonic one has to reduce the resonance frequency down to 500 Hz.

The following options are available:

- increase the filter capacitor to 4 mF
- insert an extra choke L_F of 76 μH
- or a combination of the two

Compensation / Filtering



16 MVA feeding transformer

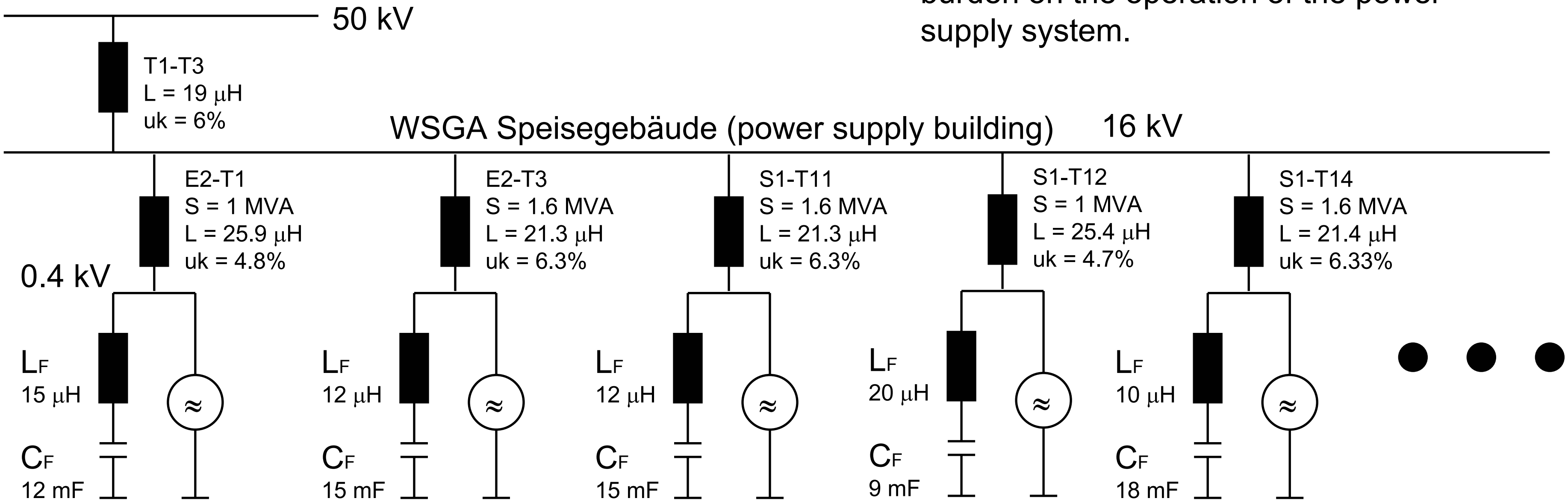
▯ Indicates a transformer with a compensation network

Compensation / Filtering

Based on the network, a system diagram has to be derived. Note, that its the main feeding transformer which provides all the coupling between the different circuits. If it was an ideal source – we had no problems.
Furthermore, the synthesis of the filtering scheme has to avoid resonnances, a cumbersome task for systems with a high power density as it is usual for accelerator systems.

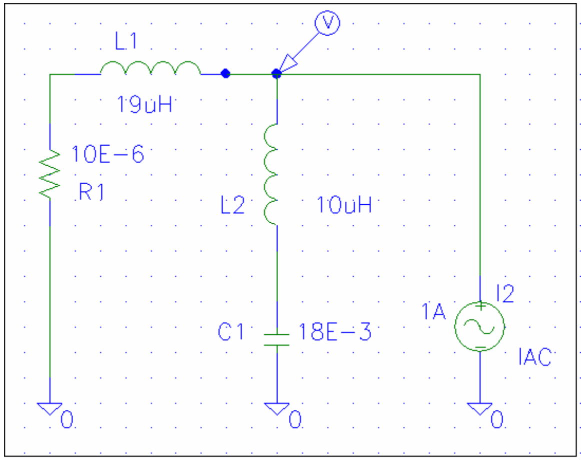
The subsequent diagram shows part of the analysis performed at PSI for its MV supply system. The green filled load circuits of the former page contain compensated filters.
At PSI we use modular sections of 60 μH chokes in series with 3 mF capacitors.

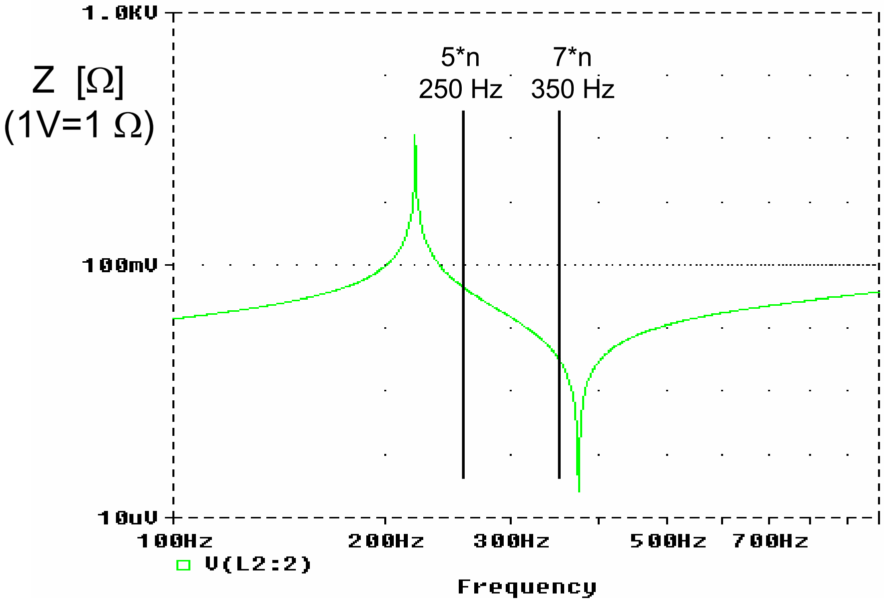
Another problem is seen instantaneously: Whenever a section is isolated, the resonance frequencies change! – A steady burden on the operation of the power supply system.



Simulation of compensation system

Feeding from the load

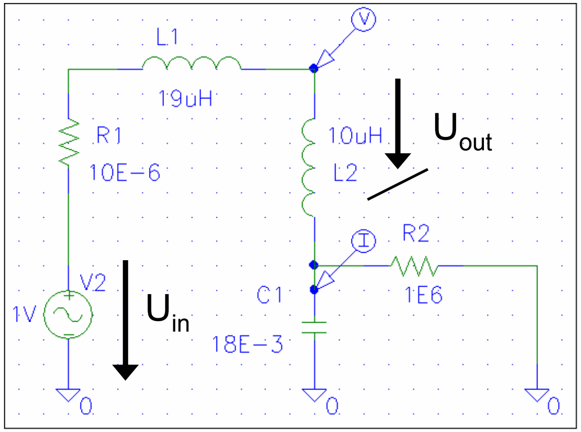


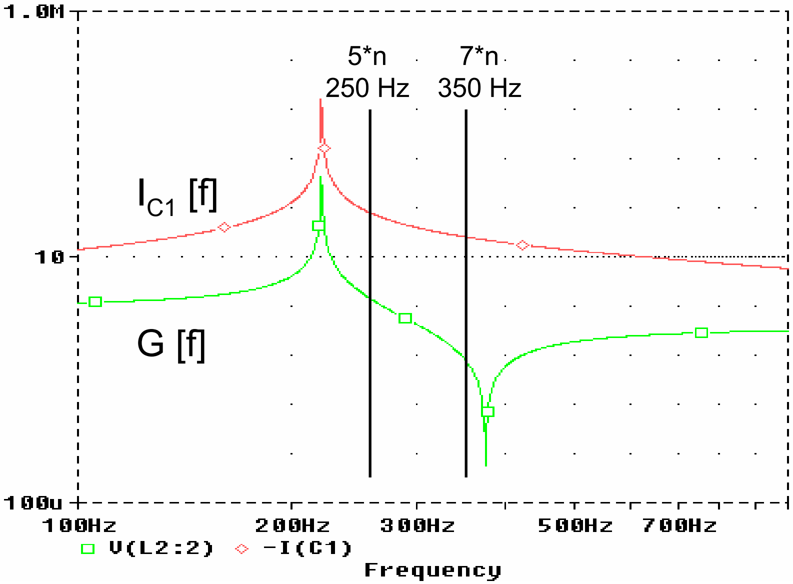


L1 and R1 based on 16 MVA transformer

Feeding from the source

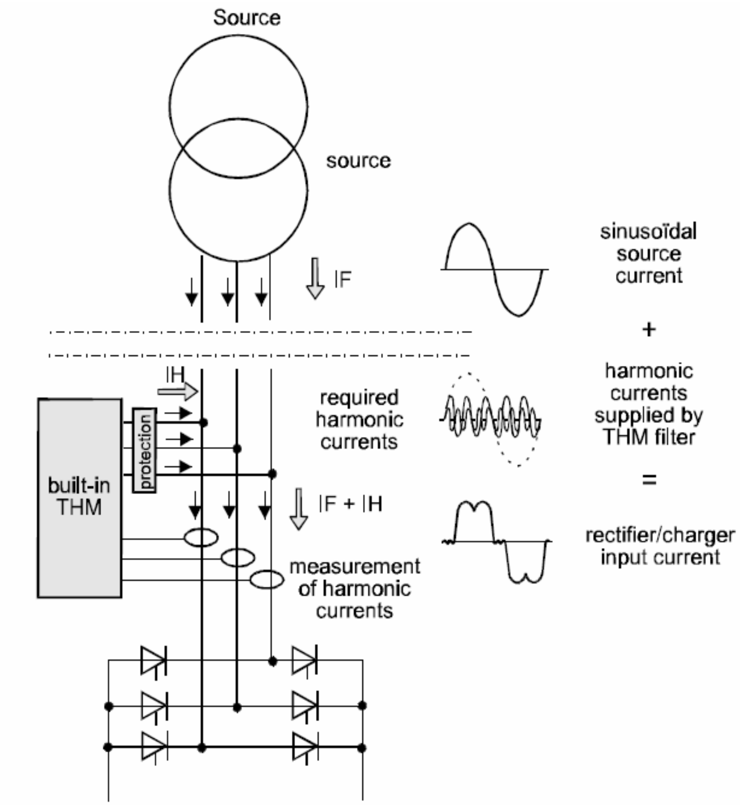
$$G\,[f] = \frac{U_{out}}{U_{in}}$$



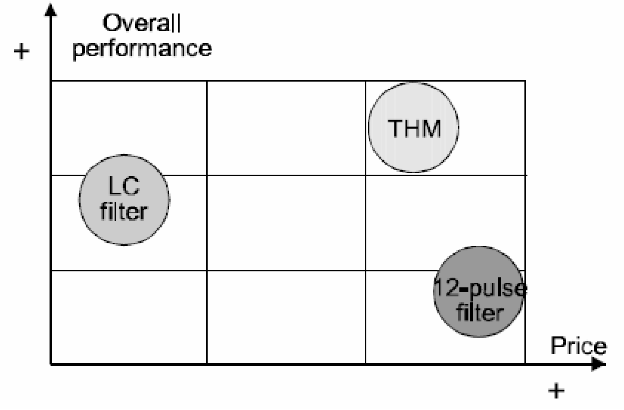


Compensation / Filtering

Today active filtering of harmonics is often suggested. The subsequent figure shows the principle of measuring the harmonic content of the power converter and to generate the required harmonic content. These systems are often referred to as Total Harmonic Management filters (THM) or static Var compensators (SVC)



Despite all this, filtering with passive means is still the most economic way to fulfil system requirements.



☞ The ***low-cost*** **solutions** offering average performance. These solutions implement a **standard passive filter**. It is possible to reinforce the solution, depending on the installation (compensated filters or non-compensated filters with contactor).

☞ The ***high-performance*** **solutions**, which are also more expensive, compliant with the recommendations of the IEC 61000-3-4 guide. These solutions implement **active filters**, such as THM or SVC.

Acknowledgements

I would like to thank my staff for their support and their enthusiasm to operate a complex power supply network at a very high level of availability.

Special thanks are to be mentioned to
Dr. Felix Jenni
Gottfried Irminger
Ulrich Spillmann
Werner Fichte
Rene Künzi

References

[1] Recommendations for the assessment of public power supply compatibilities (German); VEÖ - Verband der Elektrizitätswerke Österreichs and VSE - Verband Schweizerischer Elektrizitätswerke (1997) {vse.mysign.ch/de/internet/home.html}

References

[2] IEC International Electrotechnical Commission, Standards and Committee Drafts for vote {www.iec.org} (2001)

[3] Investigations of the 3-level - voltage source inverter (VSI) for flexible AC-transmission systems exemplified on a static Var compensator (SVC), Gerald Scheuer, PhD thesis ETH #12389 (1997)

[4] Investigations on a static Var compensator based on GTOs at low switching frequencies (German), Dieter Wüest, PhD thesis ETH #9183 (1990)

[5] THM filtering and management of harmonics upstream of UPS; Merlin Gerin MGE UPS Systems (2000) {www.mgeups.com/techinfo/techpap}

[6] Silizium Stromrichter Handbuch, BBC Brown Boveri Corporation (1971)