Electrical network and power converters

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Abstract
Utility network parameters and performance affect power converters. Their specifications and standards put constraints on loads and limit the tolerated generation of harmonics, filtering and power-factor corrections. Static and dynamic perturbations are discussed.

1 Introduction

Utility standards have a significant influence on power converters. Knowledge of them is imperative if applications are to be operated at the edge of technology and specifications. The short-circuit behaviour with its point of reference, capacity and associated impedances is discussed as a fundamental aspect. Voltage variations are subject to standards which define flicker limits and surge magnitudes. Power converters are subject to a wide field of electromagnetic interference, some of which they generate themselves. In order to ensure proper operation, an analysis of utility load and source impedances has to be performed for the design of compensations and filters.

2 Utility standards

Table 1 lists the majority of standards applicable to power converters and to utilities supplying electrical energy.

Table 1: Selected utility standards

Standard	**Description**
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 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 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

3 Abbreviations

Table 2 defines the major abbreviations used in this paper.

Table 2: Abbreviations

Abbreviation	Definition
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 ($\sqrt{3} \times U_n \times$ 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 s
Short interruption	Any voltage value drop below 1% U_c 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% U_c 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

4 Short circuit

A detailed knowledge of the short-circuit capacity is essential when specifying or designing power converters. It may influence the entire system of converters since it will affect all other users as well. Furthermore, suppliers of equipment have to consider utility standards issued by the IEC. Inappropriate loading of the utility feed can jeopardize the operation of data-acquisition systems.

4.1 Short-circuit capacity

The short-circuit power S_{sc} derived from the line voltage divided by the line impedance at the PCC is a key parameter:

$$S_{sc} = \frac{U_p}{Z} \ . \tag{1}$$

For all practical purposes the resistive part R_{kv} can be set to zero, while the reactive part X_{kv} is the significant contributor to the impedance Z.

Two 50 kV feeders supply the electrical energy to the Paul Scherrer Institute (PSI): one power line from the substation at Beznau and the second from the substation at Umiken. The two have impedances that vary by more than a factor of two (see Table 3). The entire power system for the Swiss Light Source (SLS) had to be evaluated accordingly. Its values are used as an example throughout this paper.

Table 3: PSI 50 kV high-voltage supply

	Beznau	**Umiken**
Short-circuit capacity (S_{sc})	970 MVA	413 MVA
Short-circuit current	11.2 kA	4.8 kA
Impedance	$0.7 + j2.5\ \Omega$	$2.5 + j5.5\ \Omega$

For preliminary estimates the figures of merit given in Table 4 may be used. The specific resistance ρ [Ω mm^2/km] at 20°C is 19 Ω mm^2/km for copper and q represents the cross-section in mm^2.

Table 4: Specific resistance for feeder lines

	r_L **[Ω/km]**	x_L **[Ω/km]**
Open feeders	ρ/q	0.3–0.4
Cables	ρ/q	0.08–0.12

4.2 Transformers

The literature provides abundant information about transformers. The following symbols are used:

- 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.

The two parameters of interest in the context of the supply lines are their resistive and the reactive impedances:

$$R_T = \frac{U_{rT}^2}{S_{rT}} \times \frac{u_r}{100} \tag{2}$$

$$X_T = \frac{U_{rT}^2}{S_{rT}} \times \frac{u_x}{100} \tag{3}$$

$$u_x = \sqrt{\left(u_k^2 - u_r^2\right)} \tag{4}$$

The standard range of transformers exhibits very moderate variation of impedance figures. Table 5 gives an overview.

Table 5: Standard transformer values

S_{rT} [MVA]	Voltage levels	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

4.3 PSI example

The power converters of PSI's SLS are fed through a 10 MVA HV-to-MV substation transformer. The 16 kV in-house distribution supplies the 1.6 MVA step-down transformers from MV to LV levels. We generally use this size for most converter inputs. PSI's supply is shown diagrammatically in Fig. 1.

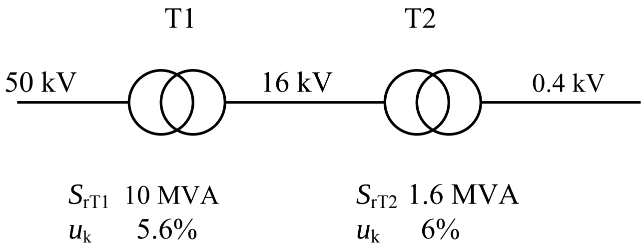


Fig. 1: PSI's one-line supply diagram

The analysis shows the following:

S_{k50kV} (the weaker of the two utility feeds) = 413 MVA,

$$S_{kT1} = \frac{S_{rT1}}{u_k} = 179\,\text{MVA} \qquad S_{kT2} = \frac{S_{rT2}}{u_k} = 26\,\text{MVA}.$$

The serial summation of the short-circuit capacities leads to the interesting, though logical result that the short-circuit power is *dominated by the last transformer*:

$$\frac{1}{S_{k0.4}} = \frac{1}{S_{k50kV}} = \frac{1}{S_{kT1}} = \frac{1}{S_{kT2}} = \frac{1}{413} = \frac{1}{179} = \frac{1}{26} = \frac{1}{21.5} \ . \tag{5}$$

Hence it suffices to evaluate the last transformer to derive a first estimate of the power converter's behaviour.

5 Voltage standards

The EN 50160 standard specifies the nominal voltages for Europe but is not an electromagnetic compatibility (EMC) standard; however, it describes the maximum values or variations of the voltage characteristics. Normal operating conditions include significant deviations from the nominal values.

Table 6 lists the major parameters that have to be considered when specifying converters, especially when high dynamic properties are an essential. In addition, the terminology may be misleading; engineering for 50 Hz systems has a different time-scale than when trying to provide ‘stable’ direct current to magnets of an electron storage ring.

Table 6: Standard voltage values

Parameter	Description
Nominal voltage	U_n = 230/400 V r.m.s.
Slow voltage changes	$U_n \pm 10\%$ (for 95% of 10 min periods)
Rapid voltage changes ($t > 1$ s)	$U_n \pm 5\%$ (LV level) $U_n \pm 4\%$ (MV level)
Short interruptions (indicative)	$U < 1\%\ U_n$ ($t < 180$ s)
Long interruptions (indicative)	$U < 1\%\ U_n$ ($t > 180$ s)
Temporary and transient overvoltages (indicative)	$U < 1.5$ kV (LV distributions) $U < 3\ U_n$ (MV distributions)
Long-duration surges: > 100 µs	– due to fuse operation 1–2 kV unidirectional waveform – due to power factor correction capacitors $< 3\ U_n$ – oscillatory waveforms up to kHz
Medium-duration surges: 1 to 100 µs	– due to lightning strikes up to 20 kV
Short-duration surges: < 1 µs	– due to local load switching

6 Flicker

Load changes will inevitably cause voltage variations. The tolerable limits are crucial to power converters as source of load changes as well as consumers on the utility line. The rate of changes for flicker purposes is defined as

$$r = \frac{N}{T} = \frac{\text{number of changes}}{\text{time in minutes}} \tag{6}$$

For PSI’s SLS booster with a repetition rate of 3 Hz, $r = 180 / 1$ [changes per minute].

The relative voltage change is the disturbing parameter. It affects us humans as well as our equipment. The value can be inferred from the equivalent load change and the feeding short-circuit capacity.

$$d = \frac{\Delta U}{U_\text{v}} = \frac{\Delta S_\text{equ}}{S_\text{kV}} = \frac{\Delta P_\text{equ}}{S_\text{kV}} \ . \tag{7}$$

For single-phase loads, significantly larger magnitude variations will result:

$$d = 6 \times \frac{\Delta S_{\mathrm{equ}}}{S_{\mathrm{kV}}} \ . \tag{8}$$

IEC 61000 tolerates an upper limit depending on r with a maximum of $d = 3\%$.

Let us consider the PSI SLS booster power converter. It swings its current from 40 A to 1000 A at a rate of 3 Hz. Figure 2 gives a limit of 0.65% for $r = 180$ (3 Hz). The short-circuit capacity of the supply is $S_{\mathrm{kV}} = 21.5$ MVA from Eq. (5). The equivalent load variation of the booster bending-magnet power converter is $S_{\mathrm{equ}} \approx 1$ MVA.

$$d = \frac{\Delta S_{\mathrm{unit}}}{S_{\mathrm{kV}}} = \frac{1}{21.5} = 4.6\% > 0.6\% \tag{9}$$

Consequently, the converter swing may not be loaded directly on the mains. The standard, however, leads to the maximal value of ΔS_{equ} which complies by considering the short-circuit capacity of $S_{\mathrm{kV}} = 21.5$ MVA with the limit of $d = 0.5\%$:

$$\Delta S_{\mathrm{equ}} = d \times S_{\mathrm{kV}} = 0.6\% \times 21.5 = 129 \text{ kVA} \ . \tag{10}$$

6.1 Flicker compatibility

Figure 2 shows the curve of equal severity ($P_{\mathrm{st}} = 1$) for rectangular voltage changes on LV power-supply systems with the d_{limit} of IEC 61000-2-2.

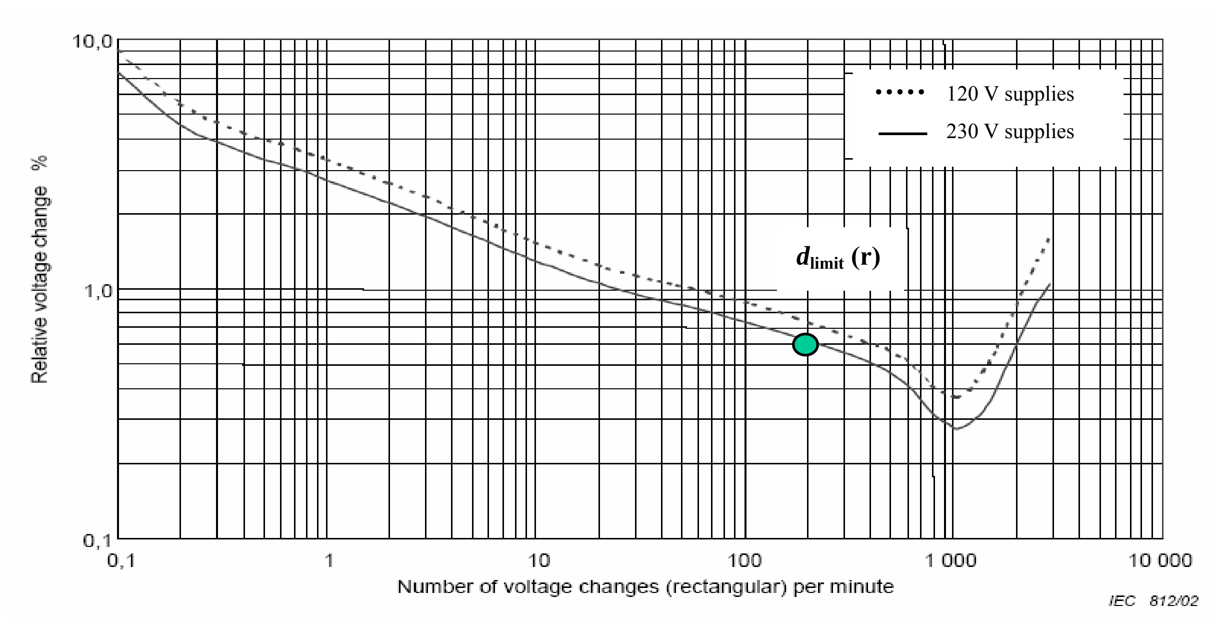


Fig. 2: Flicker of equal severity according to IEC 61000-2-2

7 Harmonics

All power converters produce harmonic currents. The compatibility levels are subject to the different current levels of the equipment.

7.1 Public LV mains supplies for $I \leq 16$ A per phase

For *public LV mains* IEC 61000-2-2 specifies the voltage characteristics for $I \leq 16$ A per phase. Its values are given in Table 7.

Although most of the time within a laboratory we do not have to fully comply with the public standards, purchased equipment, however, is designed for an environment that fulfils the standards, and its specifications may be waived if an equipment supplier finds a mains supply with excessive harmonics.

Table 7: Voltage characteristics for public LV mains supplies, $I \leq 16$ A per phase

Non-multiples of 3		**Multiples of 3**	
Harmonic order *n*	**u_n [%]**	**Harmonic order *n***	**u_n [%]**
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		

7.2 Emission limits

Currents of the corresponding harmonic number v must remain below I_v in order to fulfil the emission limits (see Table 8),

$$\frac{I_v}{I_{\text{equ}}} = \frac{p_v}{1000} \times \frac{\sqrt{S_{\text{sc}}}}{\sqrt{S_{\text{equ}}}} \quad . \tag{11}$$

Table 8: Emission limits for public LV mains supplies, $I \leq 16$ A per phase

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

*Supplies with a neutral show all 3rd harmonics nearly in phase for all three phases. This adds arithmetically in the neutral (→ 18)

Figures of merit:

No further investigations are required if

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

7.3 Public low voltage mains supplies for $I > 16$ A per phase

For *public LV mains,* IEC 61000-3-4 specifies the admissible current emission values based on three different connections. Its values are gives in Table 9.

The following definitions apply:

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

The short circuit emission impedance R_{sce} separates the different connections and the manufacturer has to state in his documentation the compliance with the IEC 61000-3-4 based on an R_{sce} – value.

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 > 75 A per phase.

Note: *For Stage 3 an arbitrary value may be chosen. It is the purchaser's responsibility to verify the compatibility with the intended use.*

Table 9: Admissible current emission values for public LV mains supplies, simplified connection (Stage 1)

Non-multiples of 3		Multiples of 3	
Harmonic order *n*	**I_n/I_1 [%]**	**Harmonic order *n***	**I_n/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		

Connection procedures for Stage 2 and Stage 3 depend very much on the R_{sce} value and may be subject to local (in-house) specifications or agreements. A thorough analysis will be required in order to evaluate the admissible harmonic current distortion factors and individual harmonic currents.

7.4 Industrial LV mains supplies

For *industrial LV mains,* IEC 61000-2-4 specifies the voltage characteristics. It defines three classes of electromagnetic environment:

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.).

An extract of compatibility levels is gived in Table 10. However, for very short term (< 3 s) the values may exceed the ones given by a factor of up to 1.5.

Table 10: Voltage characteristics for industrial LV mains supplies, from IEC 61000-2-4

	Non-multiples of 3		
Harmonic order *n*	**Class 1** u_n **[%]**	**Class 2** u_n **[%]**	**Class 3** u_n **[%]**
5	3	6	8
7	3	5	7
11	3	3.5	5
13	3	3	4.5
17	2	2	4

7.5 Total harmonic distortion

In addition to the limits for individual harmonics, the total harmonic distortion (THD) is also limited. The values for the three classes of electromagnetic environment are gives in Table 11.

Table 11: Total harmonic voltage distortion of IEC 61000-2-4

	Class 1	**Class 2**	**Class 3**
u_{THD}	5%	8%	10%

7.6 Current emission limits in megavolt 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.

8 Power-factor compensation

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

However, the compensations form resonant circuits with the upstream supply impedances. Their resonance frequency (f_{res}) is mainly determined by the ratio of the short-circuit power at the IPC (S_{kV}) to the power of the compensation (Q_C):

$$f_{res} \approx 50 \times \sqrt{(S_{kV} / Q_C)} \ . \tag{12}$$

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.

9 Power converters

9.1 Standard six-pulse rectifier

Figure 3 shows an ideal six-pulse rectifier system.

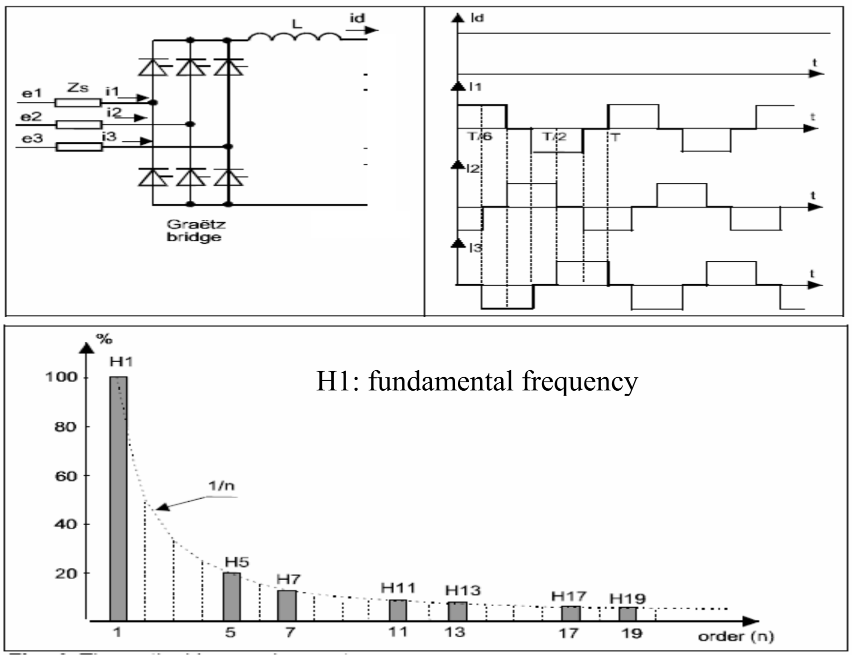


Fig. 3: Ideal six-pulse rectifier system with zero-source impedance and infinite filtering choke *L*

Real systems have limited filtering chokes and current variations are not instantaneous. Furthermore, non-zero-source impedances lead to voltage distortions (u_{THD}), shown in Fig. 4 as a function of the SCR delay angle α.

Table 12: Harmonics of a six-pulse rectifier

	Ideal	**Real**
Harmonic order *n*	**% of H1**	**% of H1**
3	0	1
5	20	32
7	14	5
11	9	8
13	8	4

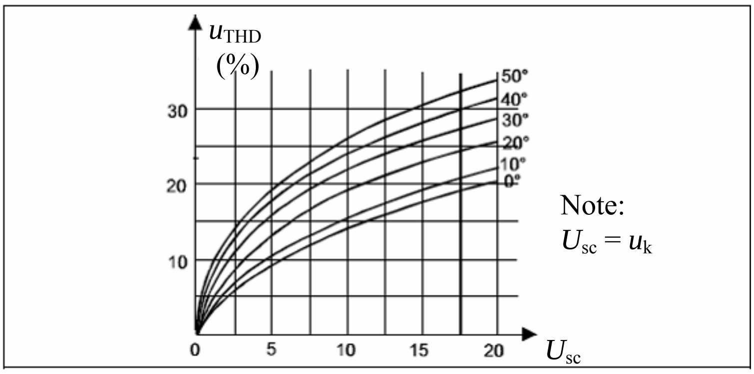


Fig. 4: THD as a function of SCR delay angle α

9.2 Standard twelve-pulse rectifier

Figure 5 shows an ideal twelve-pulse rectifier system.

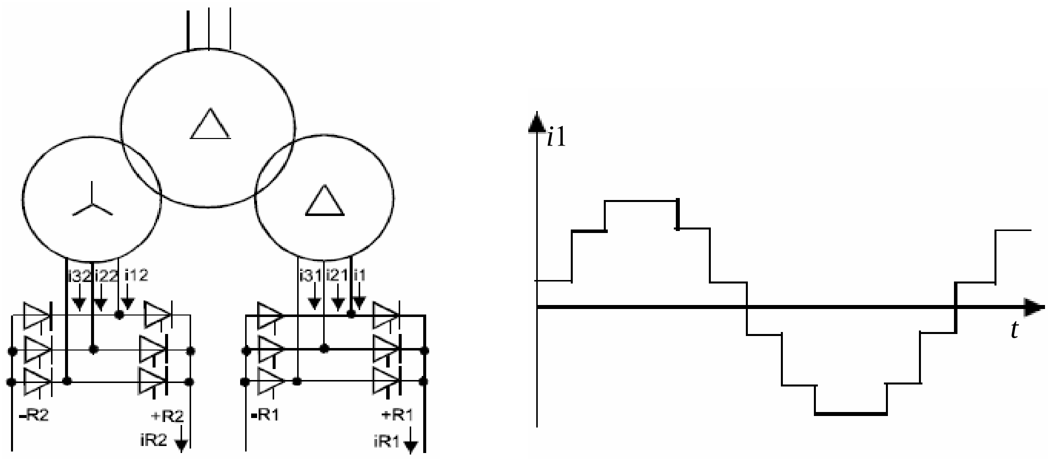


Fig. 5: Ideal twelve-pulse rectifier system

The ideal system with zero-source impedance and infinite filtering choke L will show the current waveform depicted for $i1$ in Fig. 5. Its comparison with a real one shows the difference; however, neither of the two really fulfils the IEC 61000-3-4 requirement for Stage 1 nor Stage 2.

Table 13: Harmonics of a twelve-pulse rectifier

	Ideal	**Real**
Harmonic order *n*	**% of H1**	**% of H1**
3	0	0
5	0	2.8
7	0	1.5
9	0	0
11	9.1	9.1
13	7.7	4.7
17	0	1
19	0	0.7
i_{THD}	**13.6 %**	**12.9 %**

10 Compensation and filtering

Today, although active filtering is available and its theory known, the most common approach to reduce the emitted harmonic currents into the network is by means of passive filtering. Two aspects have to be considered:

- harmonics from the network, i.e., source (see Fig. 6);
- harmonics from the load side (see Fig. 7).

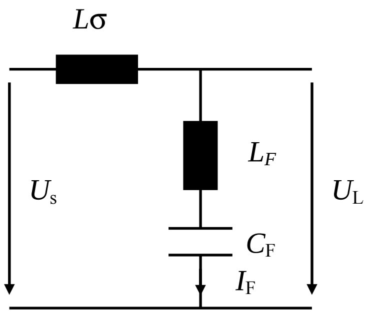


Fig. 6: Feeding from the network

$$\frac{U_L}{U_S} = \frac{s^2 L_F C_F + 1}{s^2 (L_F + L\sigma) C_F + 1} \quad . \tag{13}$$

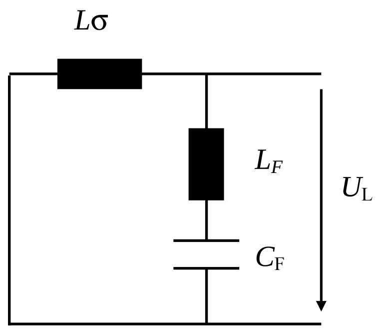


Fig. 7: Feeding from the load

$$\frac{U_L}{I_L} = \frac{s^3 L\sigma L_F C_F + 1}{s^2 (L_F + L\sigma) C_F + 1} \quad . \tag{14}$$

10.1 Example of PSI's assembly hall (WMHA) supply

The assembly hall is fed by a transformer of S_n = 1 MVA and a short-circuit impedance of u_k = 5%. This leads to a stray inductance of $L\sigma$ = 25 μH. The existing power-factor compensation uses a capacitor of C_F = 1000 μF. Figure 8 shows the one-line diagram. Without the series inductance L_F, the resonant frequency would be $1/(2\pi(L\sigma C_F)^{1/2}$ = 1007 Hz.

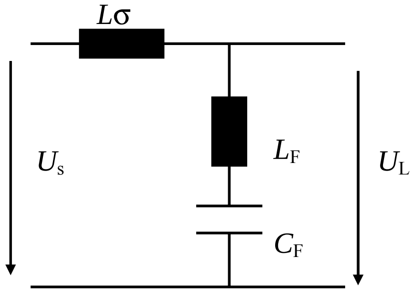


Fig. 8: Feeding from the load in the PSI assembly hall

The goal is to filter above the eleventh harmonic. This requires that the resonance frequency be shifted down to 500 Hz. The following options are available:

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

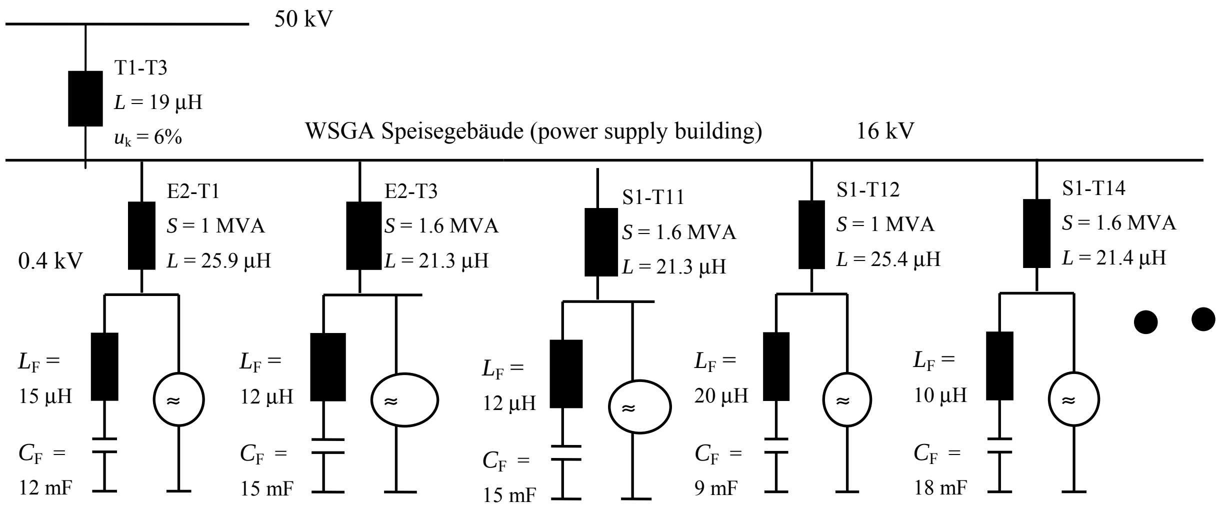


Fig. 9: Part of PSI's 16 kV utility supply system analysis

A system diagram has to be derived based on the proper utility supply system network. Note that it is the main feeding transformer that provides the coupling between the different circuits. If it was an ideal source with an impedance equal to zero, we have no problems. Furthermore, the synthesis of the filtering scheme has to avoid resonances. For systems with a high power density, as is usual for accelerator systems, this turns out to be a rather cumbersome task.

Figure 9 shows part of the analysis performed at PSI for its MV supply system. At PSI we use modular compensation filter sections of 60 mH chokes in series with 3 mF capacitors.

Another problem is seen instantaneously: Whenever a section is isolated, the resonance frequencies change. This is a constant burden for the operation of the internal power supply system.

10.2 Simulation of compensation system

The simulation of the compensation system fed from the load is shown in Fig. 10 with the network and its frequency response.

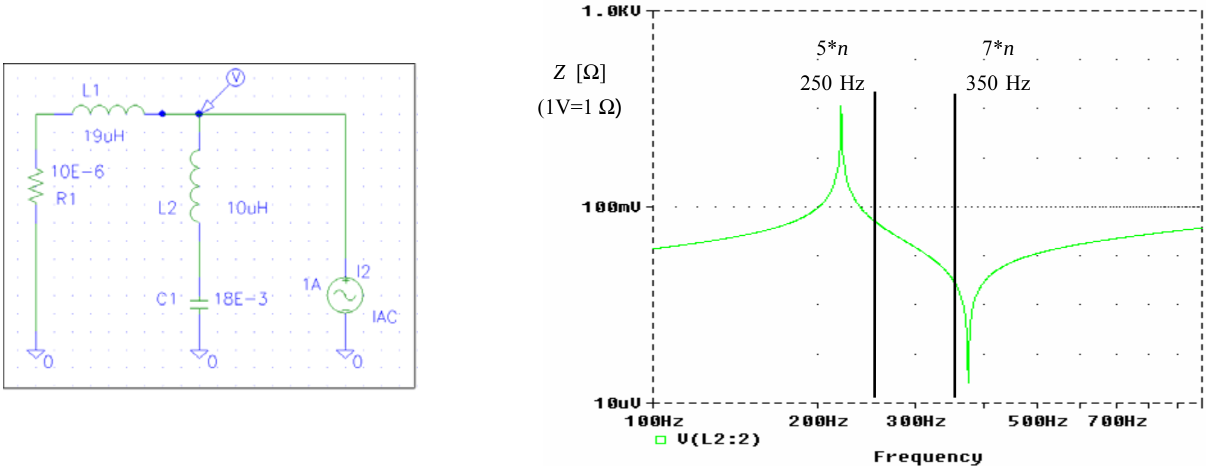
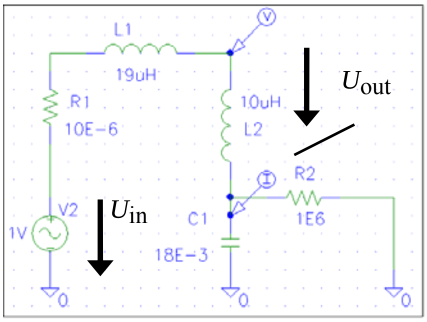


Fig. 10: Simulation of compensation system fed from the load. L1 and R1 are based on a 16 MVA transformer.



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

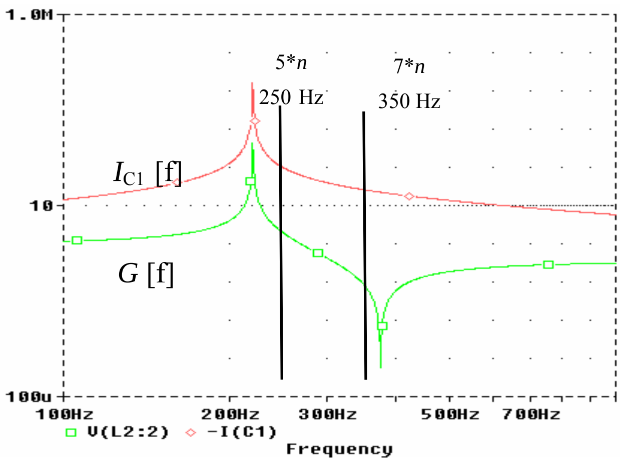


Fig. 11: Simulation of compensation system fed from the source

10.3 Active compensation system

Today active filtering of harmonics is often suggested. Figure 12 shows the principle. The harmonic content of the power converter is measured and used to calculate the required harmonic content for the compensation. These systems are often referred to as Total Harmonic Management filters (THM) or static Var compensators (SVC).

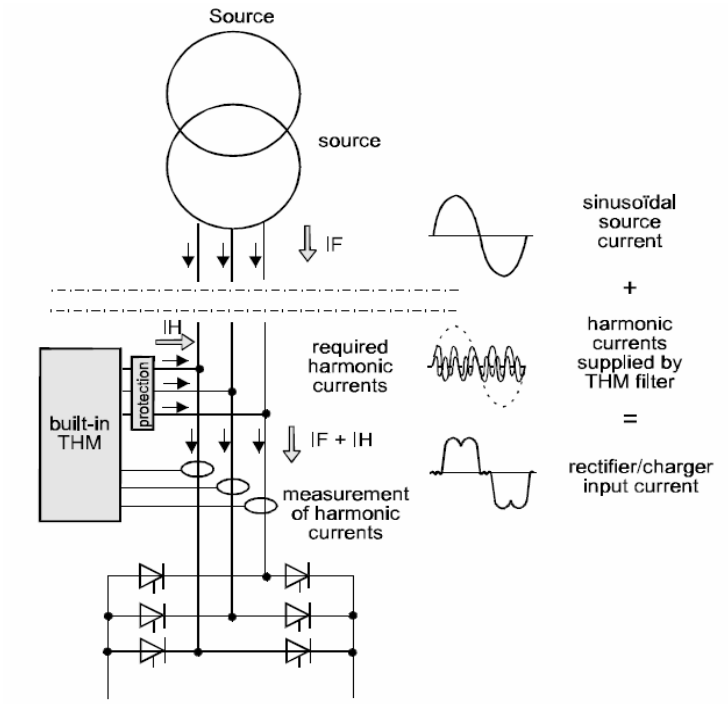


Fig. 12: Total Harmonic Management filter

10.4 Compensation system

Despite the technical possibilities and engineering challenges, filtering with passive means is still the most economic way to fulfil system requirement.

- The ***low-cost* (LC) solutions** offer average performance. These solutions are based on **standard passive filters** and their upgrade is possible depending on the installation (compensated filters or non-compensated filters with contactor).
- The ***high-performance* solutions**, also more expensive, are compliant with the recommendations of IEC 61000-3-4. These solutions implement **active filters**, such as THM or SVC.

Figure 13 provides, in graphical form, a price/performance comparison of different compensation systems.

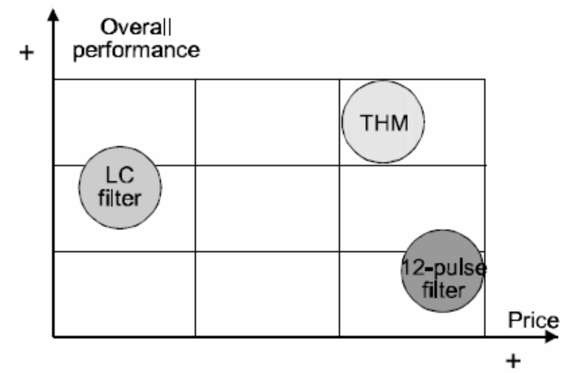


Fig. 13: Price/performance comparison of different compensation systems

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Bibliography

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

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

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

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

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

Silizium Stromrichter Handbuch, BBC Brown Boveri Corporation (1971).