CERN

Power Converters and Power Quality

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References

EN 50160 (2010)	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
VEÖ- VSE- CSRES-VDE	Technical rules for the assessment of public power supply compatibilities (in German); VEÖ - Verband der Elektrizitätswerke Österreichs, VSE -Verband Schweizerischer Elektrizitätswerke, CSRES – Ceske sdruzeni regulovanych elektroenergetickych spolecnosti, Forum Netztechnik im VDE (2007) and technical annex document (2012)
CAS 2004, Warrington	Electrical Network and Power Converters, H. U. Boksberger, PSI
CERN, ref. EDMS 113154	Main Parameters of the LHC 400/230 V Distribution System https://edms.cern.ch/file/113154/2/LHC-EM-ES-0001-00-20.pdf

Power Converters and Power Quality

- What is Power Quality?
  - Classification of disturbances
  - Statistics (example CERN)
  - Additional power quality considerations
- Electrical networks and pulsating power
  - Systems without energy storage
  - Systems with integrated energy storage
- Conclusions

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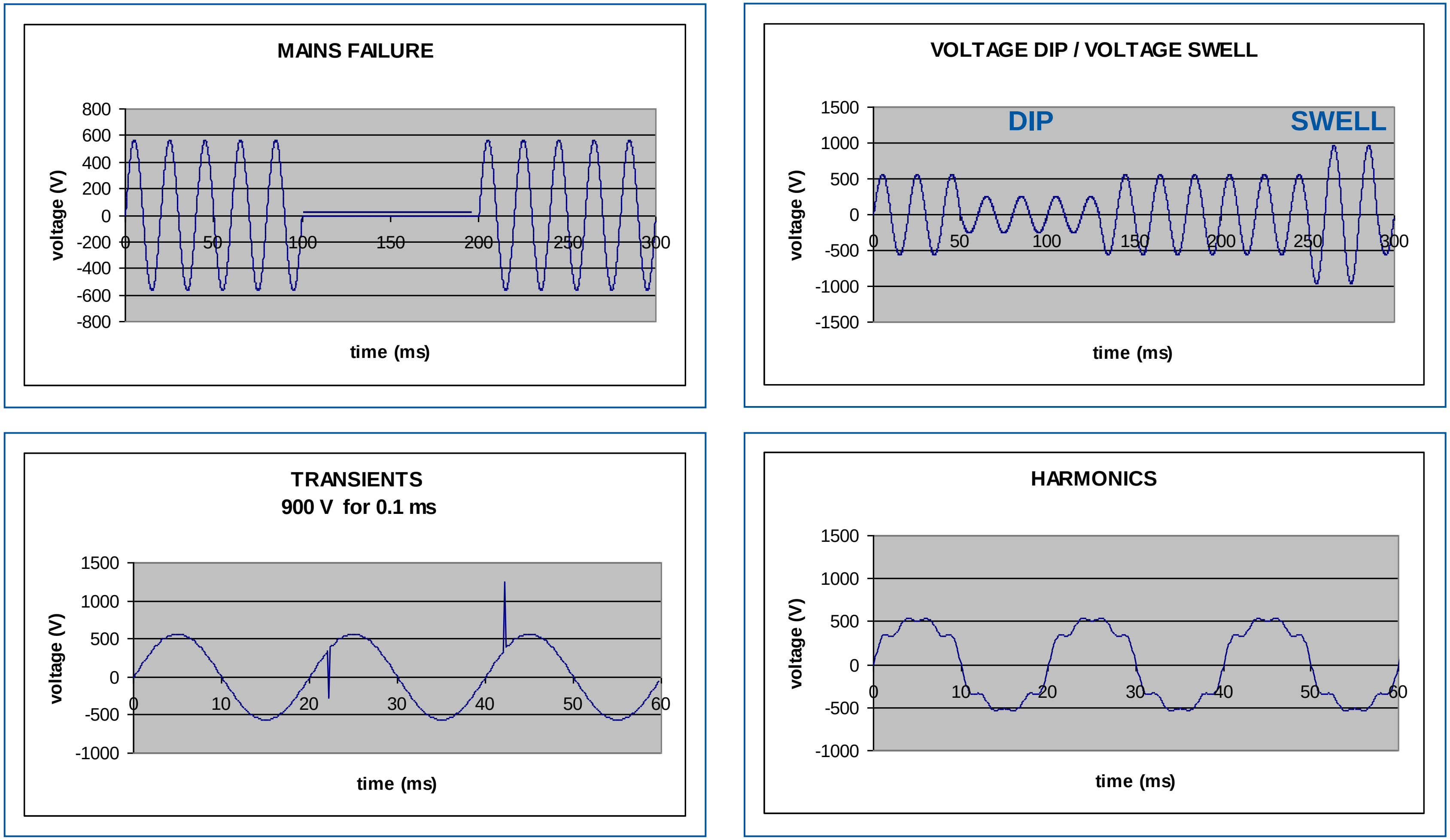
Classification of disturbances

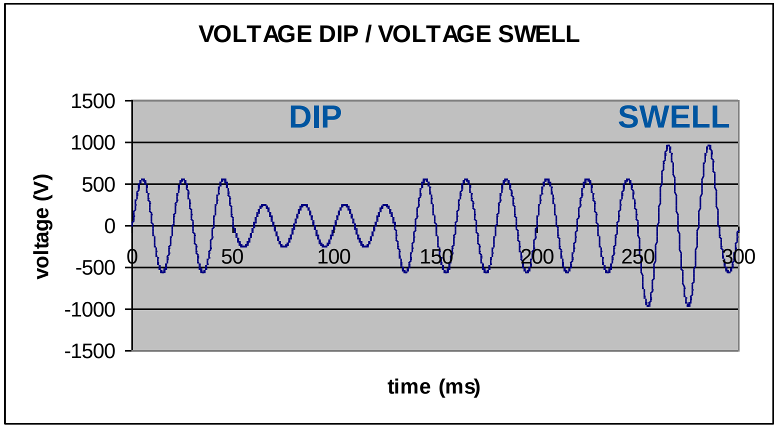


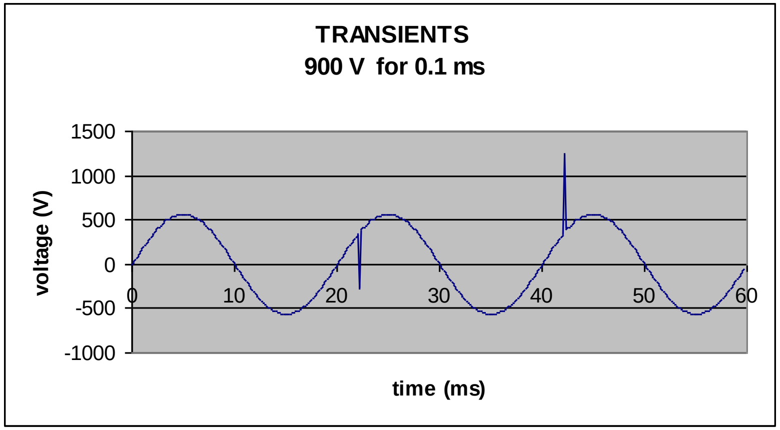
Classification of disturbances

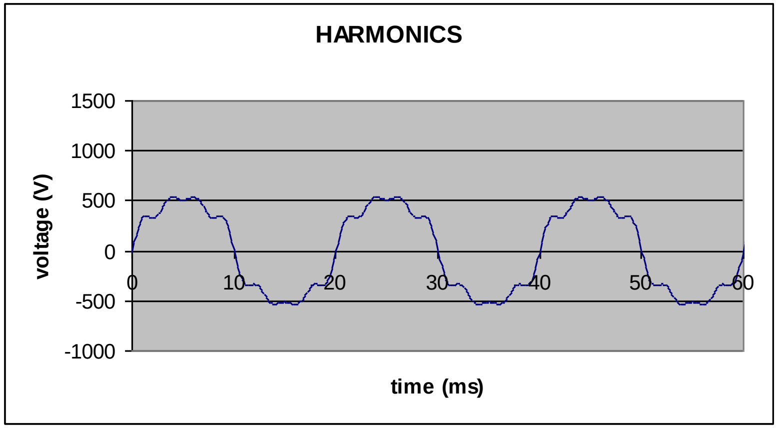
MAINS FAILURES

Causes:
- thunder-storms
- short-circuits inside CERN
- Emergency Stop operation

Consequences:
- accelerator stop







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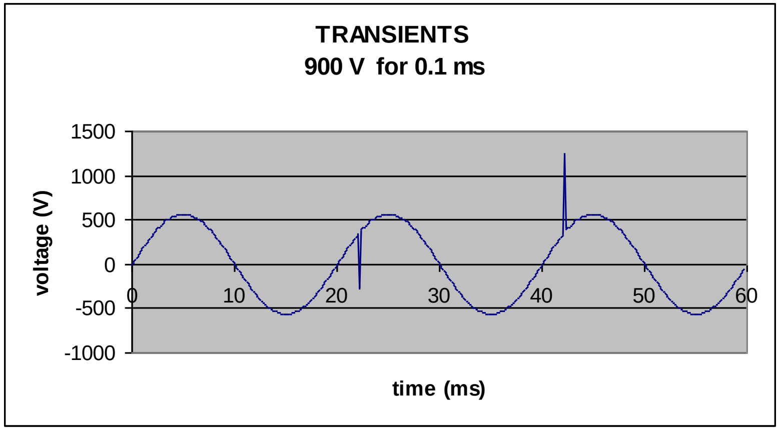
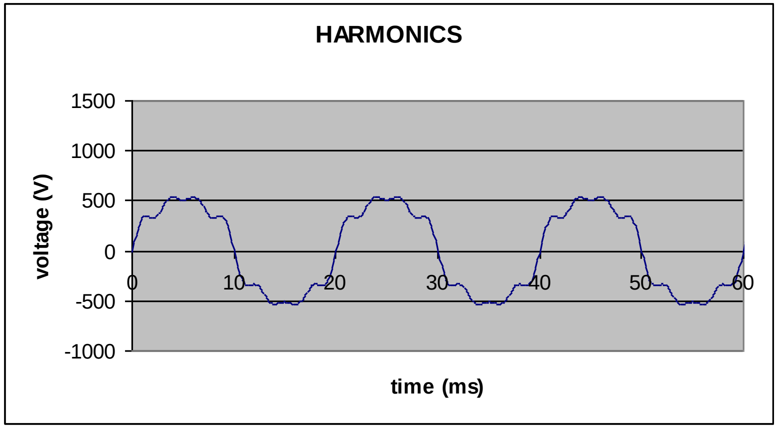
VOLTAGE DIP / SWELL

Causes:
- sudden change of load, inrush
- short-circuits inside & outside CERN
- thunder-storms

Consequences:
- sometimes accelerator stop





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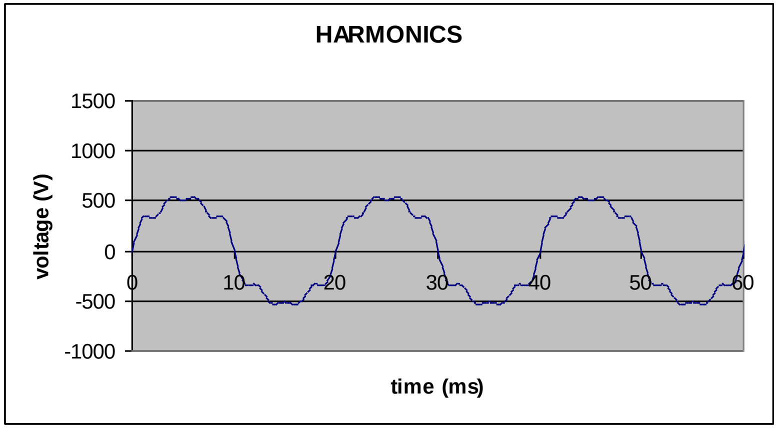
TRANSIENTS

Causes:
- switching capacitor banks ON (SVC's)
- thunder-storms

Consequences:
- failure of electronics



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TRANSIENTS

Causes:
- switching capacitor banks ON (SVC's)
- thunder-storms

Consequences:
- failure of electronics

HARMONICS

Causes:
- non-linear loads (power converters, computer centers, PC's)

Consequences:
- malfunctioning of electronics
- overload of Neutral conductor

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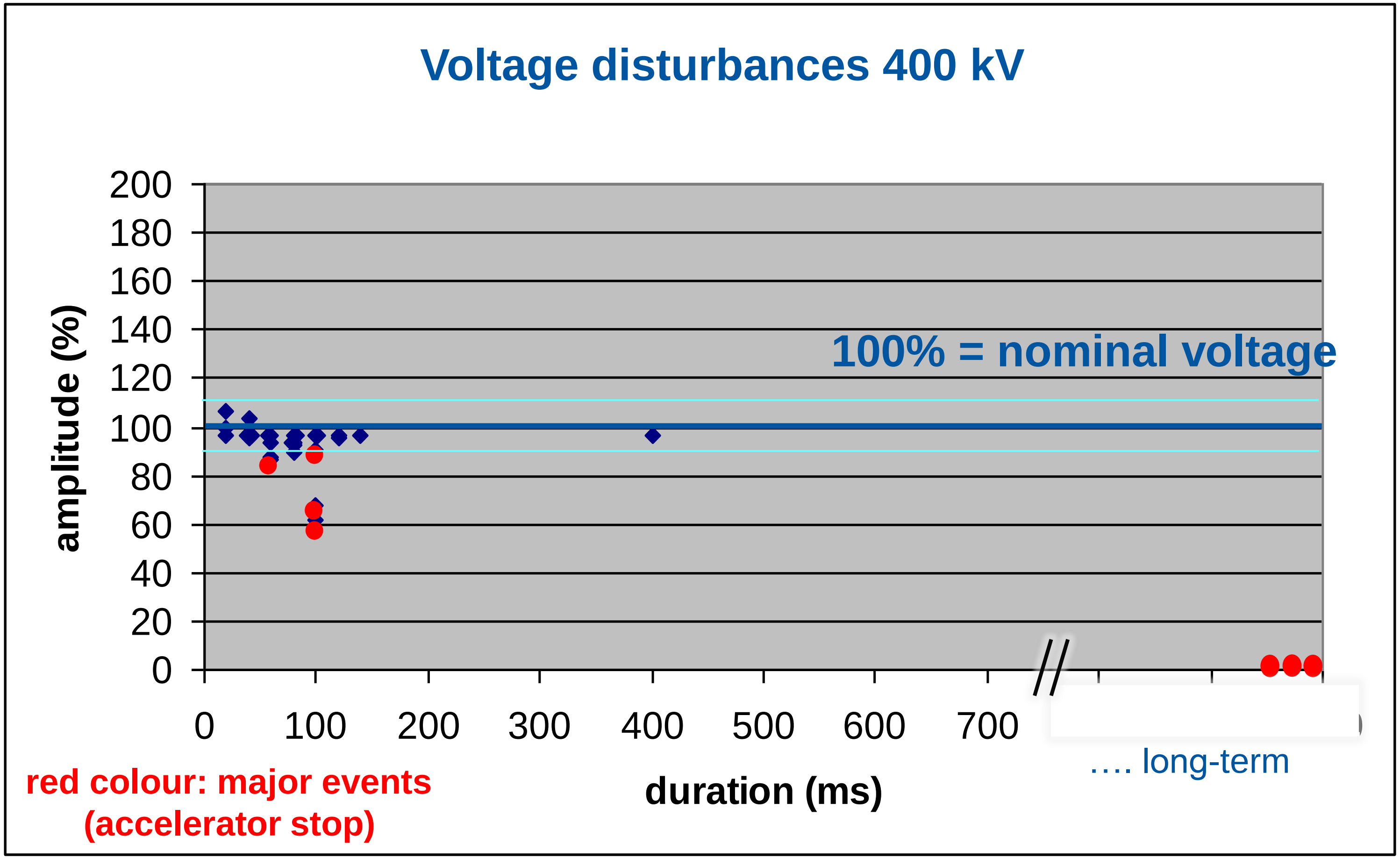
Power quality statistics (CERN network)



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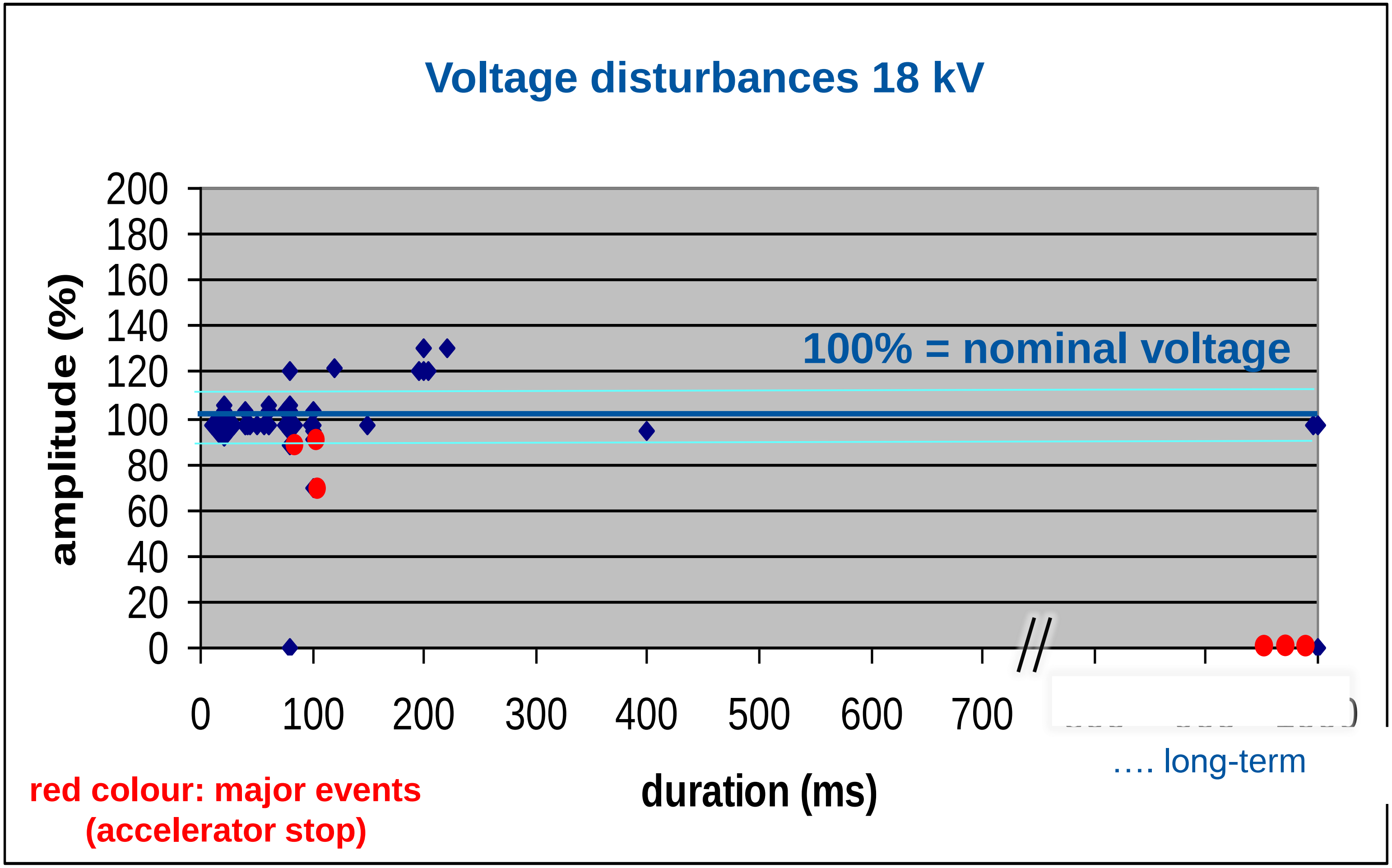

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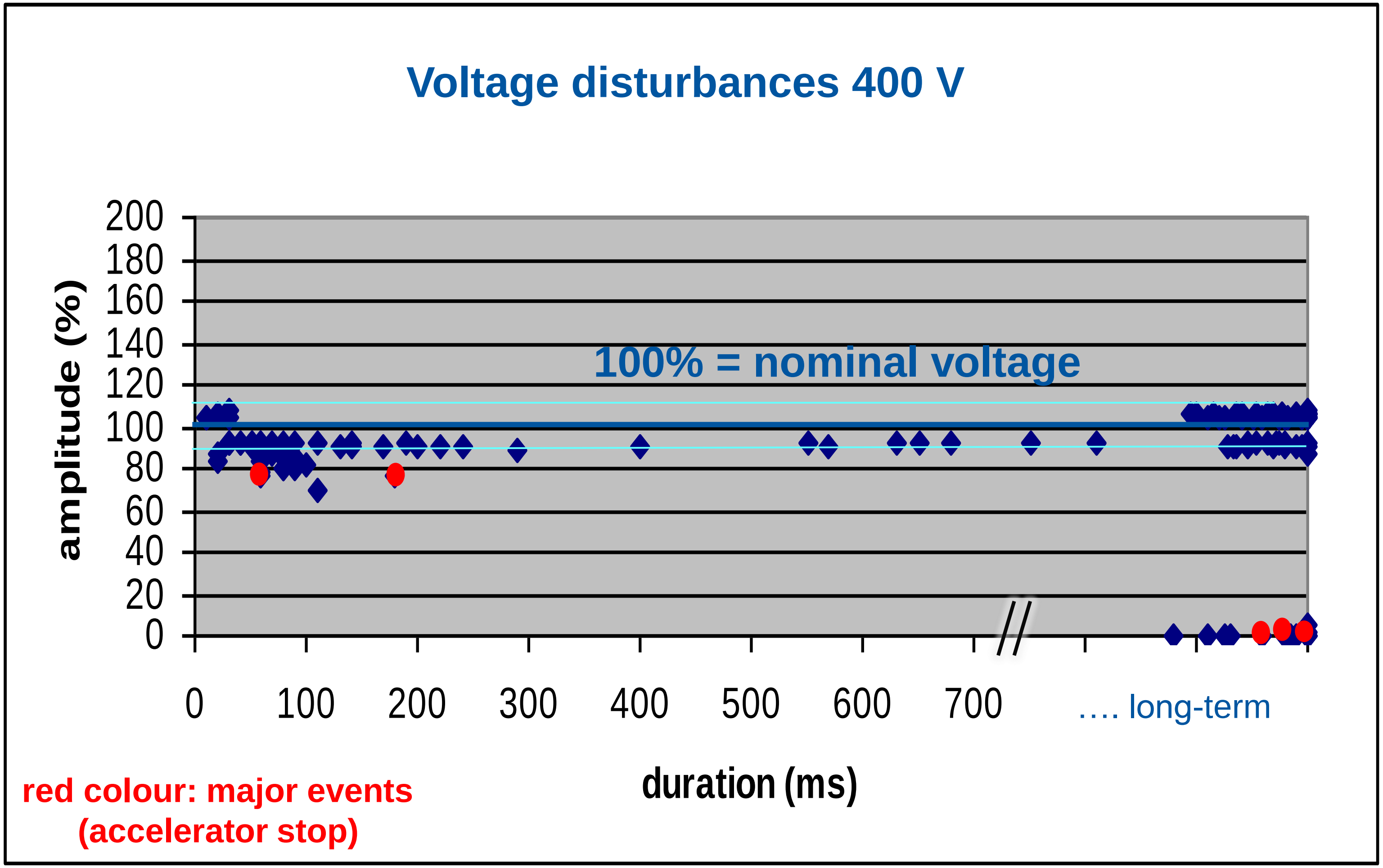
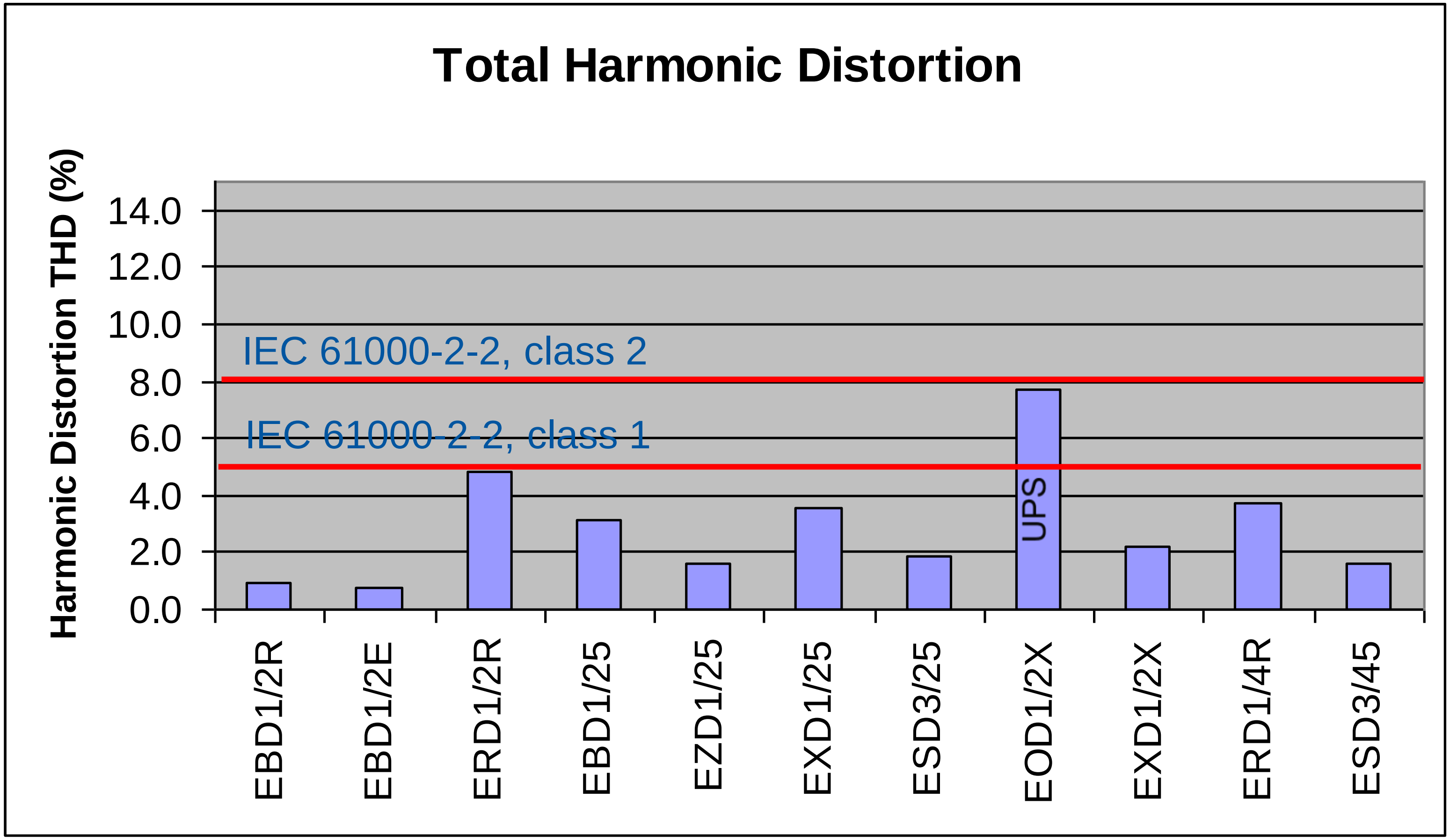


Power quality statistics (CERN 400 V networks)



Power quality statistics

The MAJORITY of power quality issues is caused inside CERN.

The MAJORITY of network disturbances has no consequences.

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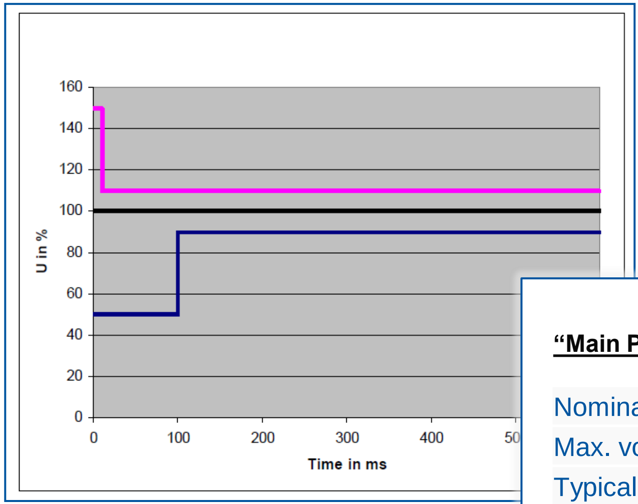
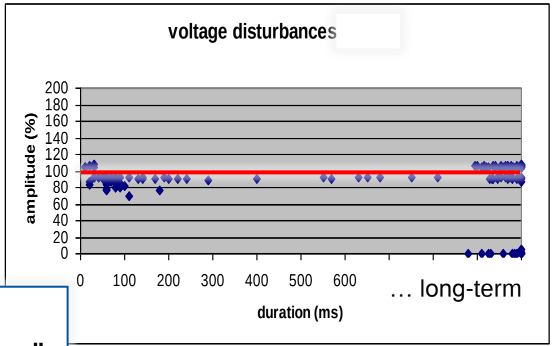
Specification of immunity of electrical equipment

Before constructing the LHC, CERN specified the immunity levels for all electrical equipment.
This internal standard intends to assure a certain minimum immunity of equipment, with the objective to significantly increase MTBF of the LHC.

Unfortunately, it shows now during LHC operation, which equipment does not sufficiently respect this standard. In particular, voltage dips and voltage swells remain the main power quality issues for LHC.



Standardised CERN immunity levels for voltage variations



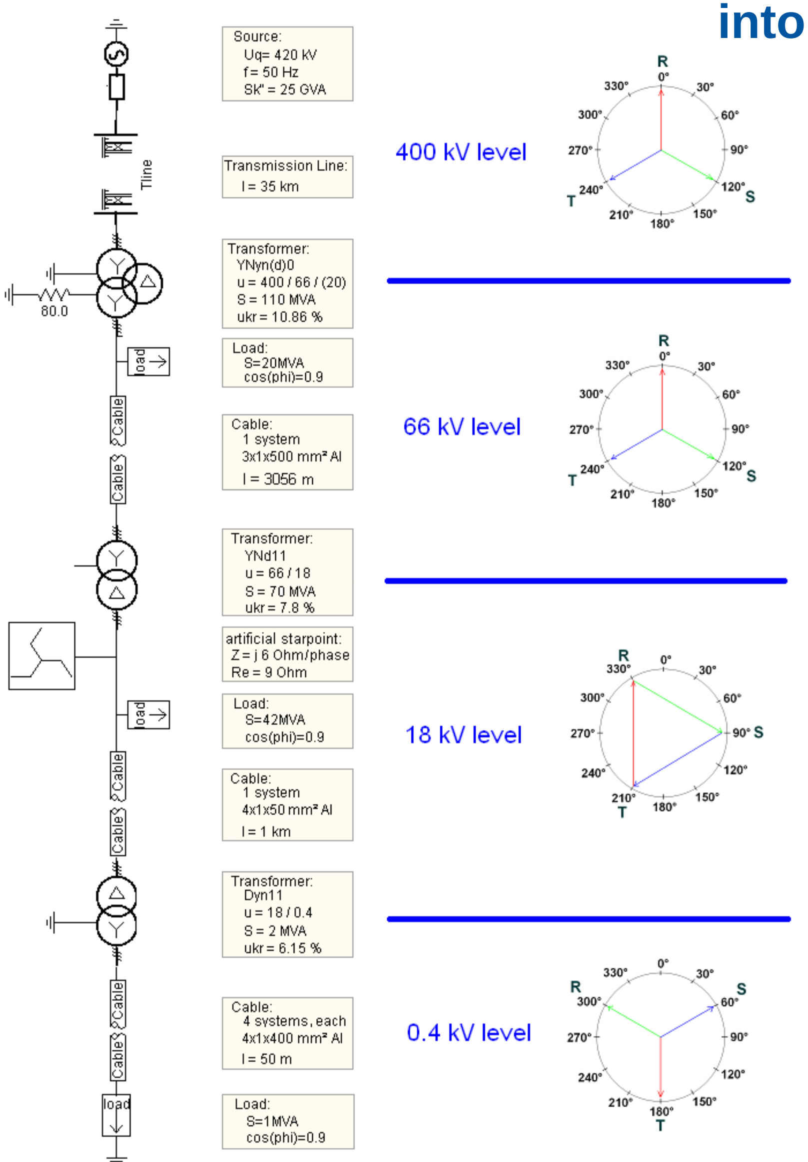
Typical disturbances

"Main Parameters of the LHC 400/230 V Distribution System"

Nominal voltage	400 / 230 V
Max. voltage variations	± 10 %
Typical voltage variations	± 5 %
Transients (spikes)	1200 V for 0.2 ms
Voltage swells	+ 50 % of Un, 10 ms
Voltage dips	- 50 % of Un, 100 ms
Total harmonic distortion (THD)	5%

https://edms.cern.ch/file/113154/2/LHC-EM-ES-0001-00-20.pdf

Propagation of external disturbances into a distribution network



Propagation of external asymmetrical disturbances into a network depends on the combination of transformer vector groups (e.g. 400 kV voltage dips going into CERN network):

		R	S	T	R-S	S-T	R-T
400 kV		50 %	100 %	100 %	75 %	100 %	75 %
66 kV		58 %	97 %	96 %	78 %	100 %	77 %
18 kV		77 %	100 %	77 %	95 %	96 %	65 %
18/0.4	0.4 kV	94 %	94 %	66 %	100 %	77 %	77 %
18/3.3/0.4	3.3 kV	94 %	94 %	66 %	100 %	75 %	78 %
	0.4 kV	94 %	94 %	66 %	100 %	76 %	76 %

Single phase dip, -50% in phase R

		R	S	T	R-S	S-T	R-T
400 kV		50 %	97 %	50 %	76 %	76 %	50 %
66 kV		57 %	87 %	58 %	76 %	76 %	50 %
18 kV		76 %	76 %	50 %	83 %	60 %	60 %
18/0.4	0.4 kV	83 %	60 %	60 %	77 %	50 %	77 %
18/3.3/0.4	3.3 kV	84 %	66 %	64 %	77 %	53 %	77 %
	0.4 kV	83 %	65 %	65 %	78 %	54 %	78 %

Double-phase dip (-50% in phases R and T, healthy phase = S)

Principle of propagation

voltage level	faulty phase
400 kV	R
66 kV	R
18 kV	R-T
3.3 kV	T
0.4 kV	T

Single-phase dip

voltage level	healthy phase
400 kV	S
66 kV	S
18 kV	R-S
3.3 kV	R
0.4 kV	R

Double-phase dip

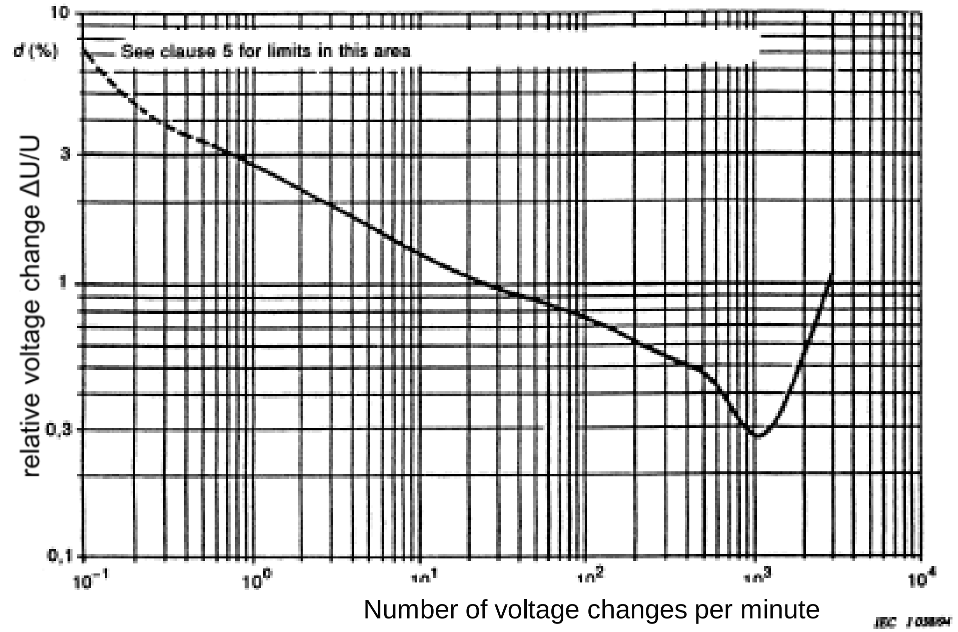
Flicker

Flicker:
Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance … fluctuates with time.

Voltage fluctuation:
Changes of r.m.s. voltage evaluated as a single value for each successive halfperiod of the source voltage

Short-term flicker indicator *P*st:
Flicker severity evaluated over a short period (in minutes); *P*st = 1 is the conventional threshold of irritability

Long-term flicker indicator *P*lt:
Flicker severity evaluated over a long period (a few hours) using successive *P*st values



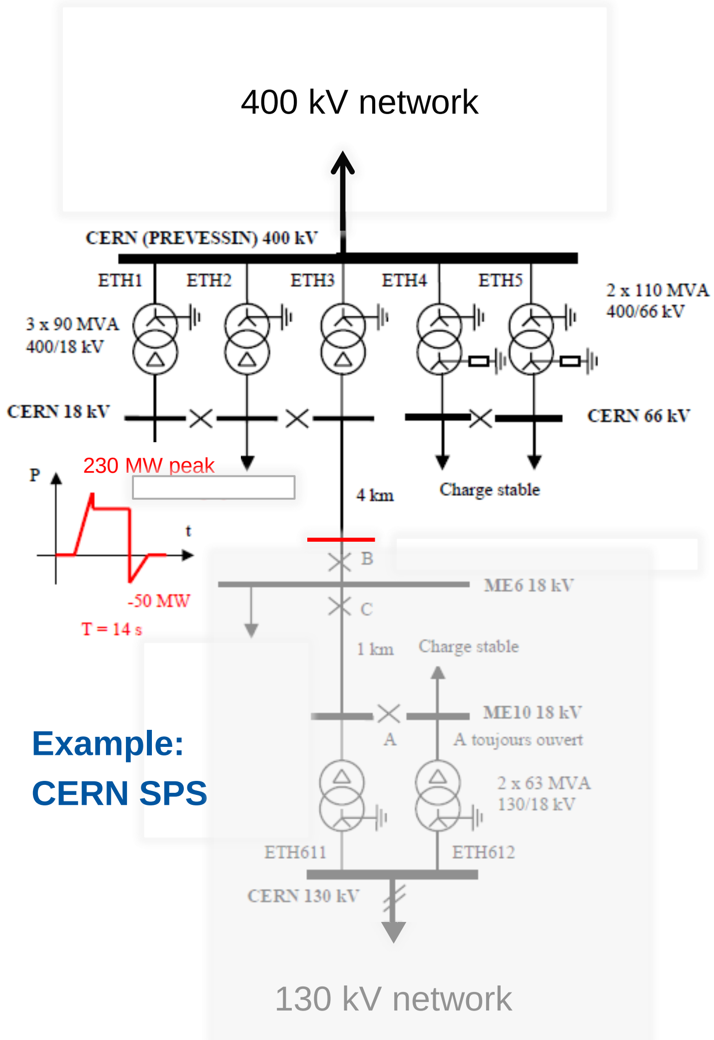
Note: 1200 voltage changes per minute = 10 Hz flicker

Ref. IEC 61000-3-3 fig. 4

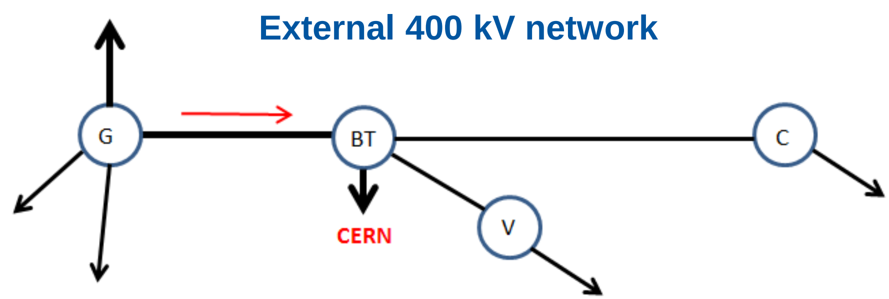
Flicker caused by power converters for accelerators

Some thoughts:
- Flicker limits are based on the empiric definitions of the human eye's sensitivity to luminance fluctuations.
- Flicker limits are important contractual parameters at the point of connection to the external grid, to be strictly respected!
- Inside the physics laboratory, the irritating effects of flicker can be reduced by strictly separating general services (lighting) and power converter networks.

Effects of pulsating loads on external networks



Example:
CERN SPS



- Pulsating reactive power is compensated within CERN (SVC's)
- Pulsating active power is supplied by the 400 kV network

Δ U (400 kV) due to SPS:	< 0.6 % pk-pk *)
Δ f (400 kV) due to SPS:	5 … 25 mHz pk-pk *)

*) *depending on 400 kV network configuration (and its S_{cc})*

In general:
Reactive power variations cause voltage variations (flicker)
Active power variations cause frequency variations in the grid

Electromagnetic environment classes
acc. IEC 61000-2-4

Class 1: Protected supplies for compatibility levels lower than those on public networks … for very sensitive equipment.

Class 2: Environments of industrial and other non-public power supplies … and generally identical to public networks.

Class 3: Industrial environments, in particular when
– a major part of the load is fed through converters; -> *Hey, that's a particle accelerator!*
– loads vary rapidly. -> *Yes, a particle accelerator!*
– ….

Power converters for particle accelerators represent the roughest type of load, comparable to heavy industry such as large arc furnaces, rolling mills etc. (class 3).

However, to operate them correctly and with the required precision, power converters for particle accelerators require compatibility levels sometimes better than the most sensitive equipment (class 1).

What do these three classes actually mean?

	Class 1	Class 2	Class 3	CERN Engineering Spec.	Example: SVC for SPS (18 kV)
Voltage tolerances	± 8%	± 10%	-15% / +10%	typically ± 5%, max. ± 10%	± 0.75% (transient)
THD(400V)	5% (short-term 7.5%)	8%	10% (short-term 15%)	typically 2%, max. 5%	0.75% (transient)
Frequency tolerances	± 1 Hz	± 1 Hz	± 1 Hz	± 0.5 Hz	± 0.5 Hz

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Power quality improvement by SVC's *)

Example: SVC for SPS (TCR 150 Mvar, -130 Mvar harmonic filters)

Building for thyristor valve, cooling and control room

Thyristor controlled reactors

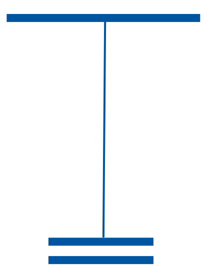
Harmonic filters

*) FACTS = Flexible AC Transmission Systems

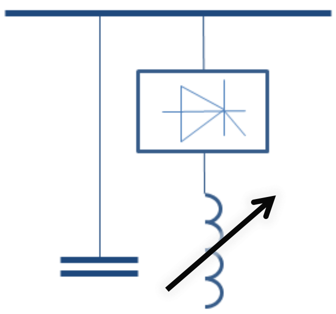
Power quality improvement by SVC's *)

<u>Capacitor banks (=harmonic filters)</u>
- constant Mvar generation, p.f. ≠ 1
- constant voltage support (constant voltage increase)
- harmonic filtering
- always requires tuning to control resonances!

<u>Static Var Compensators (SVC's)</u>
- variable Mvar generation -> p.f. ~ 1
- variable voltage support (stabilisation U_{ref})
- harmonic filtering



harmonic filters



harmonic filters

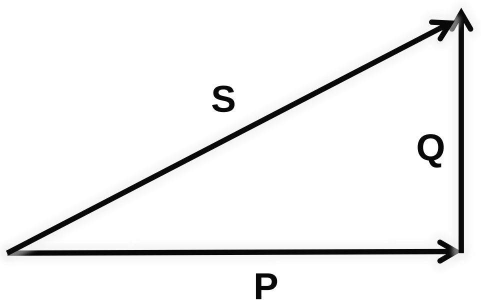
Thyristor controlled reactors (TCR)

*) FACTS = Flexible AC Transmission Systems

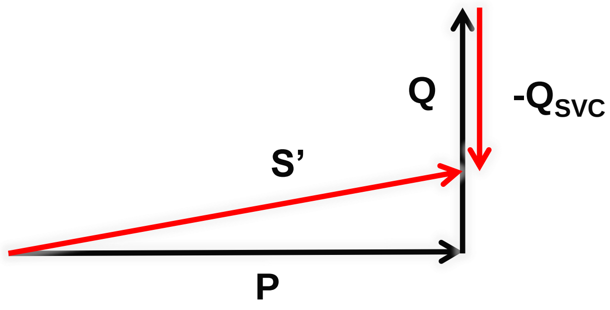
a) Reactive power compensation

Thyristor power converters consume (pulsating) active and reactive power.

Without SVC:
- load reactive power taken from the network
- transmission and distribution system needs to be rated for apparent power S
- reactive power variations cause flicker
- contractual power factor at grid connection point
- reactive power consumption costs money!



With SVC:
- load reactive power is compensated locally
- lean transmission and distribution system
- reduced transmission losses
- disturbing effects of pulsating reactive and active power eliminated (no flicker)



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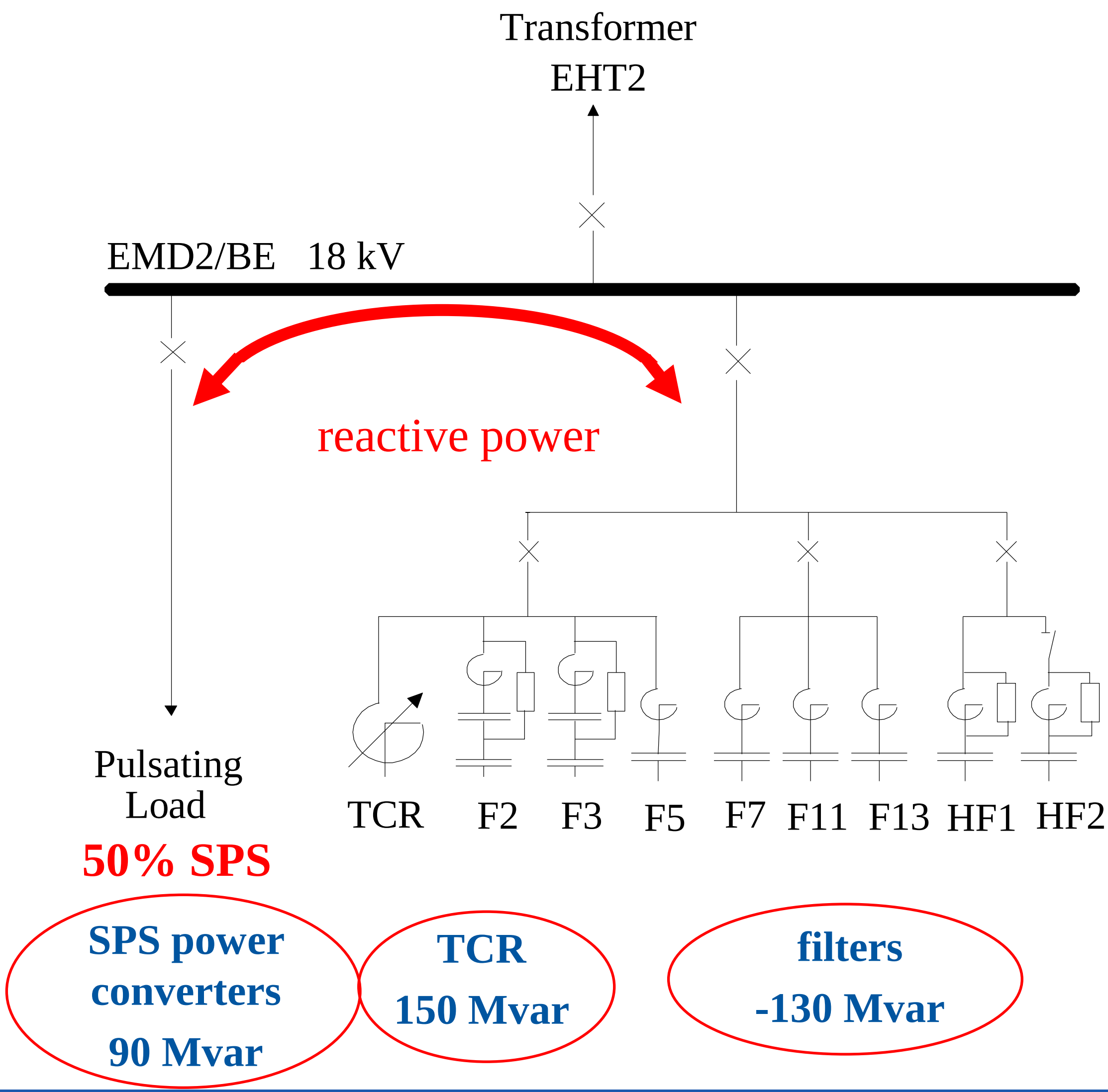

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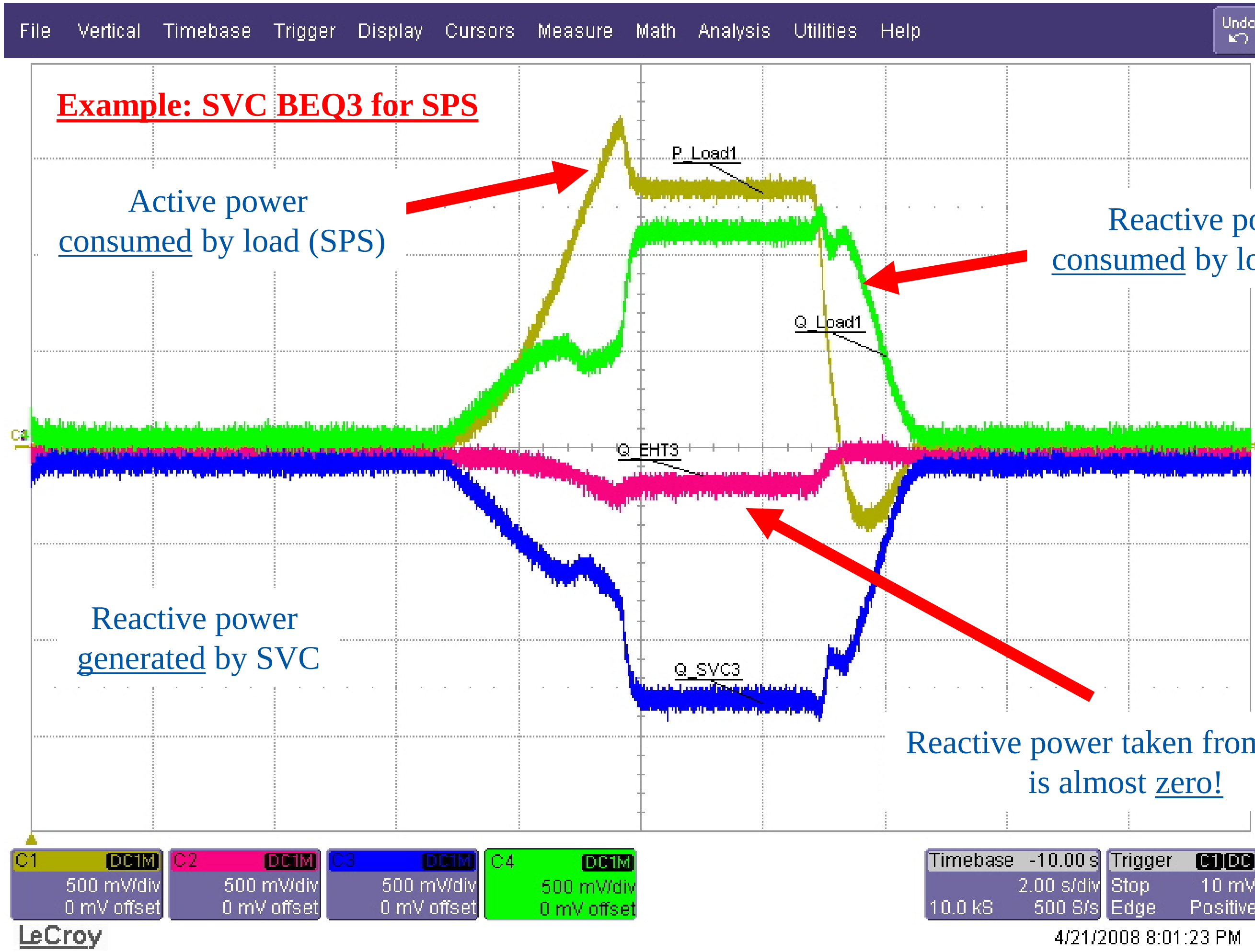
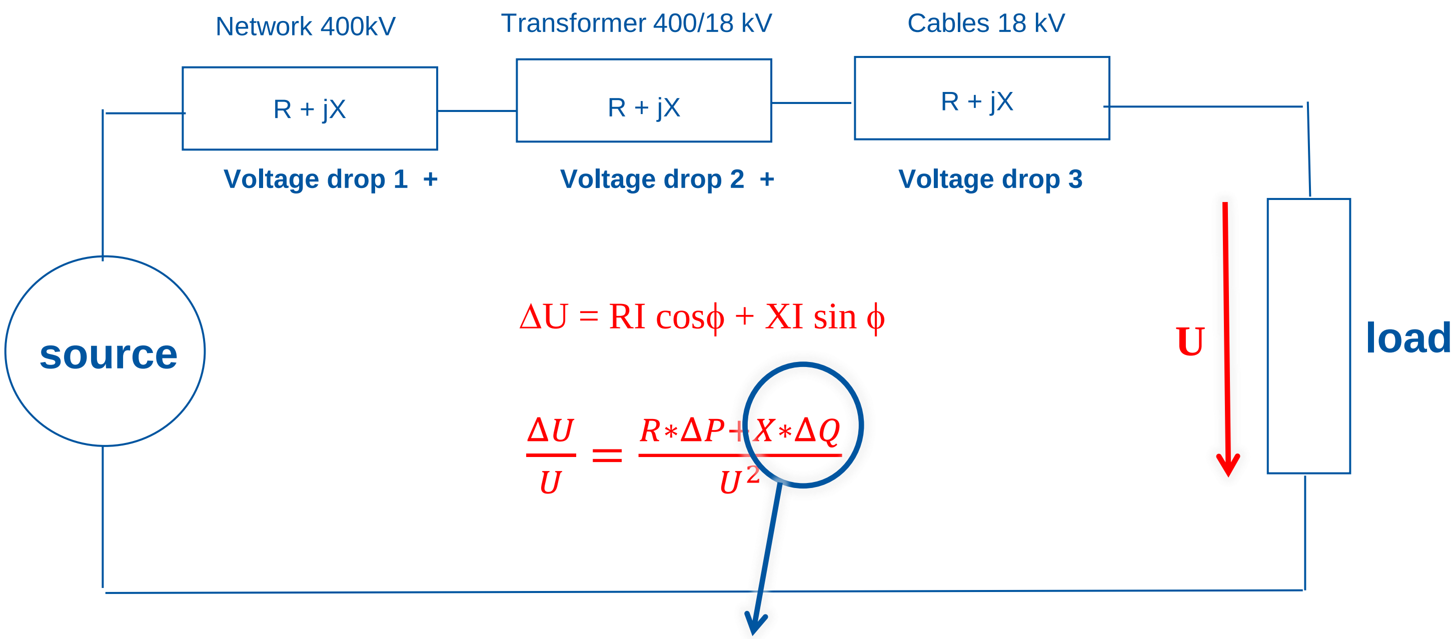


Active and reactive power

b) Voltage stabilisation

- during each power pulse, the voltage of the network decreases
- periodic power cycling causes unwanted periodic voltage drops (flicker)
- the principal cause: changing Mvars flowing through the inductance of the power network



$$\Delta U = RI\cos\phi + XI\sin\phi$$

$$\frac{\Delta U}{U} = \frac{R * \Delta P + X * \Delta Q}{U^2}$$

This term is the principal responsible for voltage variations due to (pulsating) reactive power of the load:

Inductive load -> voltage drop

Capacitive load -> voltage increase!

b) Voltage stabilisation

How to keep the network voltage constant during the power pulses?

Solution: SVC generates a specific pulse of reactive power, to compensate for the unwanted drops caused by pulsating active and reactive power of the load.

$$Q_{SVC} = Q_{load} + \frac{P_{load}^2}{2 * S_{cc}} + k * P_{load}$$

Q_{SVC}	reactive power generated by SVC
P_{load}	active power consumed by load
Q_{load}	reactive power consumed by load
S_{cc}	network short-circuit power

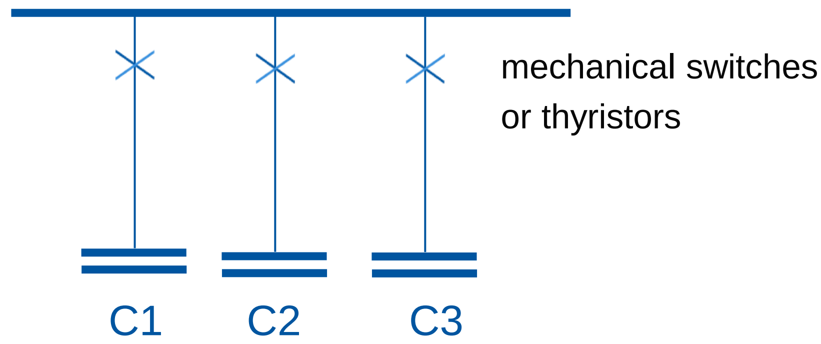
With $k = \frac{R}{X}$ of the supplying network

Nota: An SVC <u>cannot</u> assure perfect Mvar compensation <u>and</u> perfect voltage stabilisation at the same time. We need to allow for small variations of reactive power to correct the disturbing effects of active power variations.

b) Voltage stabilisation

How to vary the reactive power generation of an SVC?

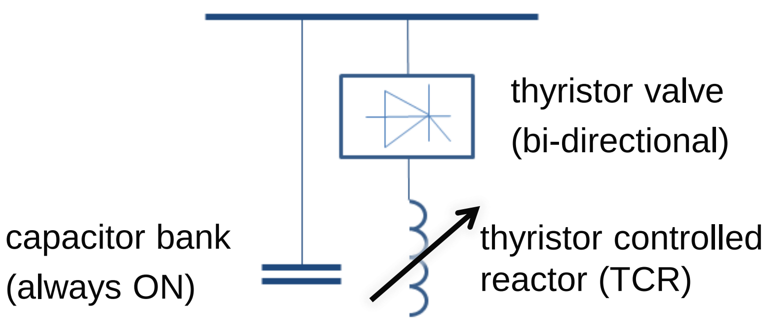
Variant 1: Variation in discrete steps



Capacitance step size, example: 2^2 2^1 2^0

Variant 2: Capacitor bank and TCR

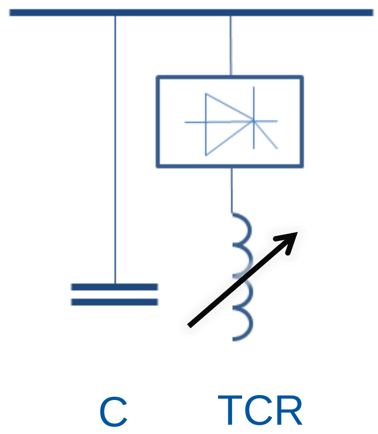
(continuous variation between 0 and max.)

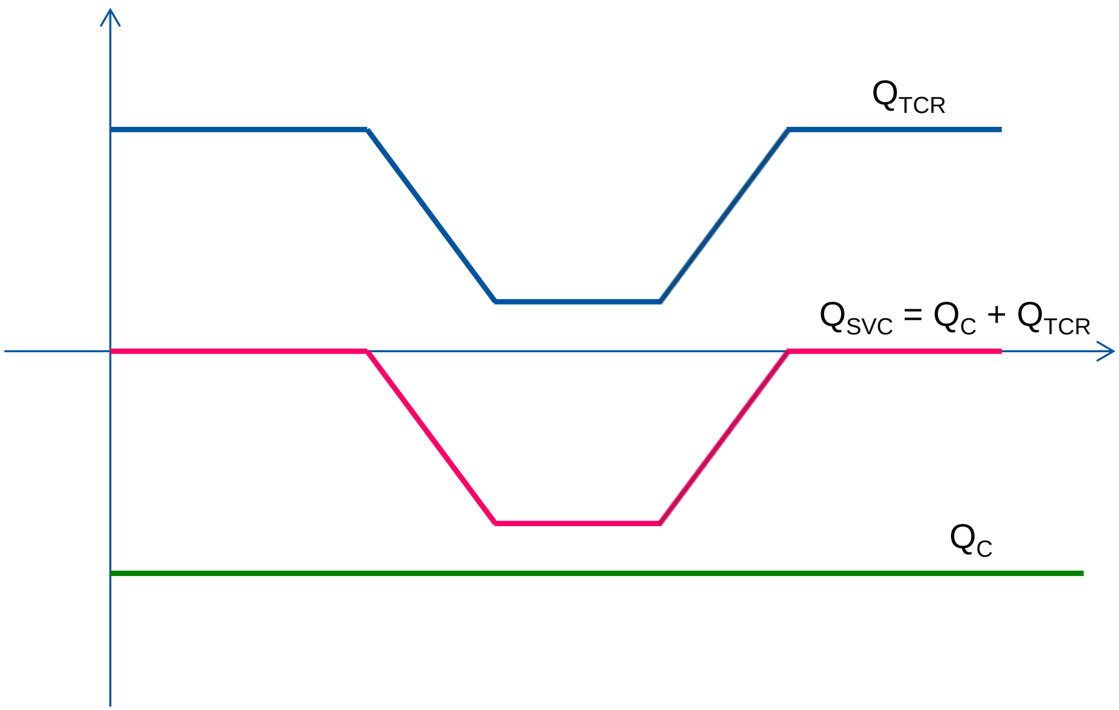


b) Voltage stabilisation

How can an SVC generate a pulse of (capacitive) reactive power?

Let's take variant 2 from previous page: Capacitors and TCR
(continuous variation between 0 and max. reactive power generation)





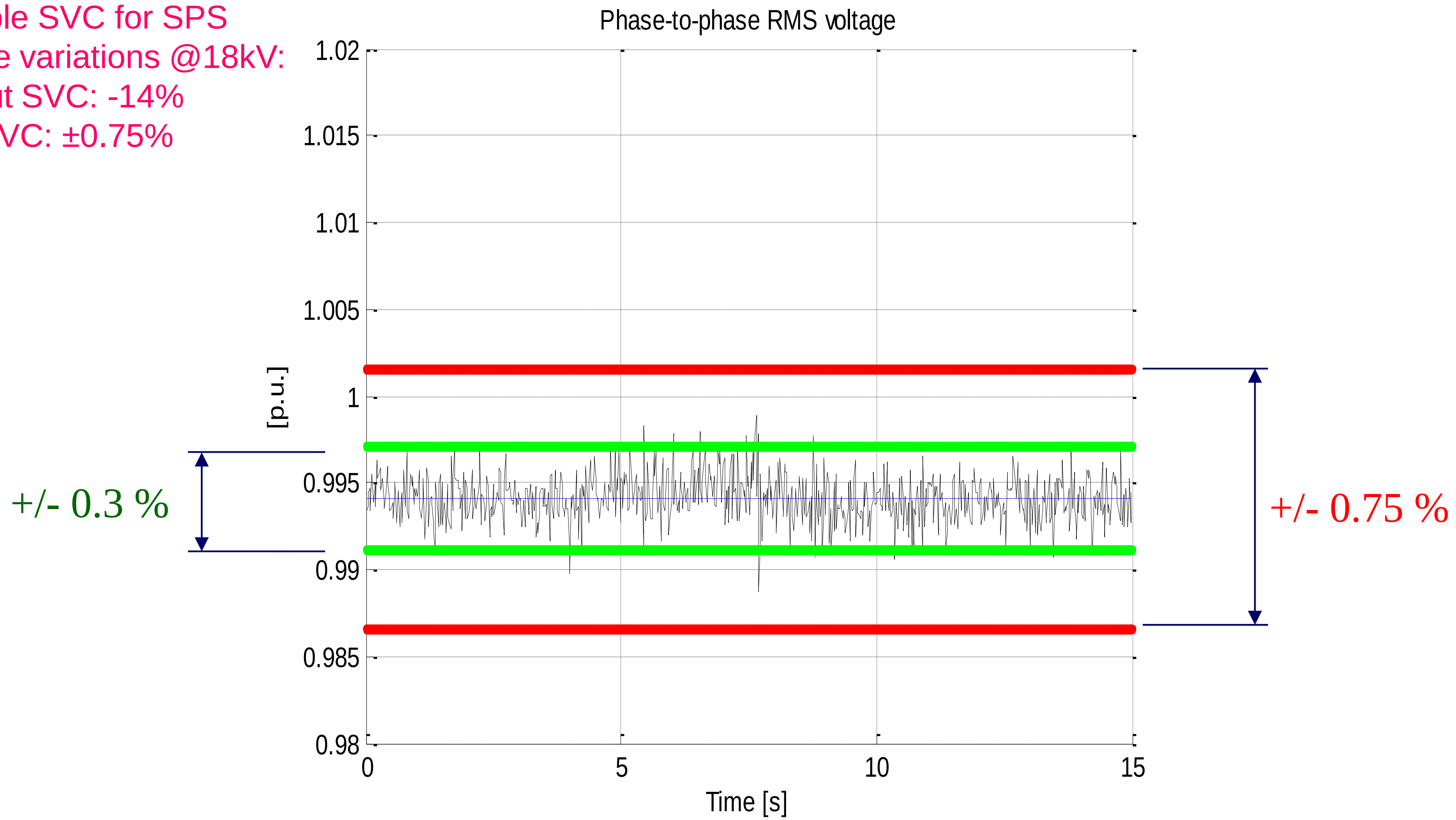
Limitations of SVC technology:
- Response time 50-100 ms, hence unsuitable for correction of fast transient network disturbances
- Mvar output decreases with network voltage, hence unsuitable for voltage support at low system voltage

$$Q = 3 * U^2 * \omega * C$$

Typically, an SVC should stabilise the network voltage to ±1%, even for fast load changes

b) Voltage stabilisation

Example SVC for SPS
Voltage variations @18kV:
Without SVC: -14%
With SVC: ±0.75%

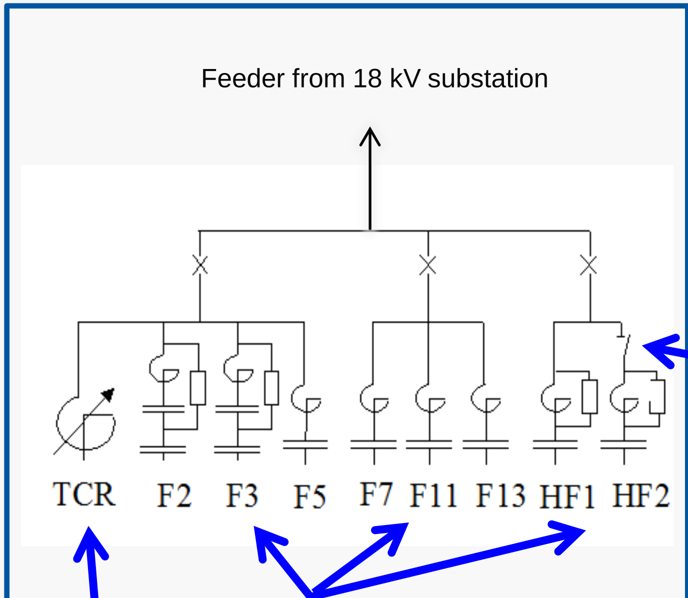


18 kV voltage response

Typical SVC response time: 50–100ms

c) Harmonic filtering

Example: SVC for SPS



$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

First parallel resonance with network (107 Hz) is mastered by 100 Hz and 150 Hz filters

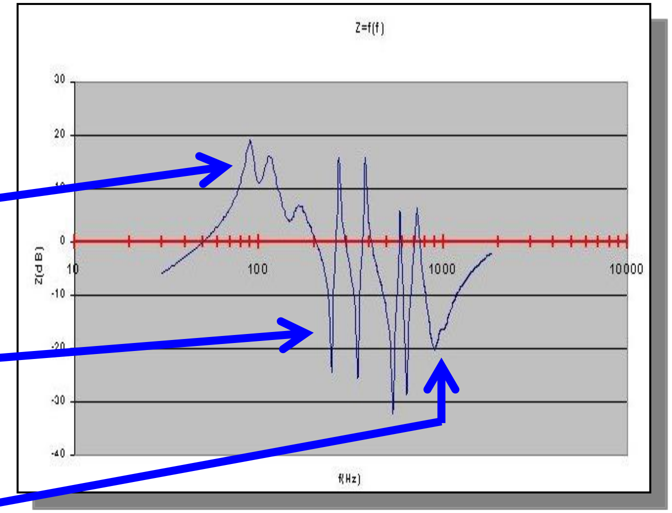
Tuned to typical harmonic frequencies of 6p and 12p thyristor converters (250, 350, 550, 650 Hz)

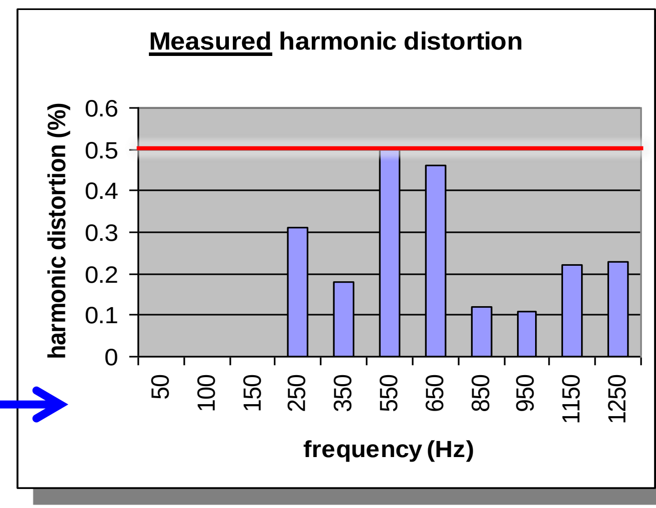
Damped high-pass filters 950 Hz and 1050 Hz

1050 Hz filter can be disconnected to operate SVC with -112 Mvar instead of -130 Mvar (reduced SVC losses)

Harmonic performance: indiv. harm. max. 0.5 % THD(18 kV) max. 0.75 %

Comparison: Limit = 8% for IEC 61000-2-2 class 2





TCR rated 150 Mvar (filters -130 Mvar) to allow 20 Mvar inductive SVC output in case of high network system voltage

SVC split in 3 groups due to circuit breaker limits for capacitive switching

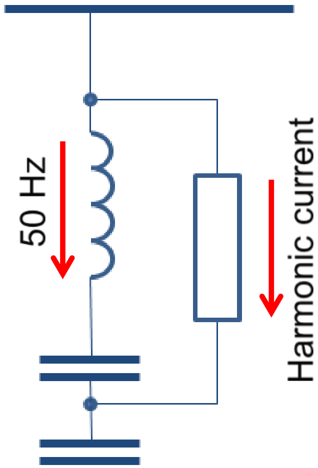
Summary of SVC performance

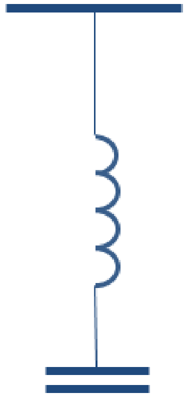
Example: SVC for SPS

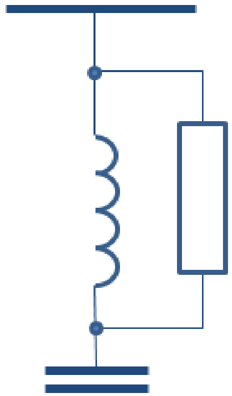
		Without SVC	With SVC
Reactive power compensation	reactive power	70 Mvar	0…10 Mvar
Voltage stabilization 18 kV	Δ U (18 kV)	14%	± 0.75 %
Harmonic filtering	THD(18 kV)	20%	0.75%

The reactive power values in the first line concern one system (50% of SPS). For total SPS, multiply by 2.

Most common harmonic filter configurations for SVC's







C-type filter
- reduced 50 Hz losses
- requires add. type of C
- typically for 100 and 150 Hz

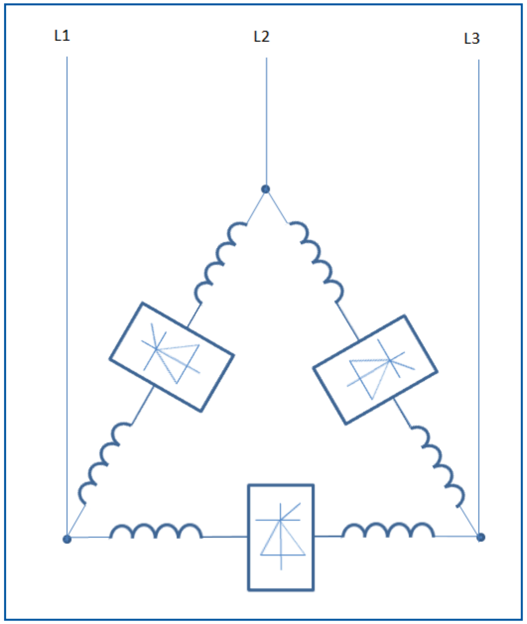
L-C-type filter
- for 250, 350, 550 and 650 Hz

High-pass filter
- 850 Hz and above

In all configurations, the capacitor banks are in double-star connection, star-points not connected to earth.

Star connection is preferred to delta, for better capacitor protection, and to limit the need for series connection of capacitor units.

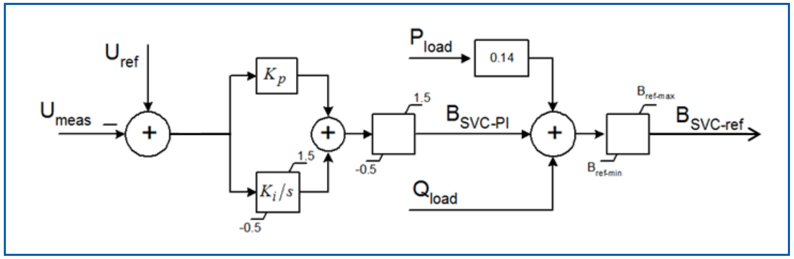
TCR configuration for SVC's



Thyristor controlled reactors (HV part)

Delta connection of reactors:

- to trap the triple harmonics in the delta (reduced harmonics from the network)
- it's cheaper to build thyristor valves with high voltage than high current (thyristor series connection)
- in unearthed star connection, the starpoint would move

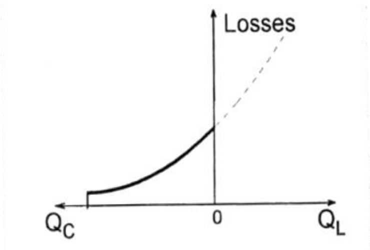


Typical TCR control strategy

Losses of SVC technology:

- at zero Mvar output, the TCR current cancels out the capacitive current of harmonic filters (unnecess. losses!)
- overall, the relative losses of an SVC are quite small:

harmonic filters = 0.1%
TCR + thyristors = 0.4%
(of total Mvar rating)



Design considerations for SVC's for particle accelerators

1. Expected performance?

- Controlling DC magnet current to ppm precision (and minimise ripple), requires clean AC supply!

2. Voltage level

- Typically, SVC's are connected to MV network 10 – 36 kV.
- Var compensation at LV level 400 V not recommended (changing network configurations, resonances …)

3. Choice of technology

- Harmonic filters (could be switched in groups, depending on load situation), with thyristors or switches
- SVC: Harmonic filters, combined with thyristor controlled reactors, compensation of reactive power
- STATCOM: compensation of active and reactive power

4. Electrical location

- Where is the optimum connection point for best SVC performance?

5. Rating

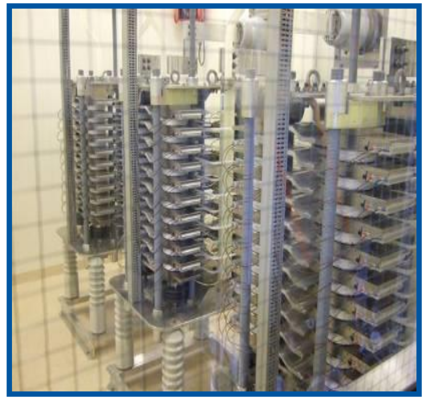
- Minimum Mvar rating of harmonic filters and TCR: to compensate for voltage variations due to Q and P
- TCR and harmonic filters do not need to have identical Mvar rating; SVC could also be asymmetrical

6. Harmonic filter design

- Typical spectrum of power converters: n*p ±1, with n = 1, 2, 3 and p = 6 or 12-pulse -> F5, F7, F11, F13 and HF filters
- Connecting capacitor banks: parallel resonance with network: $f_{res} = \sqrt{\frac{S_{cc}}{Q_{SVC}}}$, then F2 or F3 might be required

SVC – how does it look like?

TCR reactors (50 Mvar / ph)



Thyristor valve 18 kV, 2800 A

Filter reactors

Filter capacitors

Cooling plant for thyristor valve

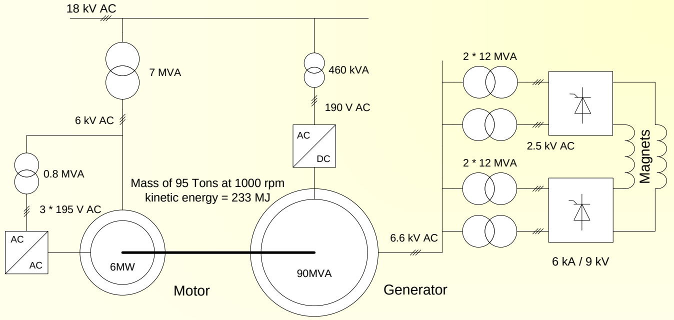
Harmonic filter protection

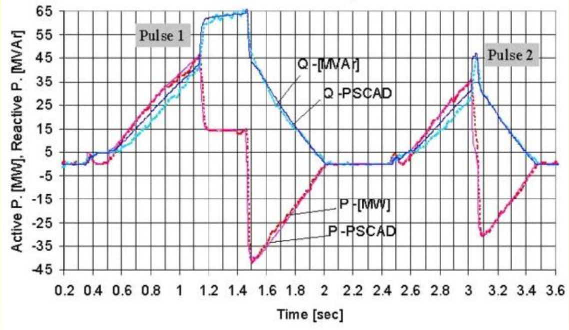
Power Converters and Power Quality

- What is Power Quality?
  - Classification of disturbances
  - Statistics (example CERN)
  - Additional power quality considerations
- Electrical networks and pulsating power
  - Systems without energy storage
  - ***Systems with integrated energy storage***
- Conclusions

Rotating machines

Decoupling of cycling pulses of active and reactive power from the network (e.g. BNL and CERN)



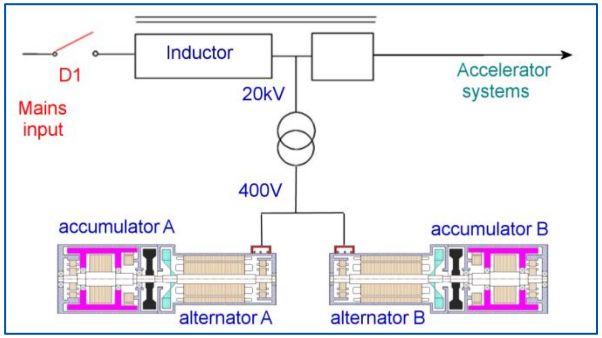


<u>Decoupling:</u>
From network: around 6 MW peak
The load: 45 MW / 65 Mvar peak

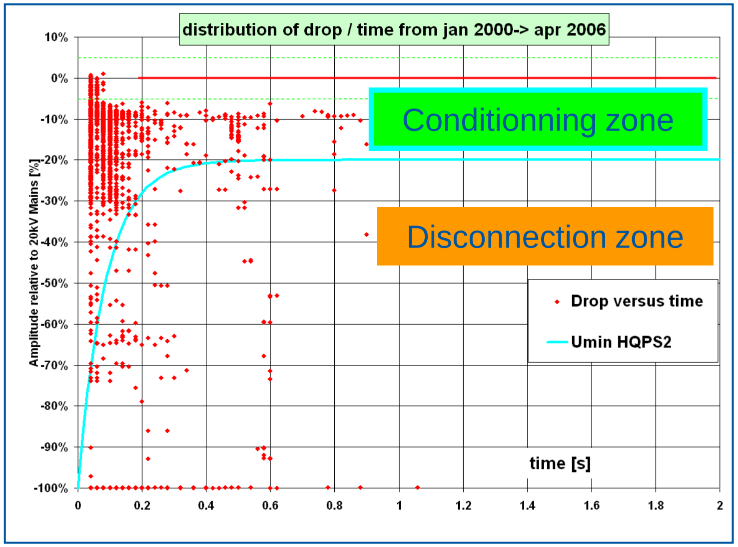
<u>Parameters (MPS CERN):</u>
Generator power: 95 MVA peak
Stored energy: 233 MJ @1000 rpm
Speed variation: 48 Hz - 52 Hz

Rotating machines

Example: Decoupling of power converters from external network disturbances (ESRF)



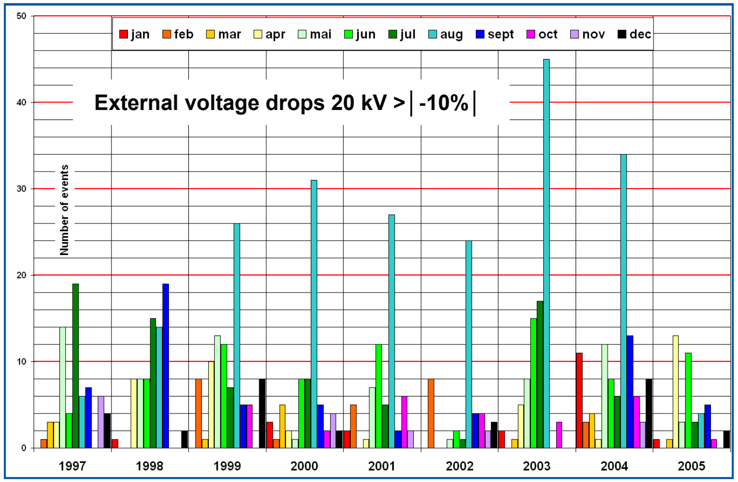
- Conditioning zone: The alternators permanently compensate for the poor power quality.
- Disconnection zone: The system isolates the incoming power and fully compensates for the drop.



Summary:

- ESRF is surrounded by 3 mountain chains. Many thunderstorms in summer.
- stored energy 100 MJ, can compensate during 3 s for 100% of missing power.
- significant power quality improvement during operation, and reduction of accelerator stops and downtime. MTBF for X-ray production increased 24h -> 60h.

Two twin rotablocs (4 accumulators and 4 alternators in one cell)



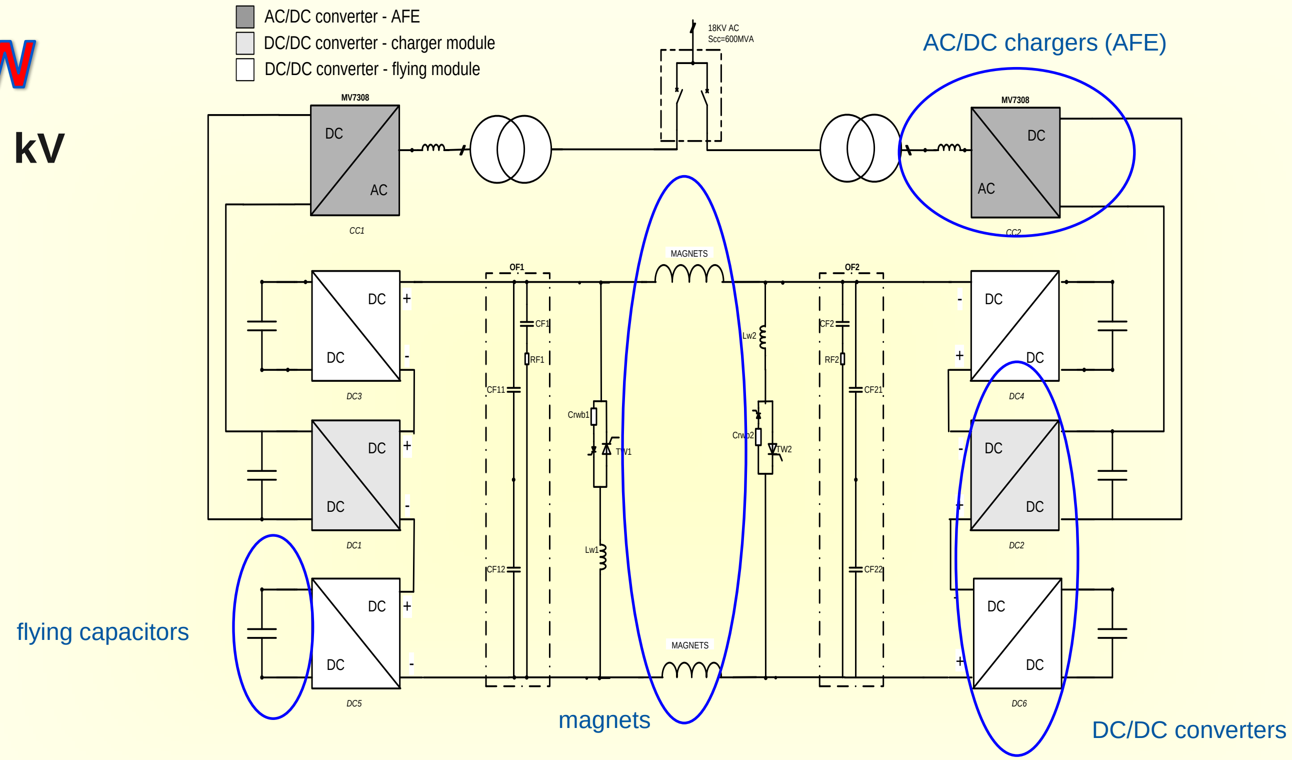
All information on this slide: Courtesy of J.-F. Bouteille, ESRF Grenoble

Power converter with integrated energy storage

Example: Decoupling of power power pulses from the network (POPS – Power System for PS)

60 MW

6 kA / ±10 kV

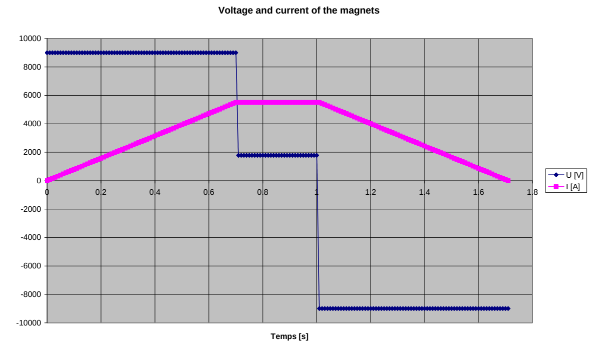


DC/DC converters transfer the power from storage capacitors to magnets.
Four flying capacitors banks are charged via the magnets, and not connected to the mains.
Only two AC/DC converters (AFE) supply the losses of the system+magnets from the mains.

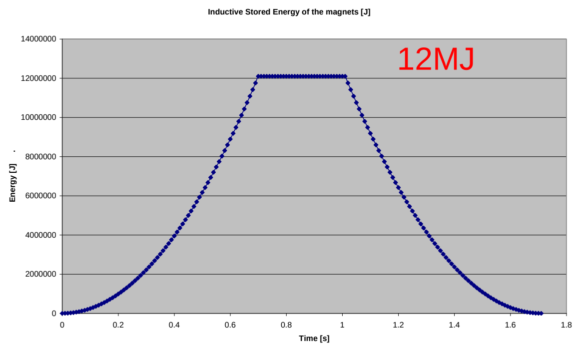
Patent: European Patent Office, Appl. Nr: 06012385.8 (CERN & EPFL)

Power converter with integrated energy storage

Magnet current and voltage



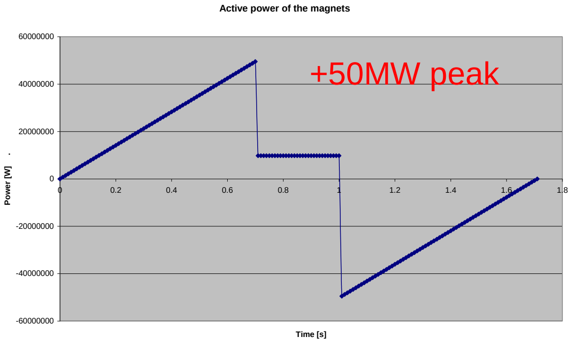
Stored energy in magnets



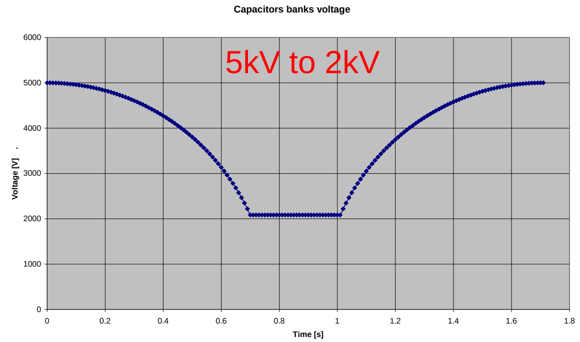
Energy storage capacitor banks (x6)

Energy management of POPS

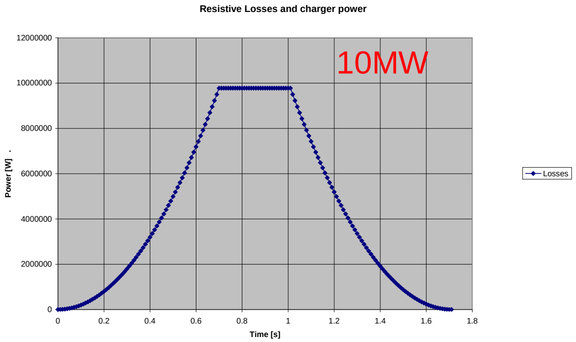
Power to the magnets



Capacitor voltage



Power from the mains = Magnet resistive losses



Power converter with integrated energy storage

POPS 6kA/±10kV

Control room | Power converter room | Cooling tower | Power transformers | Capacitor banks

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Conclusions

Excellent power quality is essential to make excellent physics!

The most important recommendations and conclusions from my talk are:

- If the IEC 61000 does not cover sufficiently the specific needs of your physics laboratory, you need to define the principal power quality standards for your electrical equipment!
- All groups installing and operating electrical equipment need to be involved in power quality considerations, from the beginning.
- Strictly separate (pulsating) power converter loads from general services loads (supply via different transformers).
- Minimise network impedances (inductances!) to reduce voltage variations and harmonic distortion in your networks.
- When choosing a power converter topology, aim to minimise the amplitude of pulsating reactive and active power.