European Organization for Nuclear Research

A novel 60 MW Pulsed Power System based on Capacitive Energy Storage for CERN PS machine

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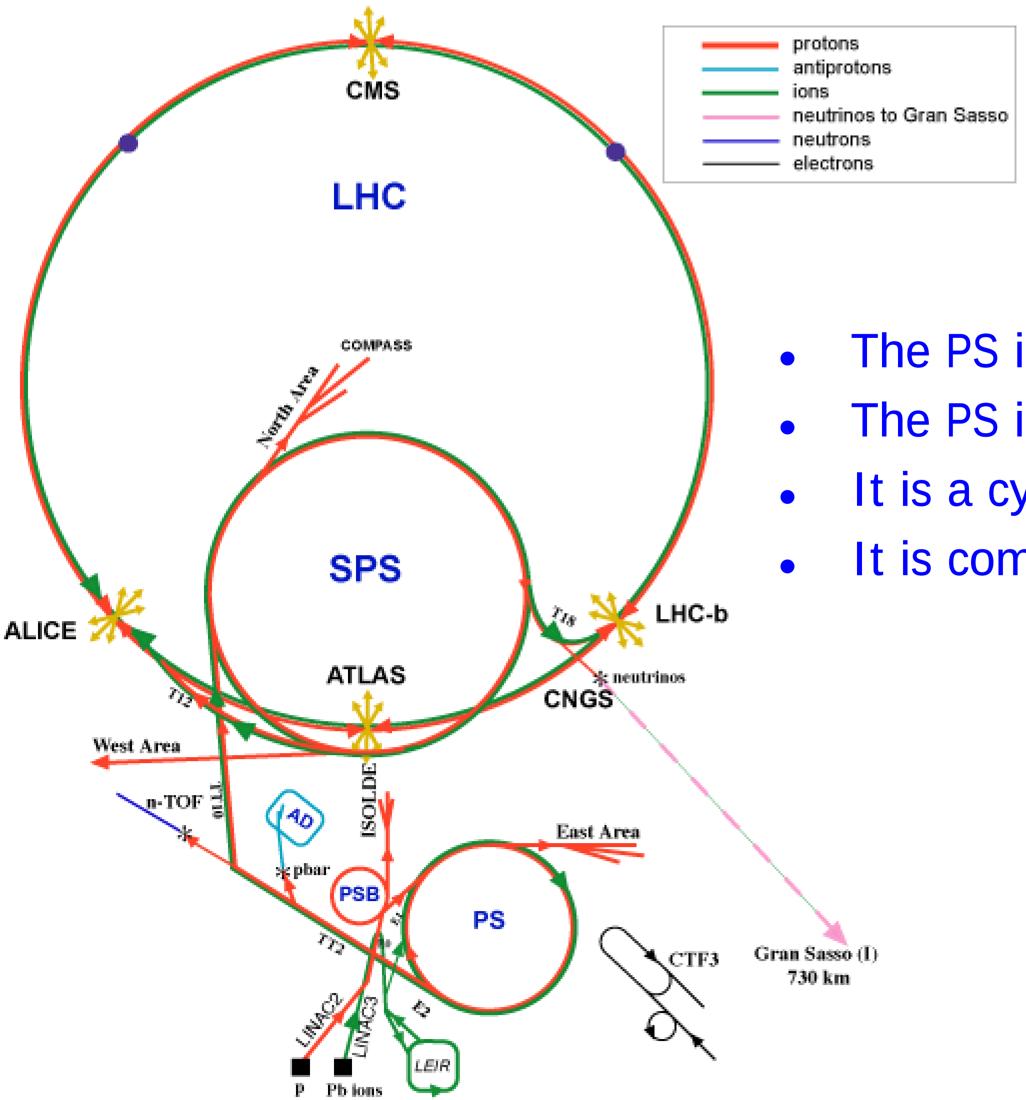
CERN, European Organisation for Nuclear Research

Menu

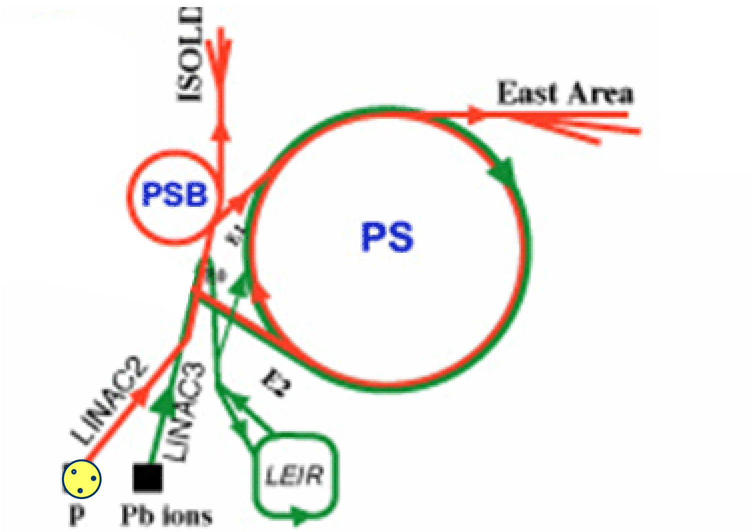
- Introduction
- PS power system
- Research of new solutions
- Novel power system with capacitive energy storage
- Introduction to POPS
- Conclusions

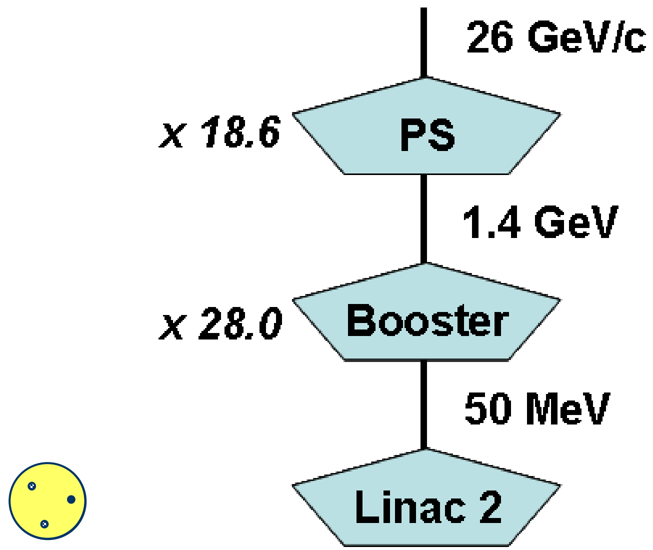
The CERN accelerator network



- The PS is in operation since 1959
- The PS is part of the LHC injection chain
- It is a cycling machine (1.2s)
- It is composed of 100 main magnets

PS machine





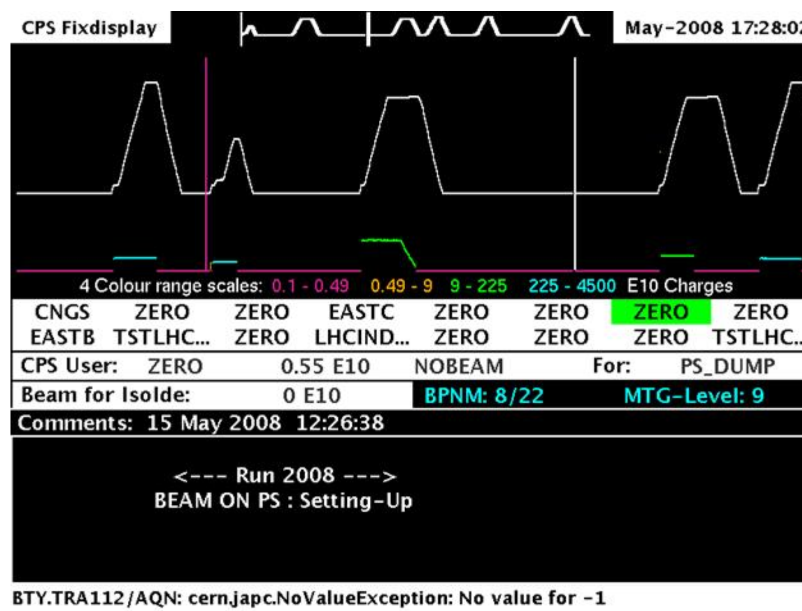
Cycle : 1.2s or 2.4s

100 magnets: 0.95H, 0.32 Ω

1- Voltage : ± 9000V

2- Current : 0 to 5500 A

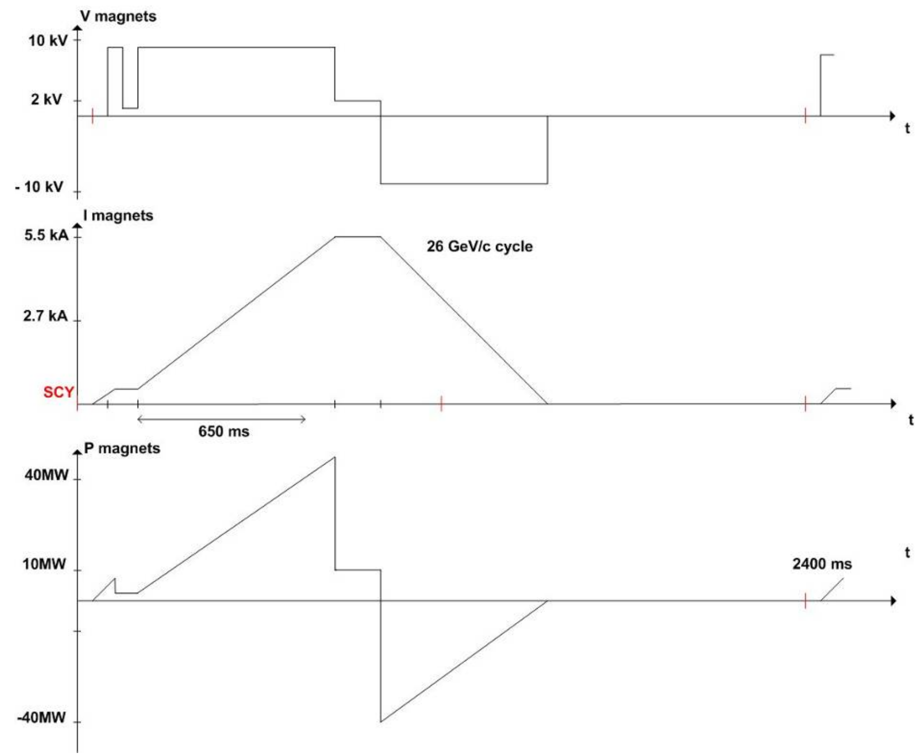
3- P = ± 40 MW
with dP/dt = ± 1 MW/ms

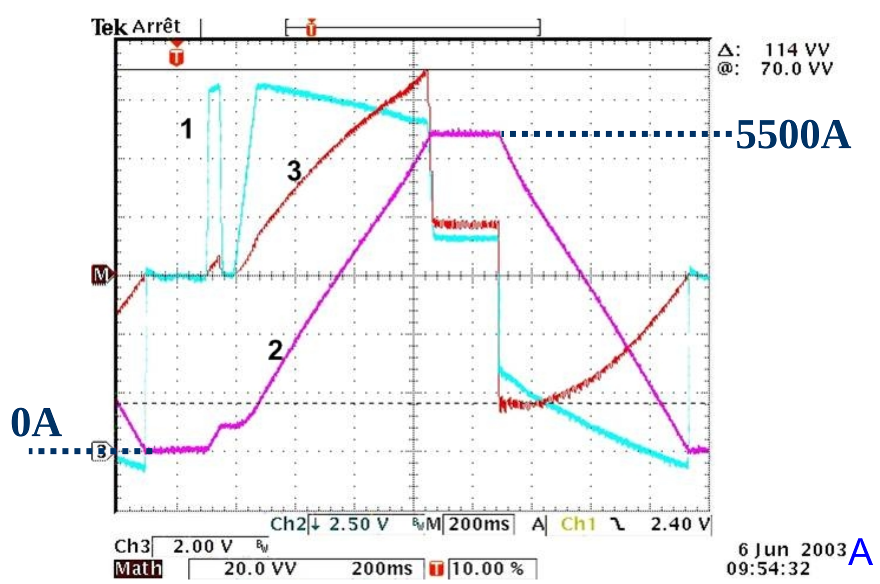


PS power profile

<u>Cycles</u>

- Low cycle: 14 GeV
  - 2.7 kA in 0.4s
  - Flat top: 0.3 s
  - Repetition: 1.2s
- Heavy cycle: 26 GeV
  - 5.5 kA in 0.7s
  - Flat top: 0.4s
  - Repetition: 2.4s
  - Rotor speed 52-49 Hz





PS actual main power system

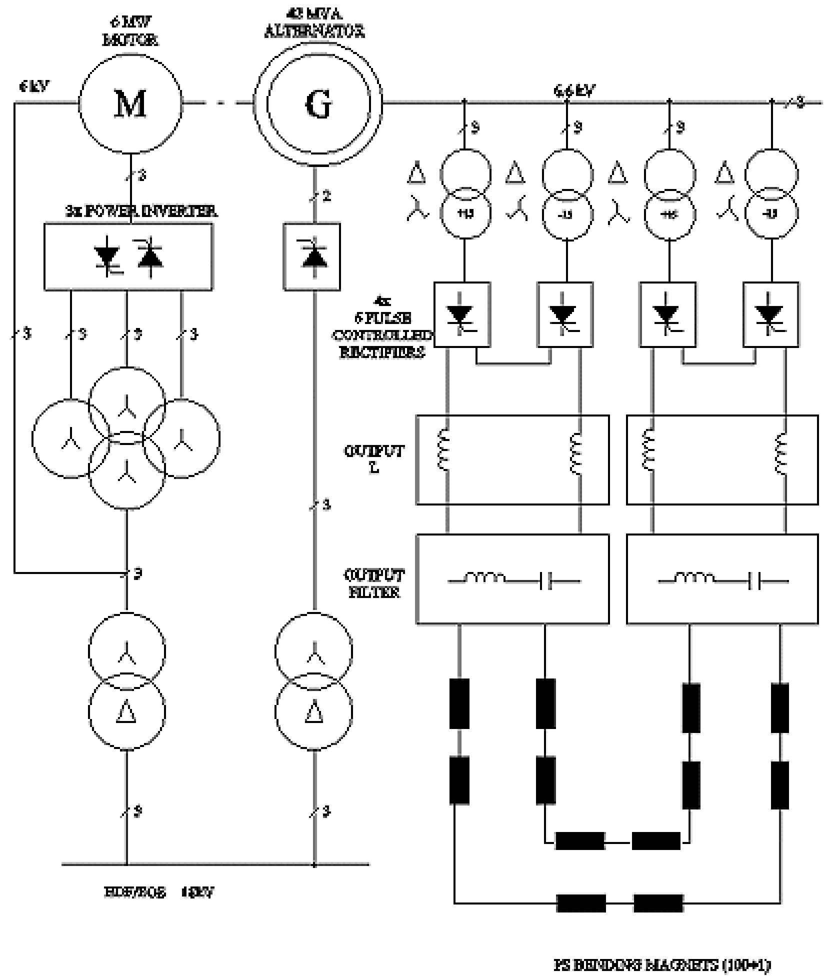
Ratings

Load: 0.95 H / 0.32 Ω

DC output: 5.5 kA / 9 kV

Thyristor rectifiers, 1978

10 millions cycles per year!



PS actual main power system

Rotating machine

SIEMENS, 1968

Generator: 90 MVA

Motor: 6 MW

Speed: 1000 rpm

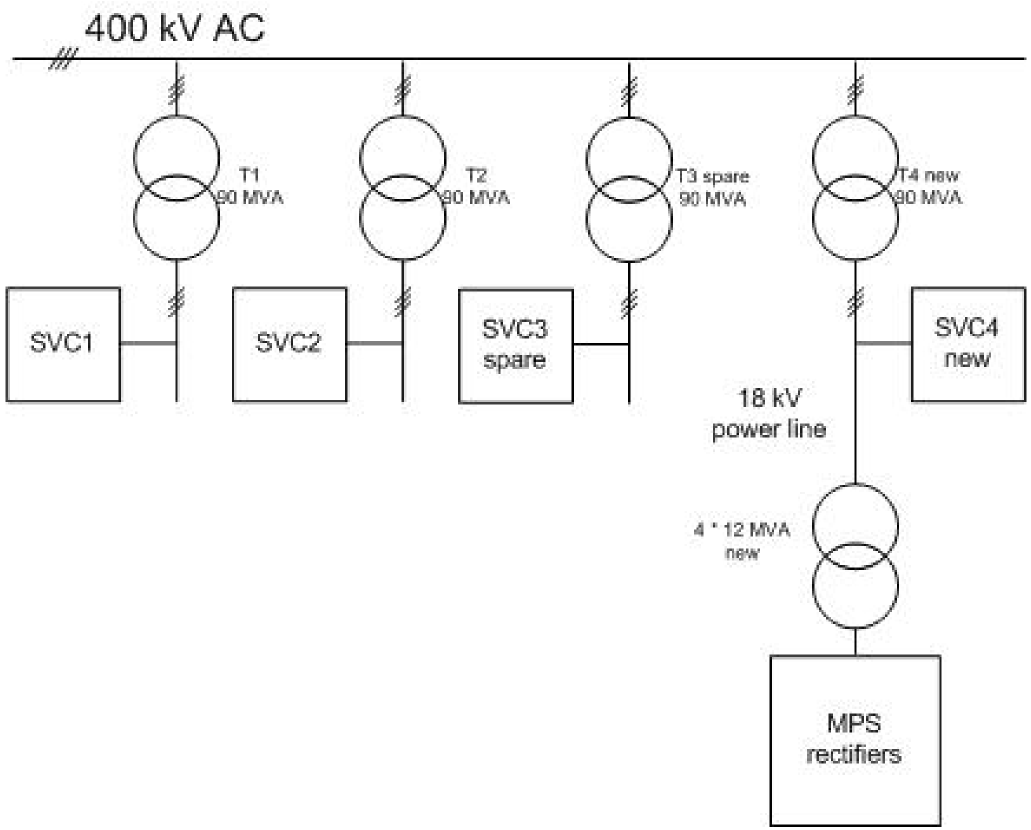
Rotors weight: 80 +10 T

Studies for new power system

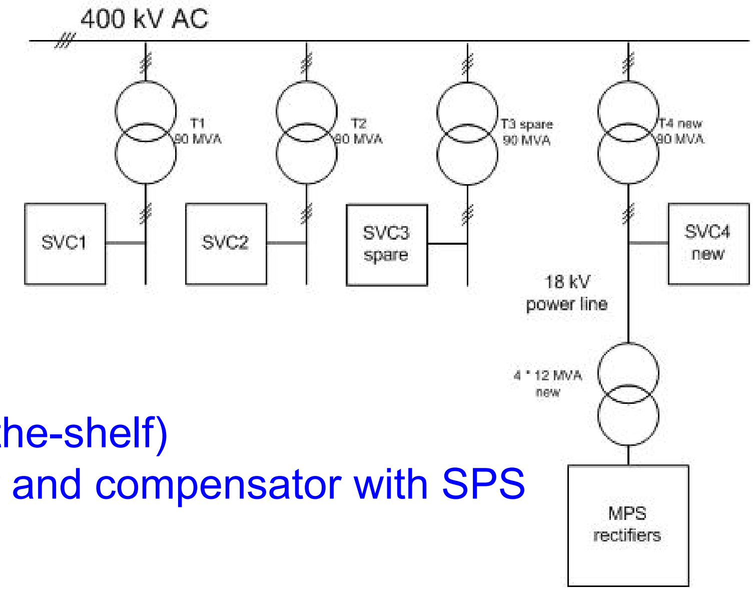
- Network solutions
- Storage system
  - Mechanical storage
  - Inductive storage
  - Capacitive storage
- Guideline
  - Suppress single point of failure
  - Modular approach with redundancy

Direct network connection on 400kV

- Many studies were done to study the connection of the rectifiers to the electrical network.
- The ONLY solution was to:
  - Connect the rectifiers via an 90 MVA transformer on the 400 kV EDF network
  - Install a reactive power compensator of 85 MVAR + 75 MVA of harmonic filters
  - Install an 18 kV power line between Prevessin and Meyrin (4 km)



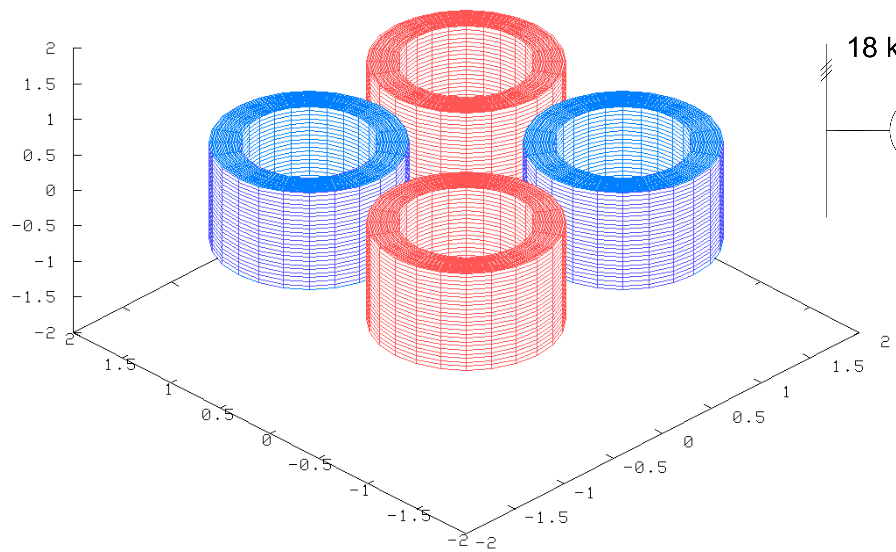
Direct network connection on 400kV

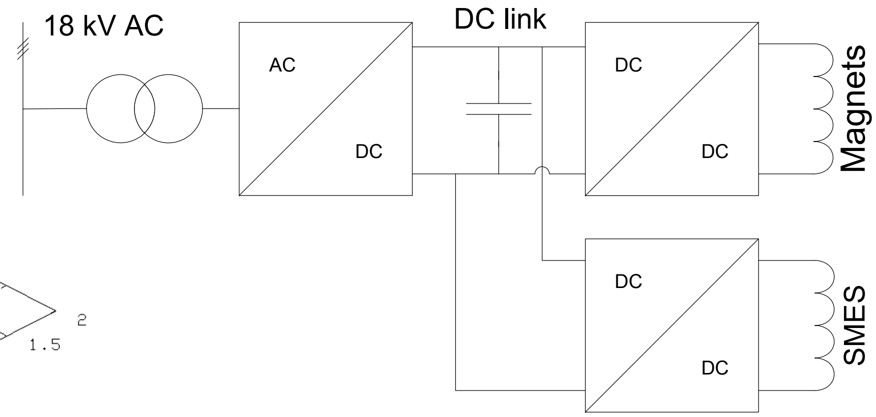


- Advantages
  - Use of “industrial” products (not off-the-shelf)
  - Good strategy for spare transformer and compensator with SPS powering
- Drawbacks
  - Cost
  - Bandwidth response limited due to thyristor technology (2Q converter)
  - **Far to be sure (the limit of this technology) to get a good voltage stability at the load** (10^{-5}; need more studies)
  - More sensitive to storms
  - Active power taken on the 400 kV (+/- 50 MW every 1.2 second)
  - (dedicated distribution)

SMES (Superconducting Magnet Energy storage)

- Use a SMES to store energy and to exchange it with the magnets
- Integration in SVC 18 kV or inside the power converter
- Energy stored must be very high to limit the variation of magnetic field
- 80 MJ to exchange 14 MJ with the magnets
- Study done by ITP Karlsruhe (DE)



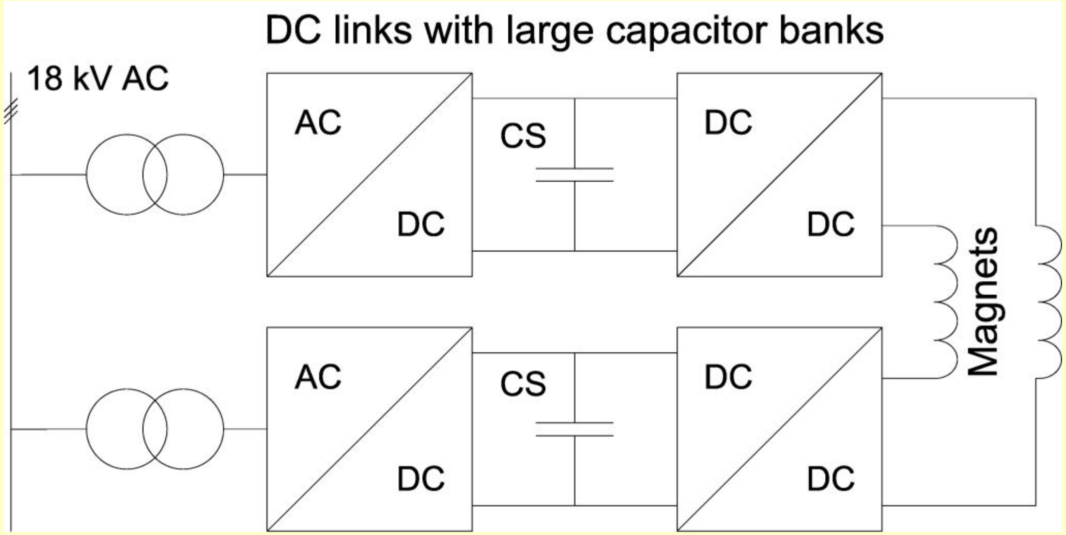


SMES (Superconducting Magnet Energy storage)

- Advantages
  - Compact solution
  - Easy to protect (short-circuit the SMES in case of problem)
  - Modular approach is possible
  - Certainly a very interesting solution in the future (higher energy and technology maturation)

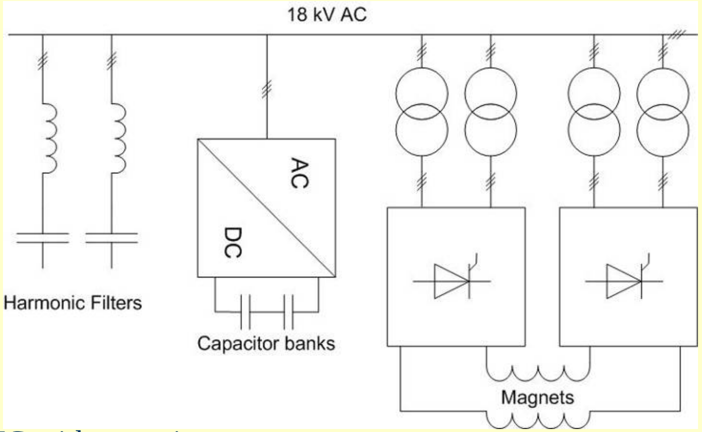
- Drawbacks
  - SMES are under study, no industrial product for this level of energy
  - Stray field
  - SMES are current sources, need two stages of conversion to supply the magnets (I-V and V-I)
  - Cryogenic infrastructure and maintenance (no cryogenic in PS)

capacitive energy storage



First ideas

EL group proposal =>

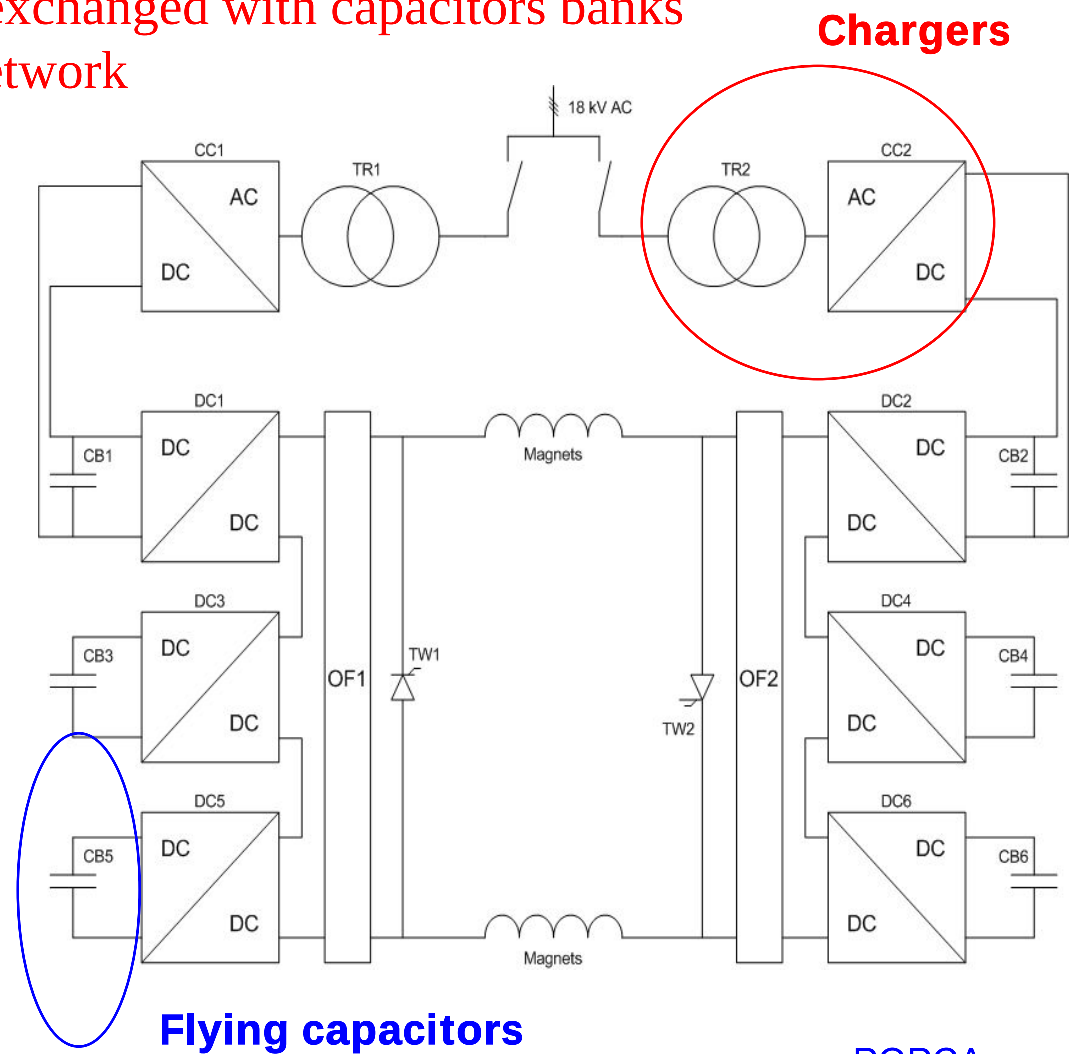


SVC with capacitor energy storage

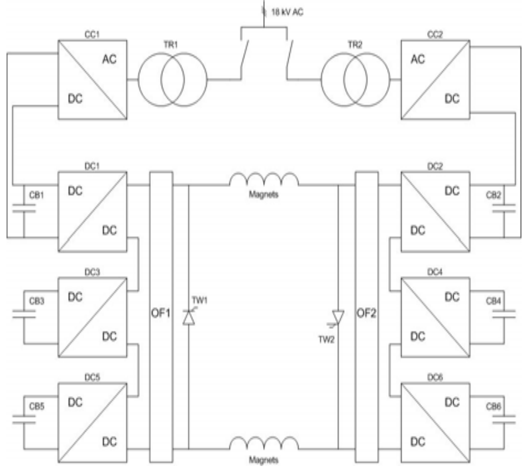
New power system based on capacitive storage

The magnet stored energy is exchanged with capacitors banks
The losses are taken on the network

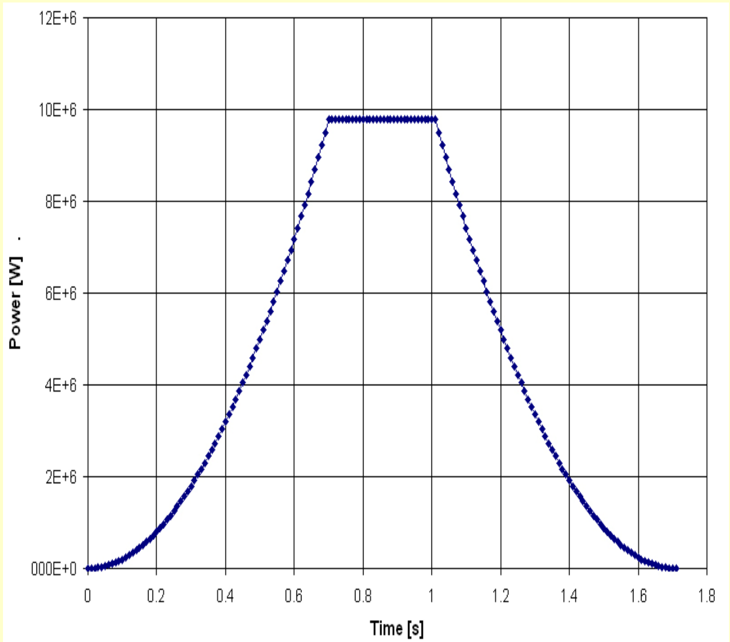
- DC/DC converters transfer the power from the storage capacitors to the magnets.
- Four flying capacitors banks are not connected directly to the mains. They are charged via the magnets.
- Only two AC/DC converters (called chargers) are connected to the mains and supply the losses of the system.



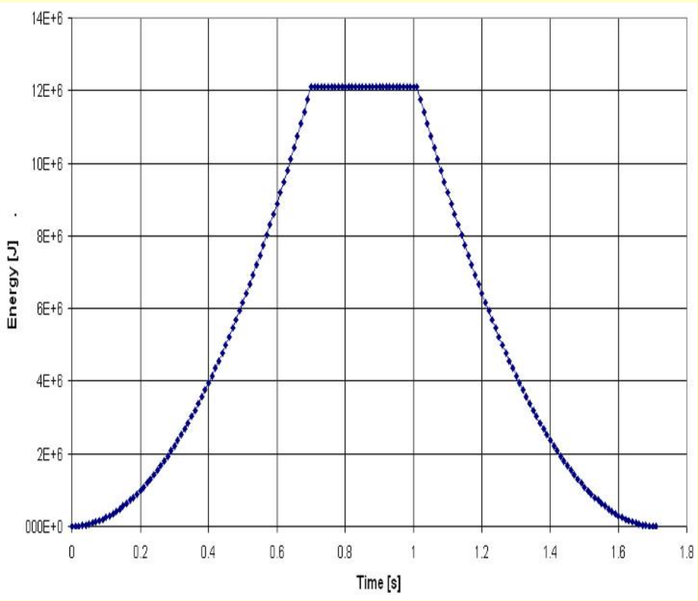
Energy management



The main losses of the system are the magnets losses. During a 26GeV cycle, the peak power of the losses is 10MW. The required energy to cover the losses is supplied by the mains. The power rating of each charger is therefore 5MW. The chargers are regulated in power with a reference that follows the magnets losses.

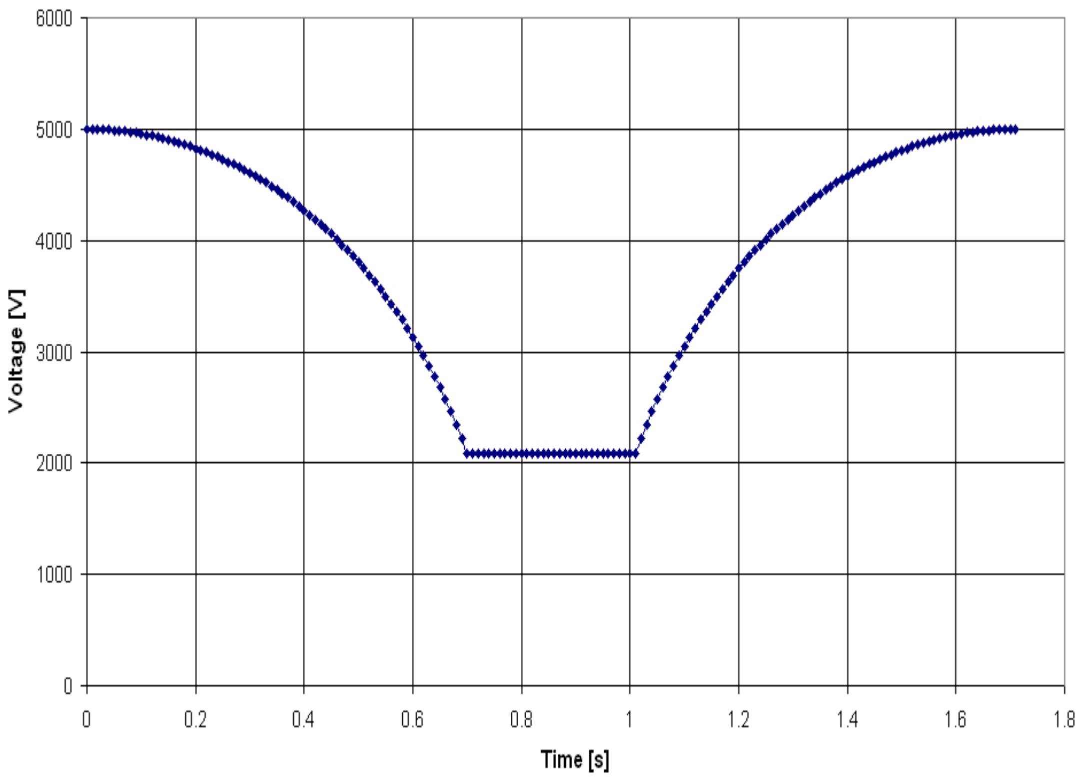


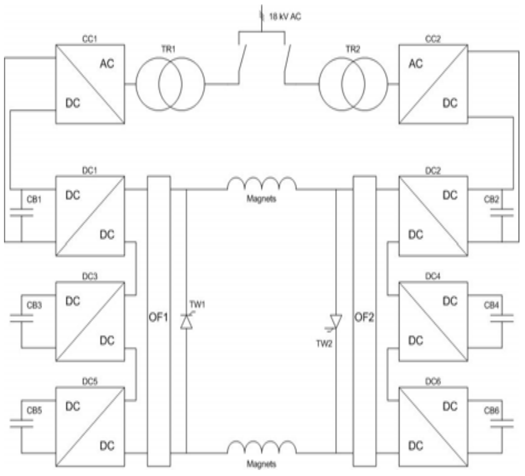
The maximum magnetic energy stored in the magnets is 12MJ for a 26GeV cycle. This energy is supplied by the capacitor banks.



Energy management

When the magnet current rises to 5.5kA, the capacitor bank voltage decreases from 5kV to 2kV. During the ramp down of the current, the capacitor bank voltage returns to 5kV

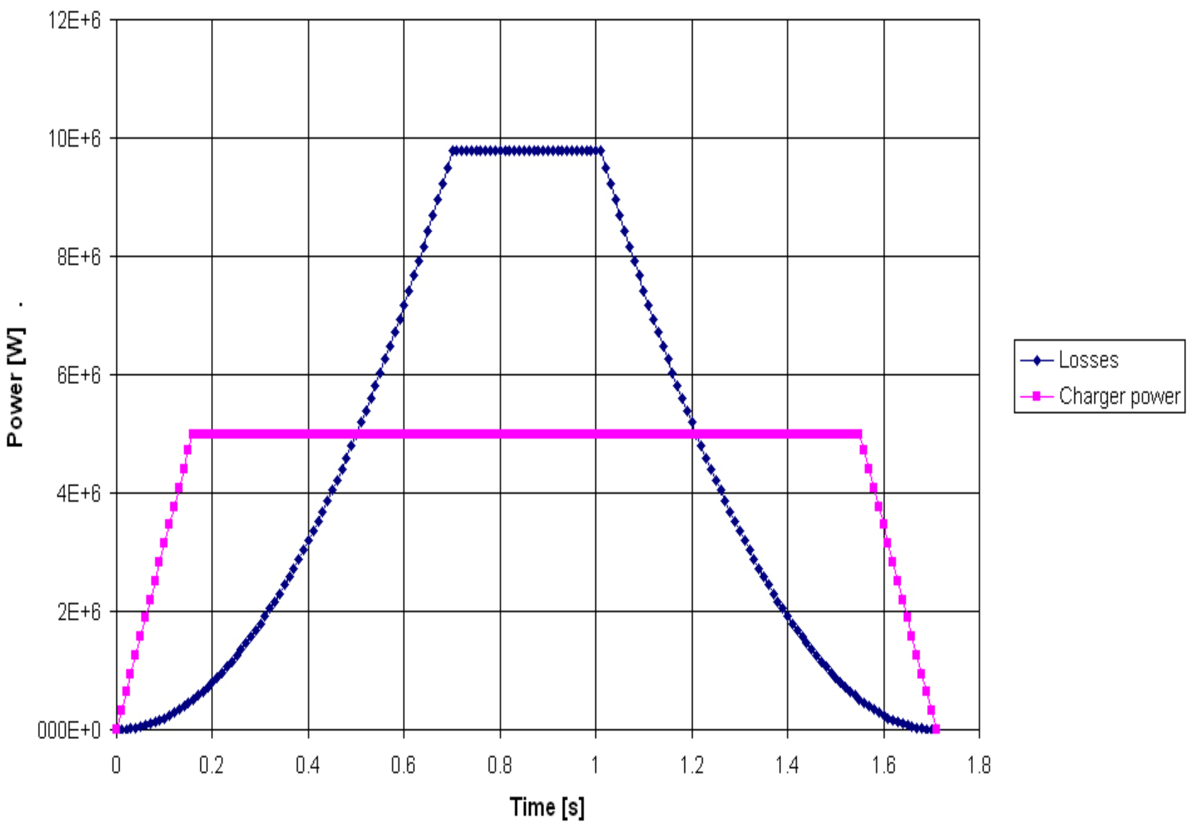


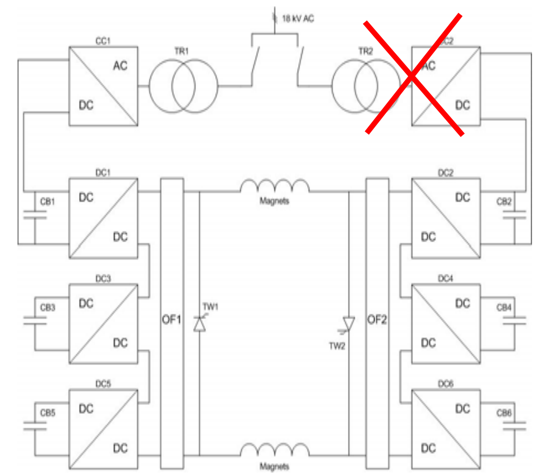


Energy management: redundancy

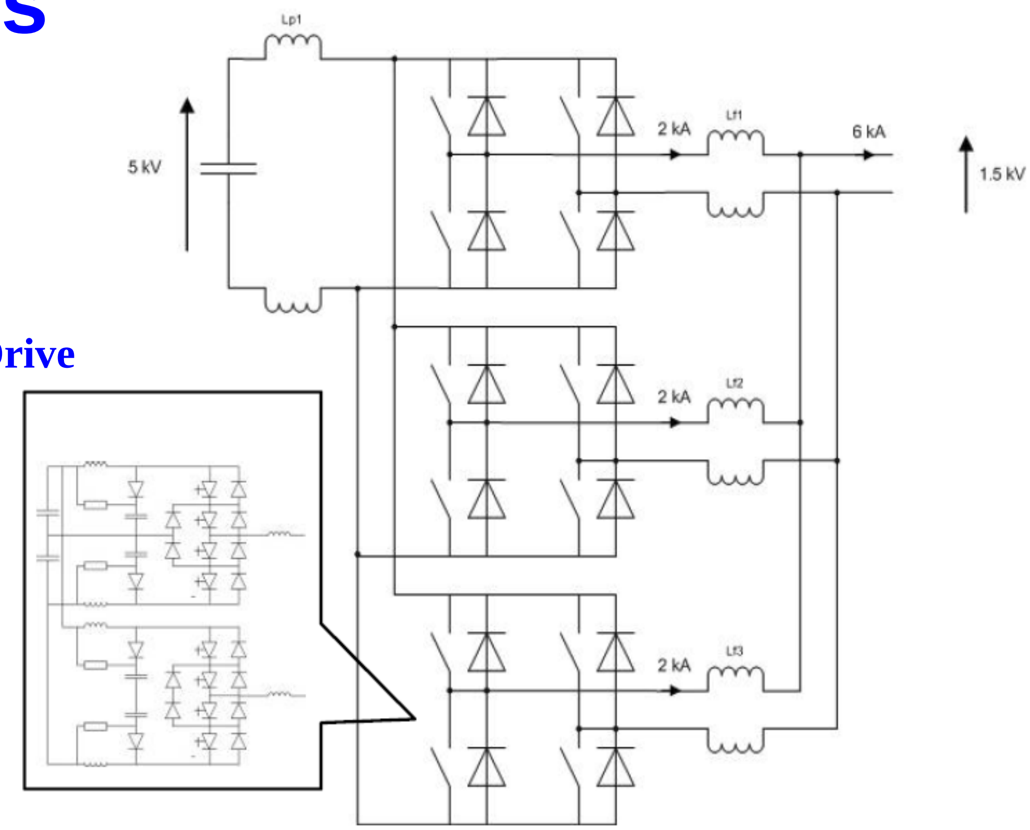
The system is designed with a redundancy policy. If a capacitor bank, a DC/DC converter or a charger is in fault, the power system can still operate with the complete performance.

Operating with only one charger is the worst case as the input power will be limited to 5MW. However, by changing the charging profile, a 26GeV cycle can still be executed.





DC/DC converters



- DC converter ratings: 6kA / 5kV
- Standard industrial products:
  2 kA / 5 kV from Medium Voltage Drive
- Solution:
  Three converters in parallel

By interleaving the firing pulses, the output filter is reduced and the bandwidth of the voltage loop is three times higher than the individual switching frequency

From studies to POPS project

- After an European tour of industry, we thought it was possible to build such a power system
- DG approved the project end of 2006
- Call for tender in 2007
- Contract signature in December 2007
- January 2008: Start of POPS project (POwer for PS)

- Contractor CONVERTEAM (ex Alstom Power Conversion)
  - Main market: Marine, Oil&Gas, industries
  - Turnover: 700M€
  - Employees: 5000

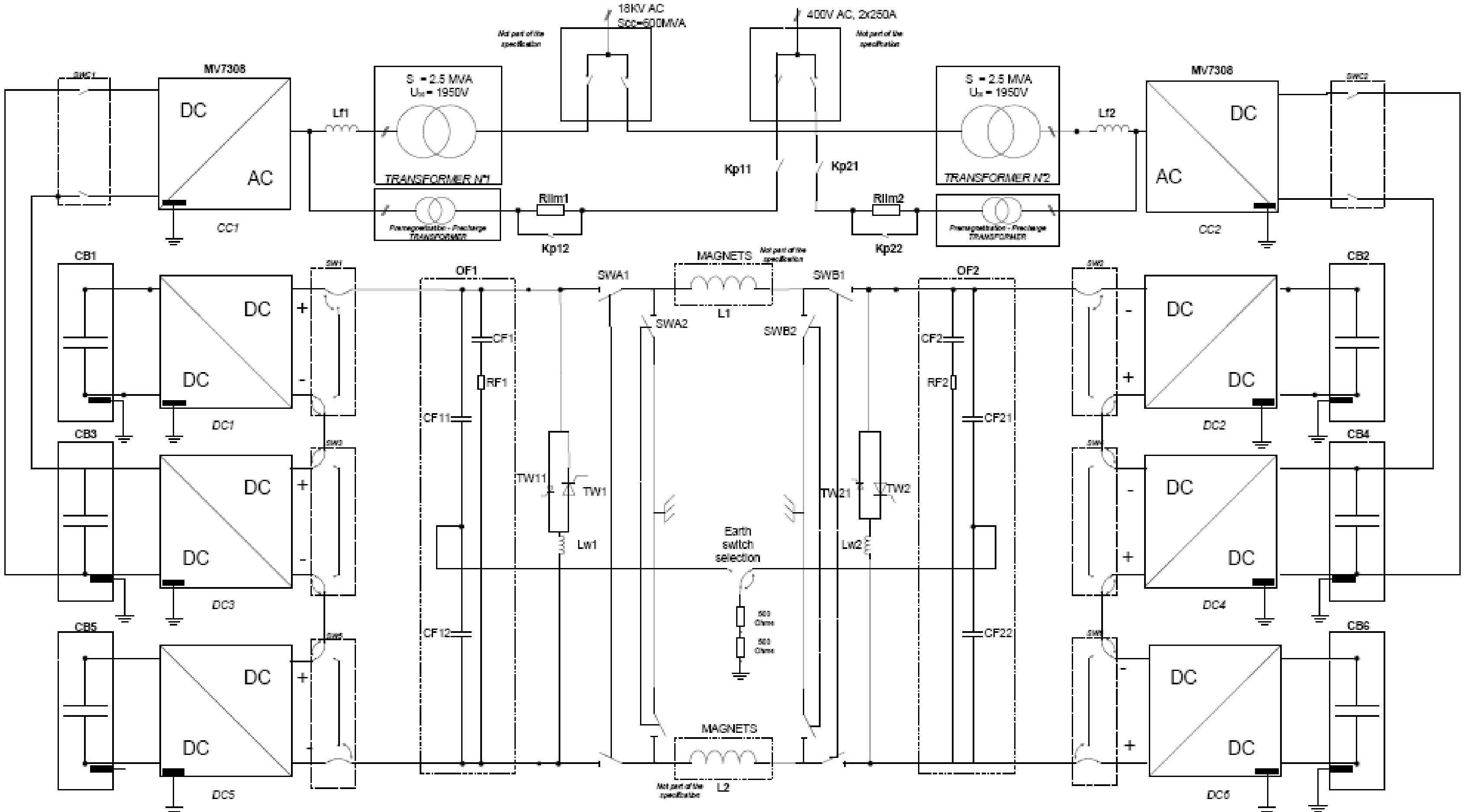
CONVERTEAM
THE POWER CONVERSION COMPANY

POPS status

- schedule
  - June 08: Design report approval
  - October 08: Civil engineering works
  - March 09: First delivery from Converteam
  - June 09: Installation
  - September 09: Start of commissioning
  - November 09: First test with magnets
  - April 2010: POPS in operation

- Budget: 12 M€

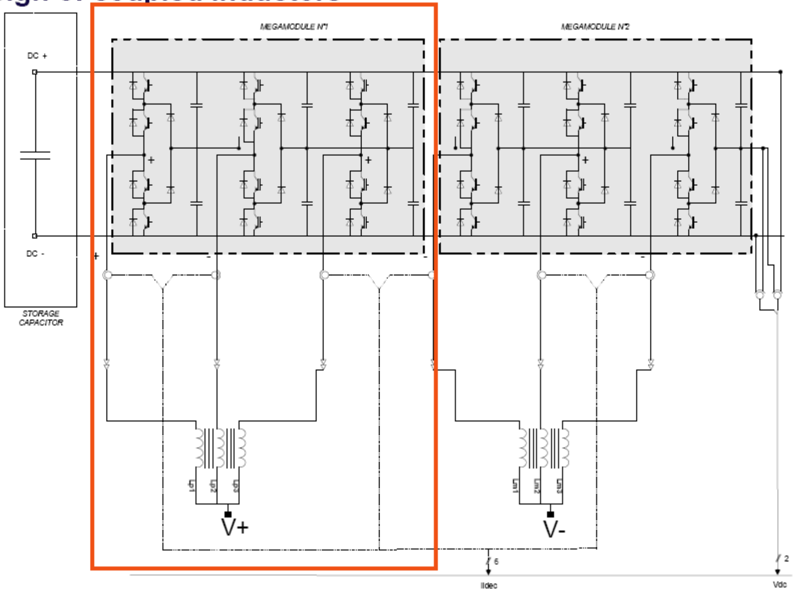
POPS topology

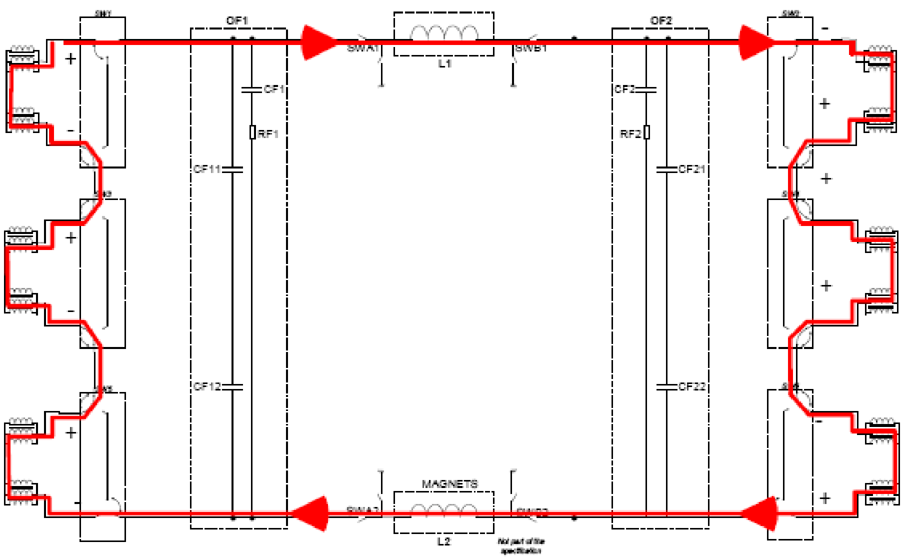


Technologies

- DC converter topology
  - Paralleling H-bridges
  - Output chokes
  - Current loop balance

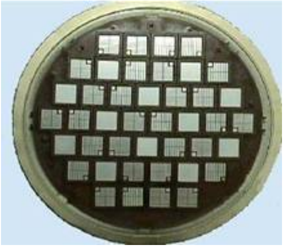
- **Design of coupled inductors**

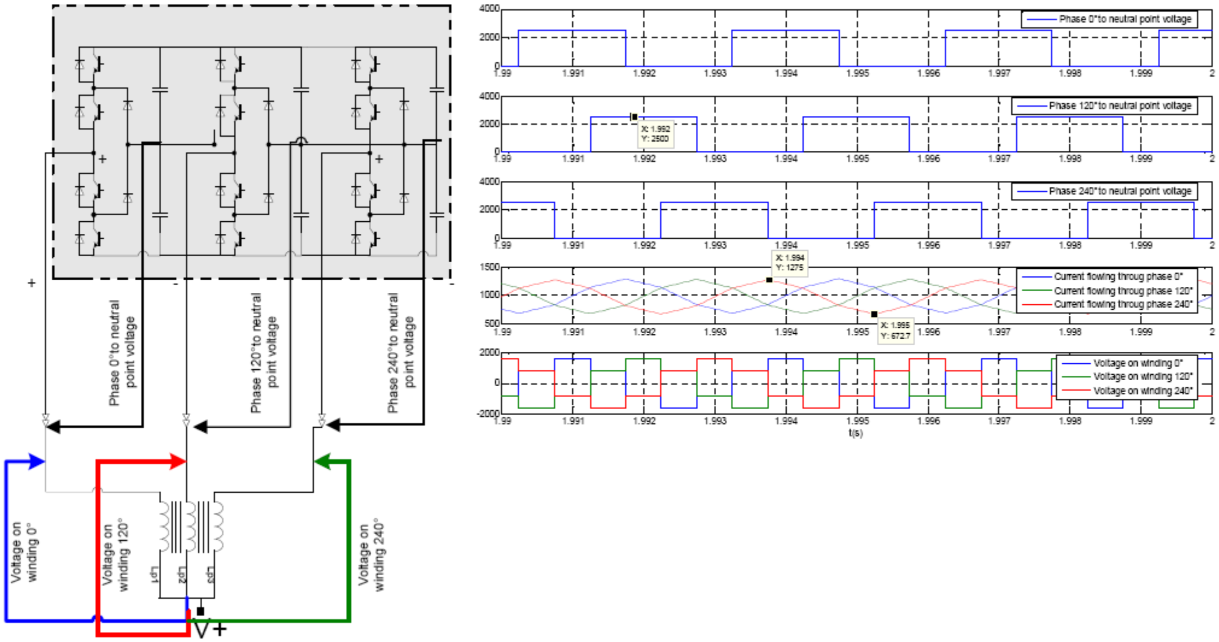




Technologies

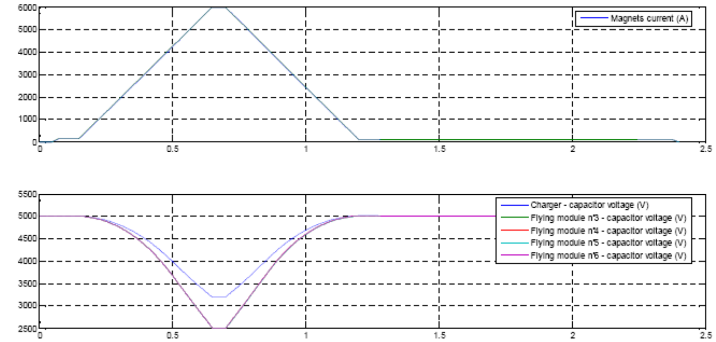
- Medium voltage Drives
  - NPC converter
  - IEGT (Press pack IGBT)
  - Water cooled
  - Coupled choked



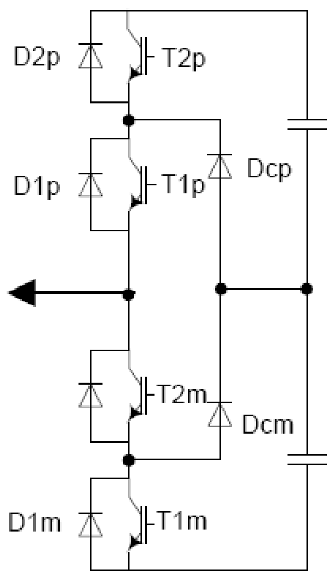


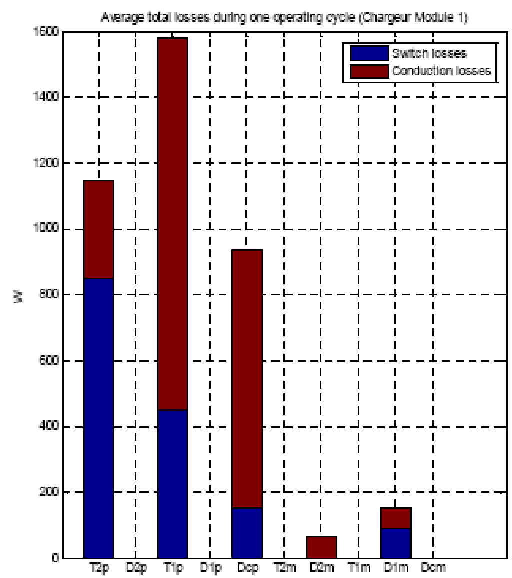
POPCA

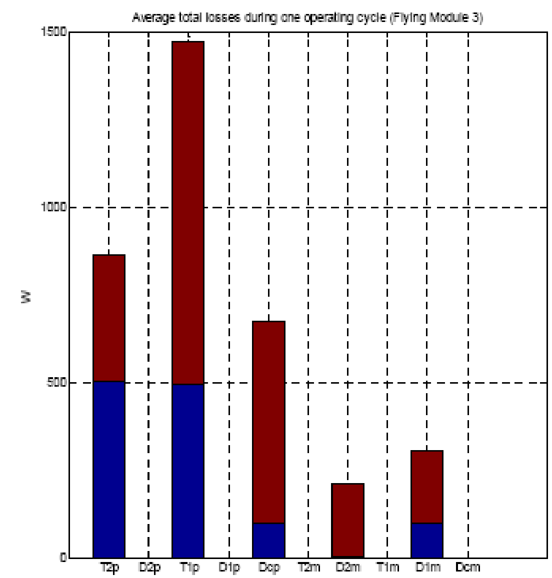
Technologies



- **Thermal design – components lifetime**
  - Use of reference cycle for semiconductor design
  - Switching frequency: 333.33Hz





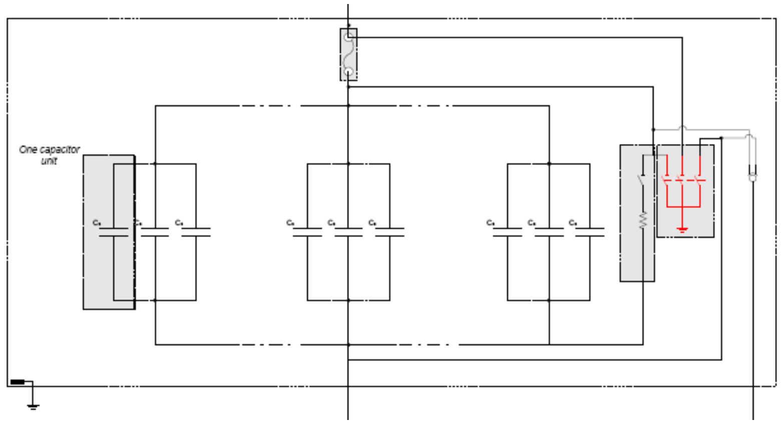


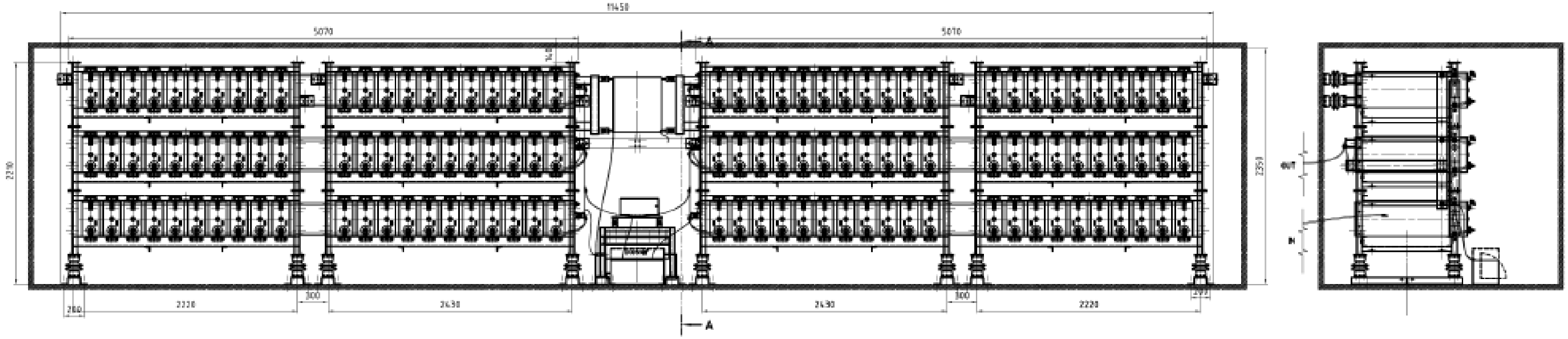
	T2p	D2p	T1p	D1p	Dcp	T2m	D1m	T1m	D2m	Dcm
ΔT_j charger module	22.26	0	25.52	0	33.6	0	7.22	0	3.27	0.1
ΔT_j flying module	21	0	22.36	0	26.66	0	13.8	0	10	0.3

Table 1: Junction temperature variation

Technologies

- Capacitor banks
  - 5kV Dry capacitors
  - Polypropylene metalized self healing
  - Outdoor containers: 2.5m x 12m, 24 tons
  - 0.247F per bank, 126 cans
  - 1 DC fuse
  - 1 earthing switch



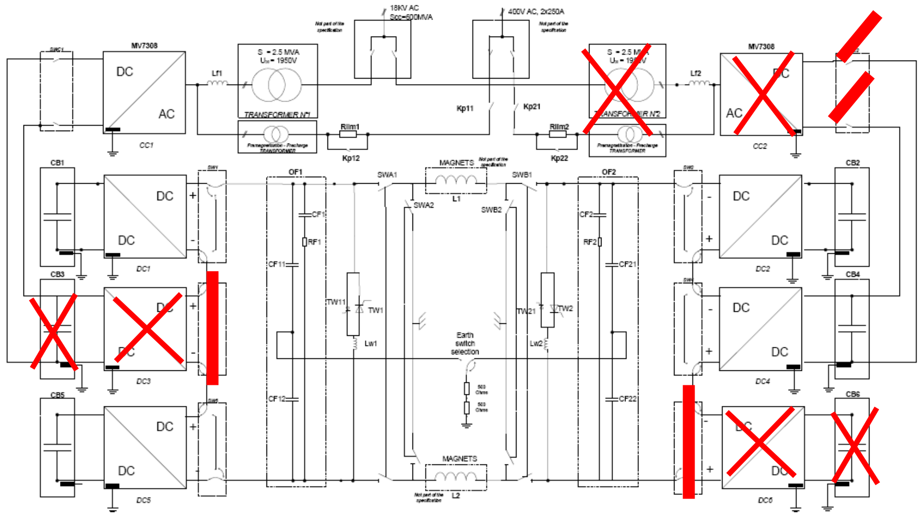


Technologies

- Redundancy
  - Can work without one capacitor bank
  - Can work without one charger
  - Can work without one DC converter

Performances

			Criterion
Normal operating mode	Ernergy stored	13.7 MJ	> 13.5 MJ
	Voltage available at the end of the shot	15618 V	> 10000 V
Considering inductive voltage drop	Voltage available at the end of the shot	14994 V	> 10000 V
Degraded operating mode	Ernergy stored	12.928 MJ	> 12 MJ
One charger module is failed	Voltage available at the end of the shot	10549 V	> 9800 V
Considering inductive voltage drop	Voltage available at the end of the shot	10127 V	> 9800 V
Degraded operating mode	Ernergy stored	12.38 MJ	> 12 MJ
One flying module is failed	Voltage available at the end of the shot	10999 V	> 10000 V
Considering inductive voltage drop	Voltage available at the end of the shot	10559 V	> 10000 V



Technologies

- Output filters
  - Normal operating mode: output voltage ripple <4Vrms
  - Degraded operating mode: <8.5Vrms (24Vpp)
  - Damping factor of the LC filter: $\xi>1$
  - Minimum voltage loop bandwidth (-3dB): 180Hz
  - Output voltage response from 0 to 10kV: 10ms
- Interleaving pulses strategy
  - Equivalent output frequency of one DC/DC converter: 2 kHz
  - Charger modules are interleaved: → Equivalent output frequency = 4 kHz
  - Flying modules are interleaved: →Equivalent output frequency = 8 kHz

Bode diagram : normal mode

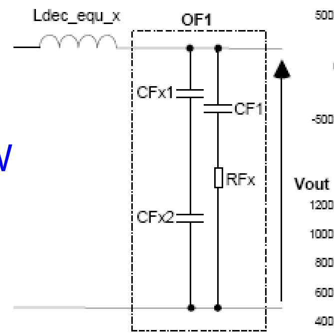
- -37dB at 2000Hz
- -49dB at 4000Hz
- -61dB at 8000Hz

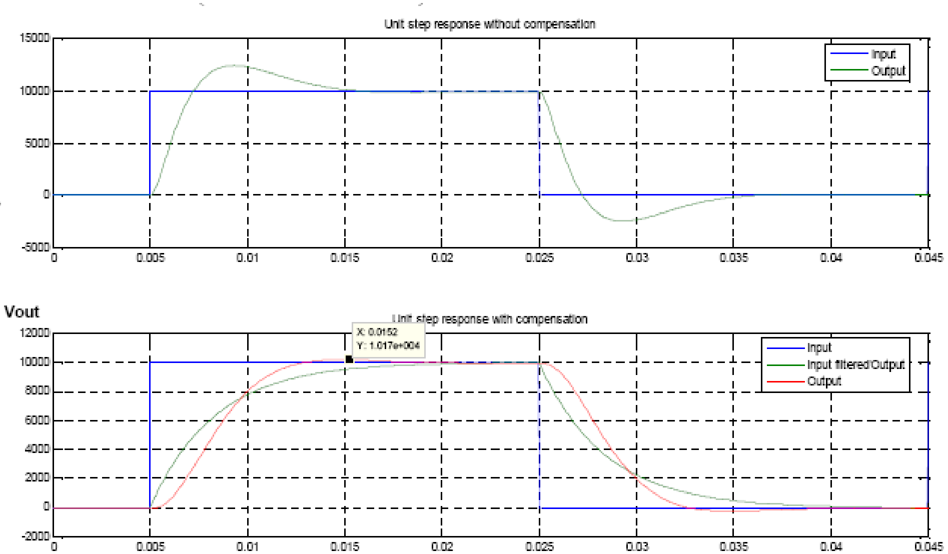
Bode diagram : degraded mode

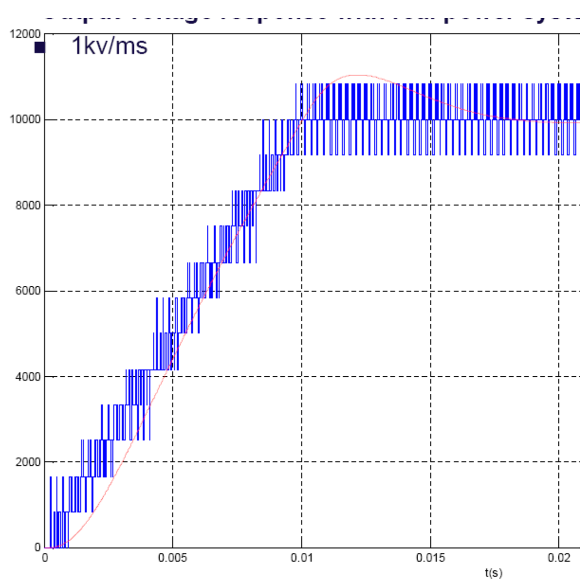
- -33.5dB at 2000Hz
- -57.5dB at 8000Hz

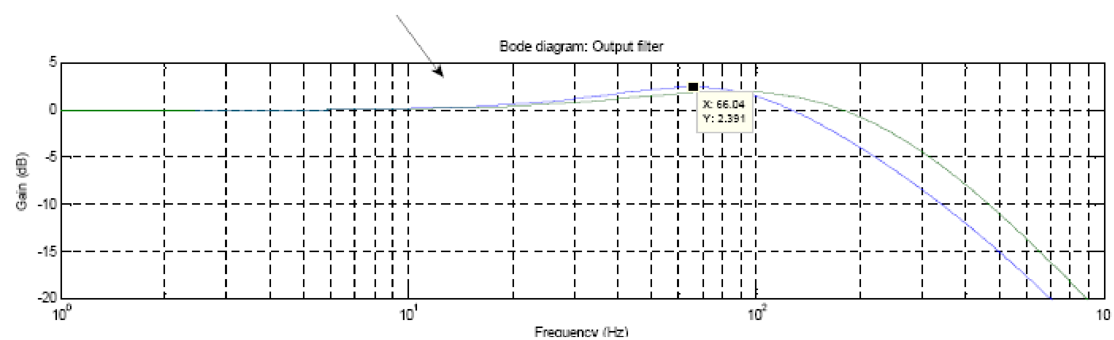
Technologies

- Output filters
  - Leq = 3mH
  - CFx1 & 2 = 0.29mF
  - CFx = 1.5mF
  - Rfx = 2.24 Ω / 10kW









Technologies

- **Total losses**

Losses in water

		Quantity	Losses	Total losses
AC/DC converter		2		
	IGBT Stack	3	6.5 KW	19.5 KW
	RCdamp	1	4.335 KW	4.335 KW
	DC capacitor	1	2.767 KW	2.767 KW
	Network reactor	1	16 KW	16 KW
	Self crowbar	0	8.4 KW	0 KW
	Rfilter damping	1	23 KW	23 KW
	Thyristor Crowbar	0	2.5 KW	0 KW
	Total			65.602 KW
Conv DC/DC - flying module		6		
	IGBT Stack (worst case)	6	6.3 KW	37.8 KW
	DC capacitor	1	2.66 KW	2.66 KW
	RCdamp	1	1.47 KW	1.47 KW
	Ldec	2	15 KW	30 KW
	Total			71.93 KW

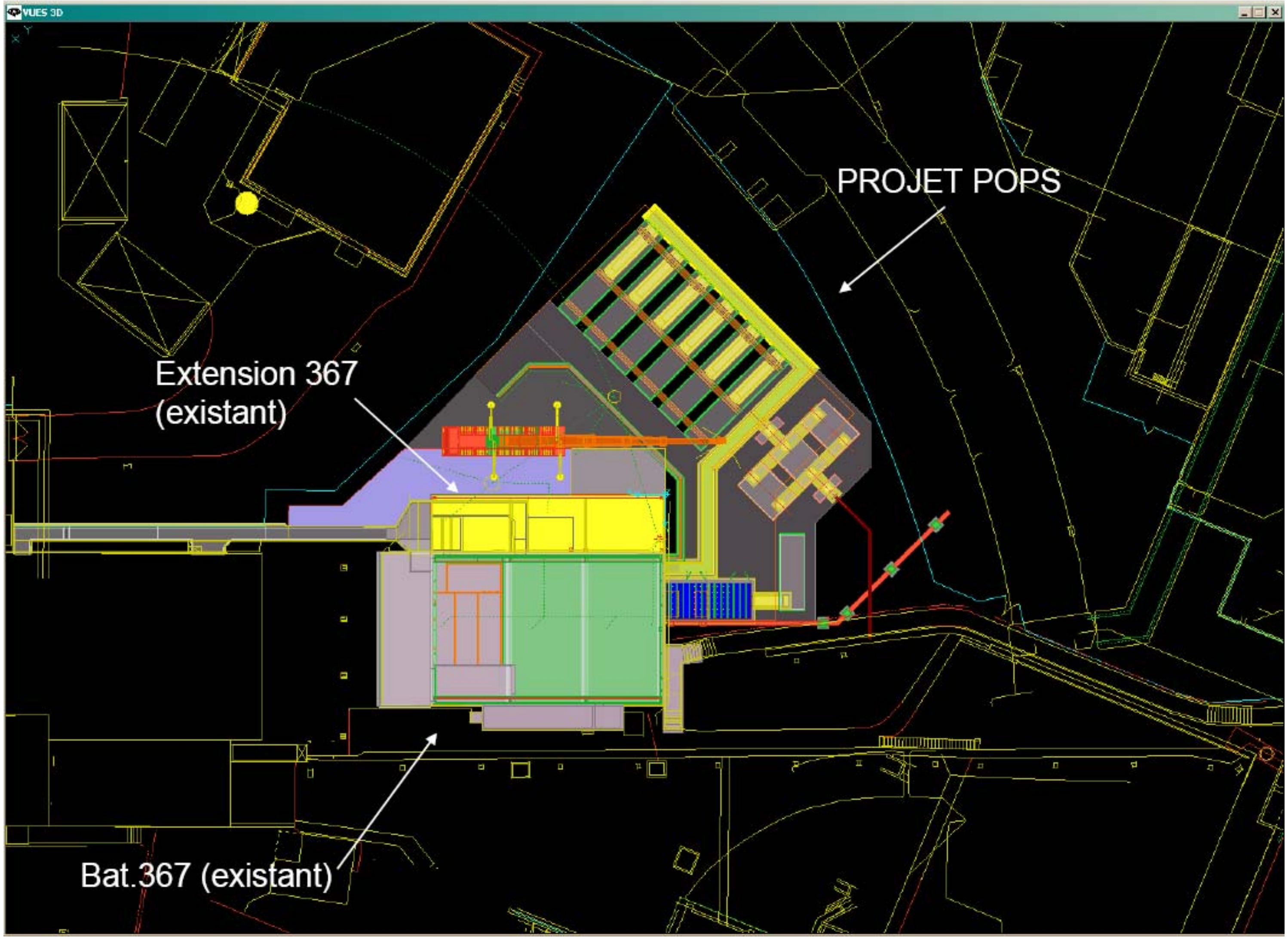
Total	563 KW
Total +10%	619 KW

Losses in air

		Quantity	Losses	Total losses
AC/DC converter		2		
	Global	1	11 KW	11 KW
	Total			11 KW
Conv DC/DC - flying module		6		
	Global	1	14.3 KW	14.3 KW
	Ldec	2	5 KW	10 KW
	Total			24.3 KW

Total	168 KW

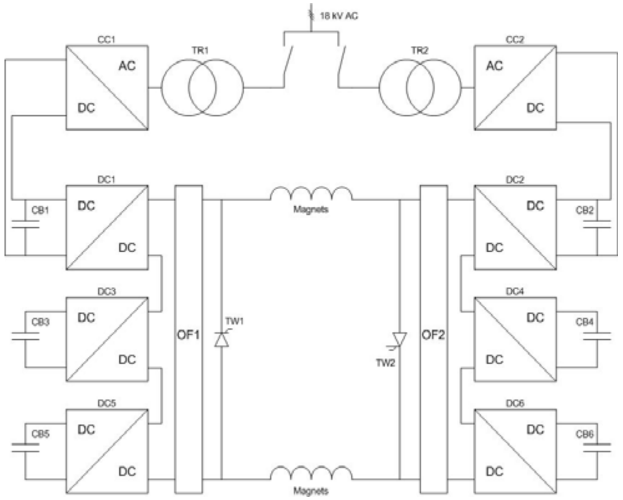
POPS layout


VUES 3D
PROJET POPS
Extension 367
(existant)
Bat.367 (existant)

POPS layout

POPS – Etat de la maquette au 5 Mai 2008

Conclusions



- The main advantages of this solution are:
    - the integration of the storage elements in the power converter topology
    - the modularity of the system with redundancy
    - the use of standard products from the medium voltage drive market

- This innovative solution has a real interest for physics laboratories and for all applications requiring rapid exchange of active power

- POPS is planned for operation in 2010

- The main difficulty was to convince industry to follow us

Patent

The global system with dedicated control has been filed as a patent application. European Patent Office, Appl. Nr: 06012385.8

Thank you for your attention