Superconducting Magnetic Energy Storage
Concepts and applications

Antonio Morandi
DEI – Guglielmo Marconi
Dep. of Electrical, Electronic and
Information Engineering
University of Bologna, Italy

Short course on Superconducting Power Applications
Sunday 17 Sep 2017
CERN - Geneva

13th European Conference on Applied Superconductivity
Monday, September 18, 2017, Geneva - Switzerland

Outline

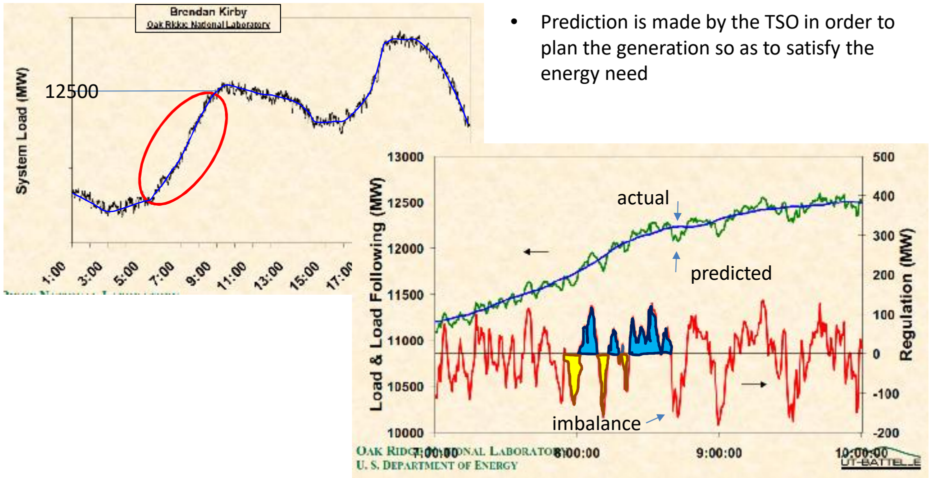
- Energy storage
- SMES technology
    - SC magnet
    - Power conditioning system
- State of the art
- Applications
    - Grid
    - Customer / Industry

The need for electric energy storage / chapter 1 - grid

- Generation / load imbalance is inherent in the power grid due to
  - **random fluctuation of loads induced by customers**
  - **variation of generation from renewables**
- Sudden and large generation/load imbalance can also occur due to contingency

- Continuous and fast regulation of the generated power and/or loads is required for controlling the frequency and stability of the grid.

Load diagram

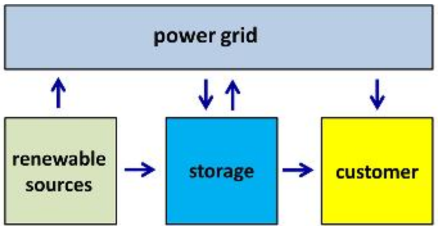


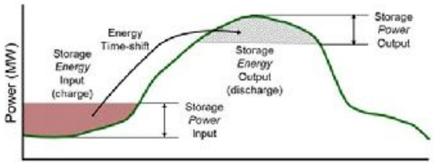
- Prediction is made by the TSO in order to plan the generation so as to satisfy the energy need

Due to random nature of fluctuations regulating power is cyclic
ì Regulation is a zero energy service

Methods/technologies for grid energy management

- **Curtailment of renewables**
- Improved control of convent. gen.
- Demand control
- Network upgrade (… Supergrid)
- **Energy storage**





Energy storage system allows to shift electric energy in time so as to decouple production and consumption

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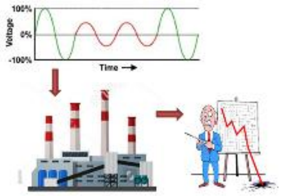
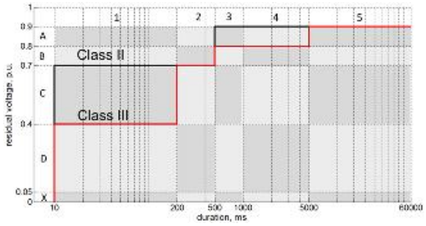
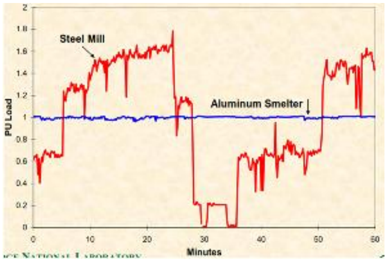
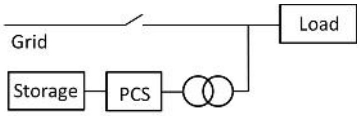
The need for electric energy storage / chapter 2 – customer





Sensitive customers (semiconductors, oil, data centers …) cannot tolerate power interruptions or voltage sags





Energy storage

- Power quality and UPS
- Leveling of impulsive/fluctuating power (industry, physics, …)

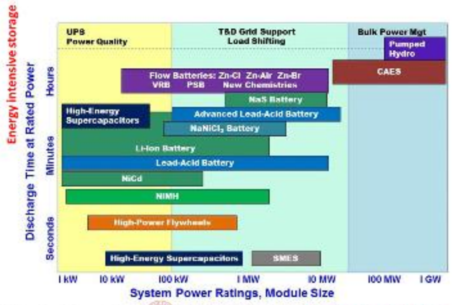
Which storage technology?

Parameters of the energy storage system

- Absorbed/supplied power, *P*
- Duration delivery, Δt
- Number of cycles, *N*
- Response time, t_r

In many applications the parameters of the operating cycle changes continuously and randomly.

No unique storage technology exists able to span the wide range of characteristics required for applications



- Most suitable storage technology must be chosen from case to case
- Hybrid systems, obtained by combining different storage technologies, represents the best solution in many cases

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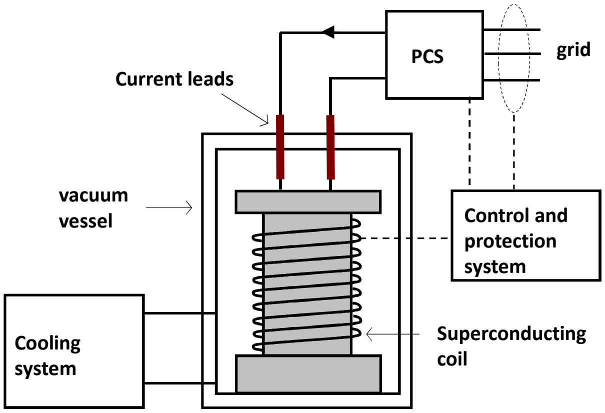
SMES – Superconducting Magnetic Energy Storage



$$W = \int_{2_{\infty}} \frac{B^2}{2«_0}\, d² \approx \int_{2_{coil}} \frac{B^2}{2«_0}\, d² = \frac{1}{2} L I^2$$

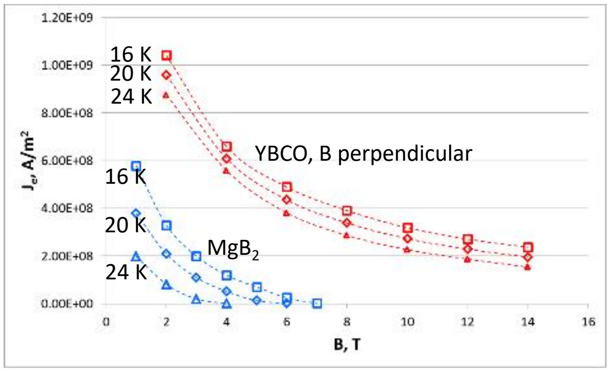
Advantages

- High deliverable power
- Infinite number of charge discharge cycles
- High efficiency of the charge and discharge phase (round trip)
- Fast response time from stand-by to full power
- No safety hazard

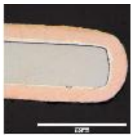
Critical aspects

- Low storage capacity
- Need for high auxiliary power (cooling)
- Idling losses

Conductor and cable



YBCO



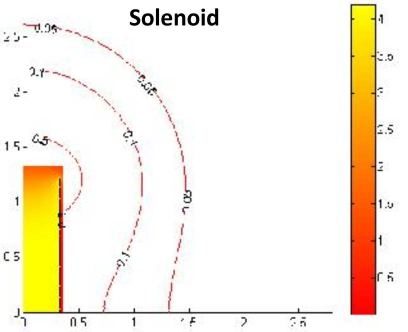
MgB$_2$

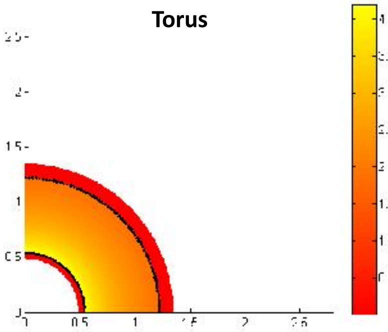
Main characteristics of a typical MgB$_2$ Conductor	
Manufacturer	Columbus
Nominal radius	1.13 mm
Number of filaments	36
Filling factor	0.14
Matrix	Ni 70%, Copper 20 %
Critical tensile strength	300 MPa
Critical current, 22 K, self field	550 A

Main charact. of a typical YBCO Coated Conductor	
Manufacturer	Superpower
Nominal Width	12 mm
Nominal thickness	0.1 mm
YBCO	1 μm
Stabilizer, copper	2×20 μm
Substrate, Hastelloy	100 μm
Critical tensile strength	550 MPa
Critical current, 77 K, self field	330 A

Layout of the winding – Arrangement of multiple pancake

5 MJ coil - 4T


Solenoid


Torus

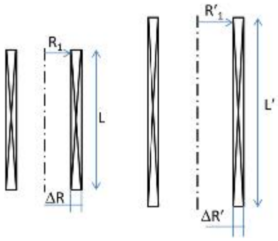
- Simpler and more cost effective
- Easier handling of the electromagnetic stress
- Smaller foot-print

- Low stray field
- Reduced component of magnetic field perpendicular to the conductor

Coil design – electromagnetics / mechanics

Scale law - Electromagnetics

$$V_{SC} = \mathrm{k}\, E^{\frac{2}{3}}$$



R′₁ = p R₁

L′= p L

Δ R′₁ = Δ R₁

H = J$_e$ Δ R₁

H = J$_e$ Δ R′₁

$$E' = \frac{H^2}{2\mu_0}\pi R_1'^2 L' = p^3 E$$

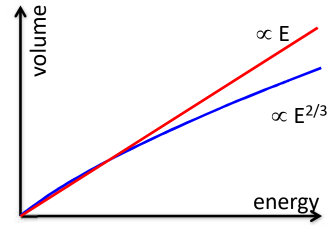
$$V_{SC}' = \pi\left((R'_1+\Delta R')^2 - R_1'^2\right)L' \approx p^2 V_{SC}$$

Scale law – Mechanics
(Virial’s theorem limit)

$$V \geq k\frac{1}{\pm}E$$

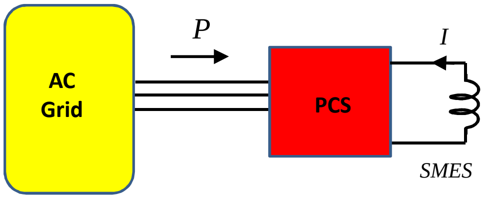
V, volume of structural material [m^3]
E, total energy of the coil [J]
σ, allowable stress [N/m^2]
k, numerical coefficient (≥ 1)

- At high energy the structural constraint is stricter than the electromagnetic one
- Additional structural (and stabilizing) material is required



For solenoid k ranges from 1 if D/L tends to zero to 3 if D/L tends to infinite.

PCS – the magic box

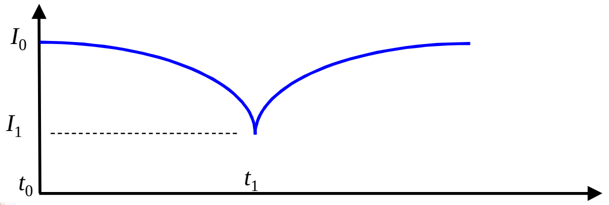


I_0, current of SMES at time t_0

I_1, current of SMES at time t_1

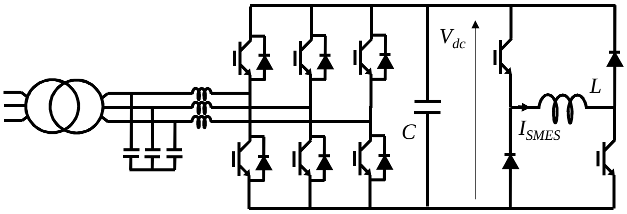
$$\frac{1}{2}L\,I^2 - \frac{1}{2}LI_0^2 = -P(t-t_0) \qquad I = \sqrt{I_0^2 - \frac{2}{L}P(t-t_0)}$$ During discharge

$$\frac{1}{2}L\,I^2 - \frac{1}{2}L\,I_1^2 = P(t-t_1) \qquad I = \sqrt{I_1^2 + \frac{2}{L}P(t-t_1)}$$ During charge



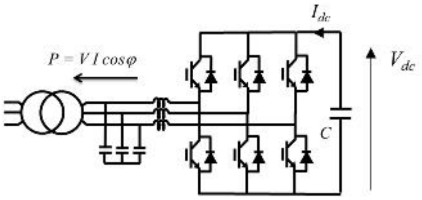
PCS - Power Conditioning System

Voltage source converter (VSC)



- **A controlled power is transferred from the DC bus to the grid by means of the inverter**

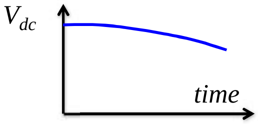
- **The voltage of the DC bus is kept constant by the SMES by means of the two quadrant chopper**



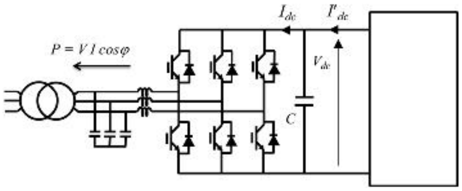
The inverter regulates the power transfer between the grid and the capacitor

An average positive current is established on the DC bus during power transfer to grid

The voltage of DC bus decreases if the capacitor is not recharged



A further circuit must be added able to maintain the voltage of the capacitor constant



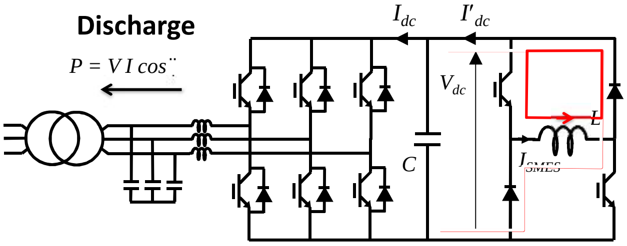
$\langle I'_{dc} \rangle = \langle I_{dc} \rangle \longrightarrow V_{dc}$ ù *constant*

$V_{dc} \langle I'_{dc} \rangle = V_{dc} \langle I_{dc} \rangle$
$\longrightarrow P' = P$

A steady power transfer is established from the circuit to the grid

Chopper control of the DC bus voltage – SMES energy injection / extraction

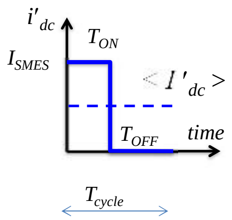
Discharge



$< I'_{dc} > = < I_{dc} >$

$\Downarrow$

V_{dc} ù *constant*



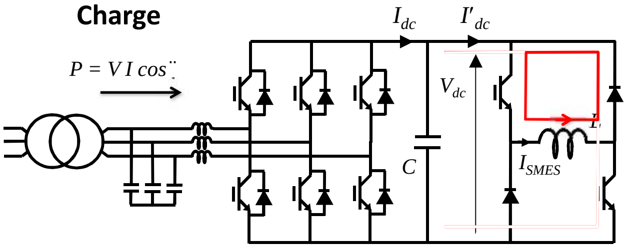
The current of the SMES decreases during the ON phase

If average power P is delivered to the grid during the interval ∆t final current of the SMES is

$$\frac{1}{2} L I_2^2 - \frac{1}{2} L I_1^2 = P \Delta t$$

I_2, current of he SMES at the end of the delivery
I_1, current of he SMES at the start of the delivery

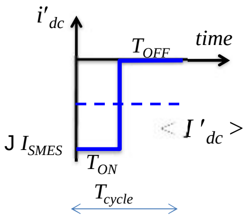
Charge



$< I'_{dc} > = < I_{dc} >$

$\Downarrow$

V_{dc} ù *constant*



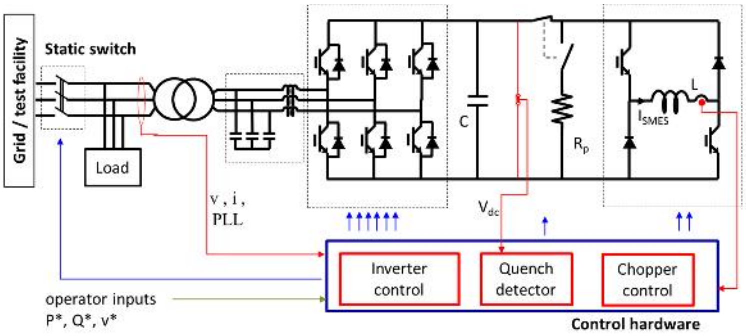
The current of the SMES increase during the ON phase

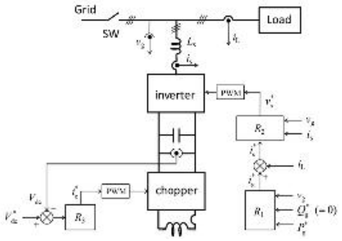
If the power P is absorbed from the grid during the interval ∆t final current of the SMES is

$$\frac{1}{2} L I_2^2 - \frac{1}{2} L I_1^2 = P \Delta t$$

I_2, current of he SMES at the end of the delivery
I_1, current of he SMES at the start of the delivery

Control system and algorithms

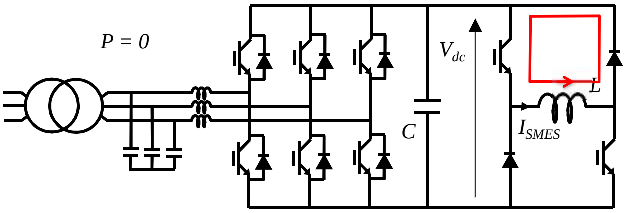




- **Control algorithm is defined based on the service to be provided**
    - Power modulation, active filter
    - Islanding operation
- **Magnet protection system integrated in the PCS both at hardware and the software level**

Idling Loss

Current of SMES free-wheels through PE switches even if no power is delivered/absorbed



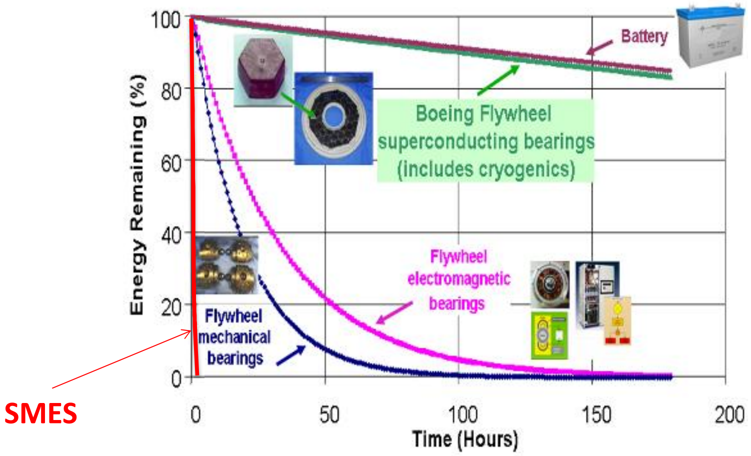
$V_{on\ IGBT} = 0.5 – 1\ \text{V}$
$V_{on\ DIODE} = 0.5 – 1\ \text{V}$

Losses are produced during the idling phase

$$P_{IGBT} = I_{SMES} V_{on\ IGBT}$$
$$P_{DIODE} = I_{SMES} V_{on\ DIODE}$$

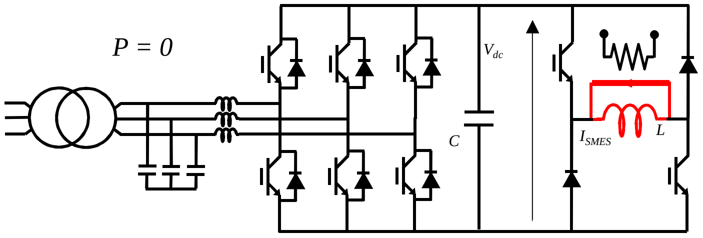
$$P_{idling} = 1 – 10\ \text{kW / kA}$$

- **Time constants of RL circuit of typical SMES (1-5 MJ) during the standby phases are in the order of hundreds of seconds, at most**



- **The whole energy of the SMES is lost in the power electronics within a few minutes**
- **Continuous recharge/compensation is needed**

The use of a thermal actuated SC switch for avoiding the losses during the standby is possible in principle but it is unfeasible in practice since it lowers the response time of the SMES



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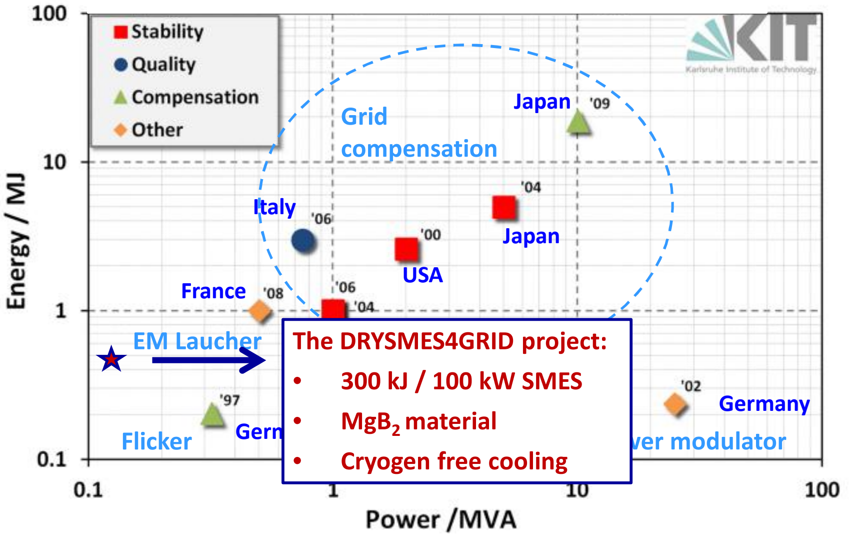
The state of the art of SMES technology



The DRYSMES4GRID project:

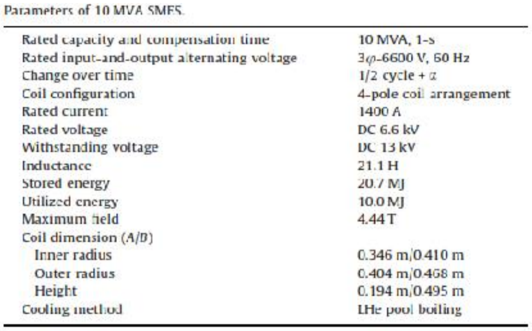
- **300 kJ / 100 kW SMES**
- **MgB_2 material**
- **Cryogen free cooling**

The Kameyama SMES

10 MW – 1 s SMES system

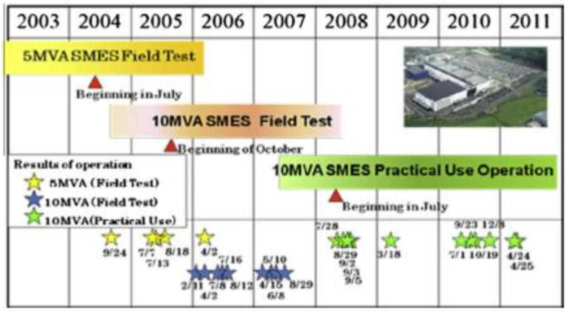
CHUBU Electric Power

SHARP



Parameters of 10 MVA SMES.

Rated capacity and compensation time	10 MVA, 1-s
Rated input-and-output alternating voltage	3φ-6600 V, 60 Hz
Change over time	1/2 cycle + α
Coil configuration	4-pole coil arrangement
Rated current	1400 A
Rated voltage	DC 6.6 kV
Withstanding voltage	DC 13 kV
Inductance	21.1 H
Stored energy	20.7 MJ
Utilized energy	10.0 MJ
Maximum field	4.44 T
Coil dimension (A/B)	
Inner radius	0.346 m/0.410 m
Outer radius	0.404 m/0.468 m
Height	0.194 m/0.495 m
Cooling method	LHe pool boiling



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1 MWh = 3600 MJ

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1 MW ò 6h NAS module

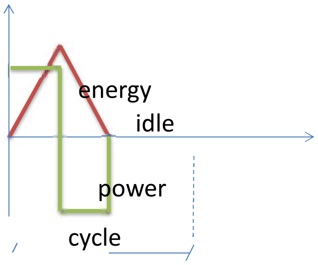
1 MW ò 10 s SMES

6 MWh
NAS system

6 MWh SMES
system

Efficiency of an Energy Storage System

P, deliverable power
Δt , duration of delivery
$\Delta\ t_{cycle}$, duration of the cycle
$\Delta\ t_{idle}$, duration of idling phase
¦$_s$, intrinsic efficiency of the storage device
¦$_c$, efficiency of the converters
P_{aux} , power required for auxiliary services
P_{idle} , power loss (if any) during idling



$$\text{¦} = \frac{P\,\Delta t}{\dfrac{P\,\Delta t}{\text{¦}_s\,\text{¦}_c} + P_{idle}\,\Delta t_{idle} + P_{aux}\,\Delta t_{cycle}}$$

By summarizing …

- **Energy capacity of SMES is much smaller compared to batteries**
- **Idling losses in power converters do not allow long term storage**
- **Cooling power continuously required**

Is the SMES useless and hopeless?

1. Power intensive systems

Example: battery system made of 1 MW × 1 h module, 1M€ cost each

Cost of battery scales with power and is roughly independent on the energy

Cost of SMES scales with energy and is roughly independent on the power

Case 1

Rated power	30 MW
Duration of delivery	1 h
Rated energy	30 MWh
Num. of modules	30

Case 2

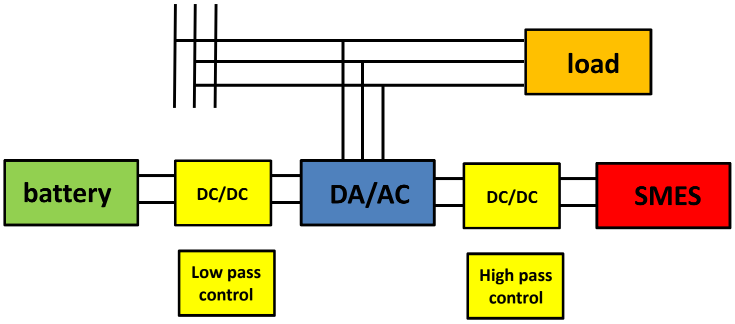
Rated power	30 MW
Duration of delivery	6 min
Rated energy	3 MWh
Num. of modules	30

Case 3

Rated power	30 MW
Duration of delivery	1 min
Rated energy	0.5 MWh
Num. of modules	30

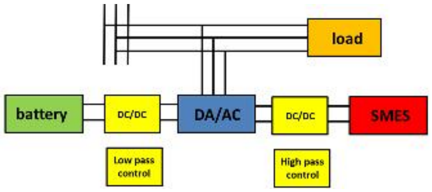
If a large power is required for a limited time SMES can represent a cost effective storage technology

2. Hybrid SMES - Battery systems



SMES can be conveniently used in combination with battery due to the complementary characteristics

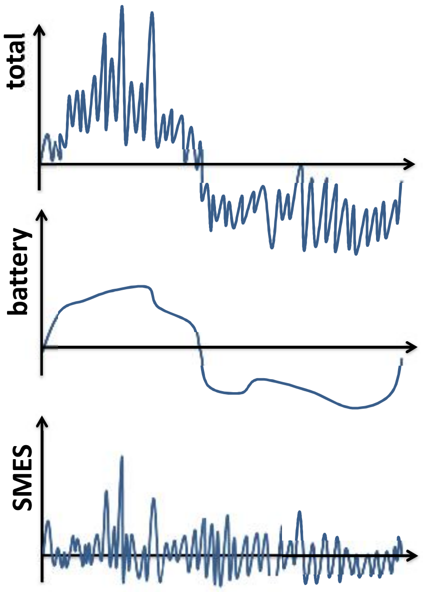
- Battery provides long term base power – hence energy
- SMES provides peak power and fast cycling



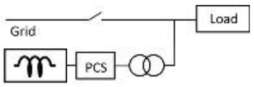
Advantages:

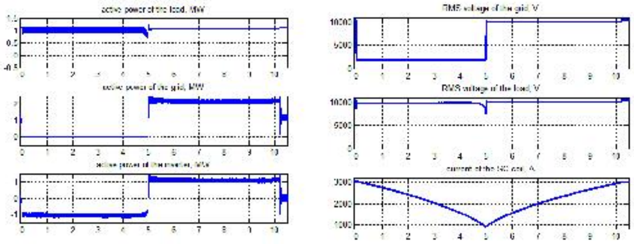
- Reduced power rating of batteries
- Reduced wear and tear of batteries (no minor cycling)
- Reduced energy rating of SMES

Power vs time



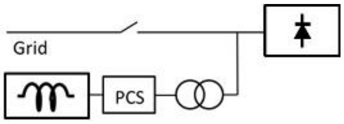
3. Protection of sensitive customers and auxiliary services

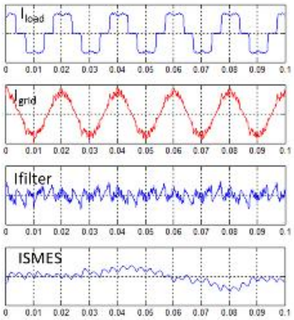




Power interruption is cancelled by the SMES

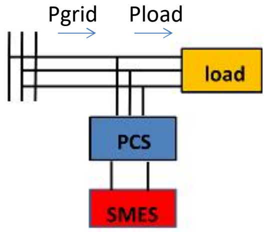
Auxiliary network services can be provided by the PCS during normal operation

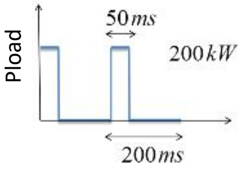


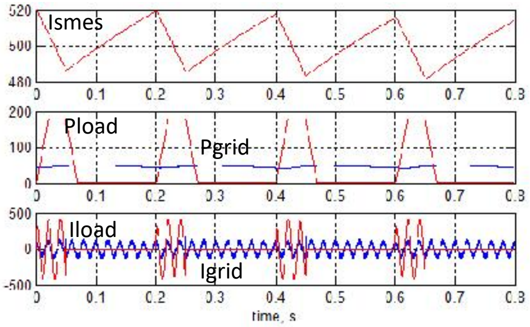


- Harmonic compensation
- Power factor correction

4. Leveling of impulsive loads by SMES

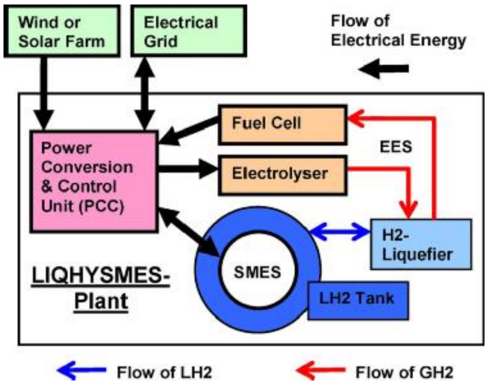






- No battery can be used for this application due to the prohibitive number of cycles
- Advantages brought by SMES can be significant also for moderate size systems

5. Hybrid SMES - Liquid Hydrogen system



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- Liquid Hydrogen is used as energy intensive storage
- Free cooling power is available for SMES due to the presence of LH2 at 20 K
- SMES is used as power intensive storage

To summarize on SMES …..

Technology

- SMES is an established power intensive storage technology.
- Improvements on SMES technology can be obtained by means HTS materials compatible with cryogen free cooling.
- Cooling and idling losses needs to be carefully considered when evaluating the viability of SMES systems.

Applications

SMES is an option for

- Hybrid storage systems with both power intensive and energy intensive features
- Fast delivery of large power for short time (pulsed loads, UPS)
- Continuous deep charge/discharge cycling