Review of Power Applications for HTS

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5th Workshop on Accelerator Magnets in HTS, Budapest 8-12 April 2019

KIT-ENERGY CENTRE

Content

- Motivation
- Power Cables
- Fault Current Limiters
- Rotating Machines
- Transformers
- SMES
- Summary

I would like to acknowledge latest information on projects from
Antonio Morandi, U Bologna
Sergey Samailenkov, SuperOx
Markus Bauer, Theva
Francesco Grilli, KIT

- a few Highlights that represent the State of the Art

Motivation

- Superconductivity enables
  - Highest current densities
  - at zero DC resistance and at high magnetic fields

- Impact on Power Applications
  - Improved energy efficiency
  - Higher power density
  - New technology
  - Higher power quality
  - Environment-friendly

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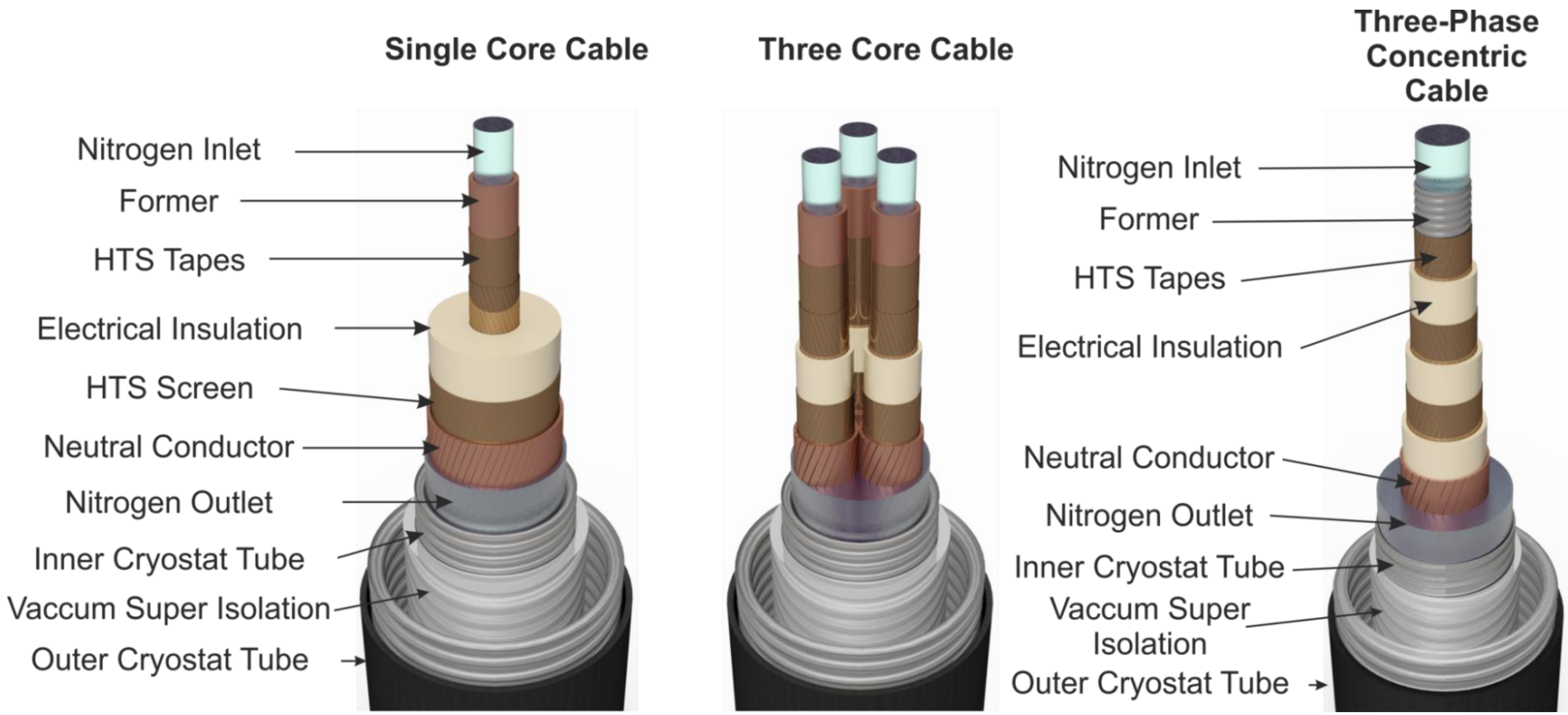
- a few Highlights that represent the State of the Art

Cables – Different Types



	Three single phases	Three phase in one cryostat	Three phase concentric
Voltage level	High voltage > 110 kV	30-110 kV	10-50 kV
Amount of superconductor	higher	higher	smaller
Cryostat loss	higher	smaller	smaller

AC Cables – Field Test Experience

Manufacturer	Place ,Country, Year	Data	HTS
??	Chicago, Shanghai, ??		??
LS Cable	Seoul, Korea, 2017	22.9 kV, 1000 m	YBCO
Nexans	Essen, Deutschland, 2014	10 kV, 2.4 kA, 1000 m	BSCCO
Sumitomo	Yokohama, Japan, 2013	66 kV, 1.8 kA, 240 m	BSCCO
LS Cable	Icheon, Korea, 2011	22.9 kV, 3.0 kA, 100 m	BSCCO
LS Cable	Icheon, Korea, 2009	22.9 kV, 1.3 kA, 500 m	BSCCO
Nexans	Long Island, US, 2008	138 kV, 2.4 kA, 600 m	BSCCO/YBCO
LS Cable	Gochang, Korea, 2007	22.9 kV, 1.26 kA, 100 m	BSCCO
Sumitomo	Albany, US, 2006	34.5 kV, 800 A, 350 m	BSCCO
Ultera	Columbus, US, 2006	13.2 kV, 3 kA, 200 m	BSCCO
Sumitomo	Gochang, Korea, 2006	22.9 kV, 1.25 kA, 100 m	BSCCO
Furukawa	Yokosuka, Japan, 2004	77 kV, 1 kA, 500 m	BSCCO

Several successful field tests with voltages up to 138 kV and cable length up to 1000 m

Cables

- Between 2001 and 2010 many large scale HTS cable demonstrators have been tested in the grid

Columbus

Ultera
13.2 kV, 3 kA, 200 m
Triaxial™ Design
BSCCO 2223
Energized 2006
High reliability

Figure: Ultera

LIPA

Nexans
138 kV, 2.4 kA,
600 m
Single coaxial design
BSCCO 2223
Energized 2008

Figure: Nexans

Gochang

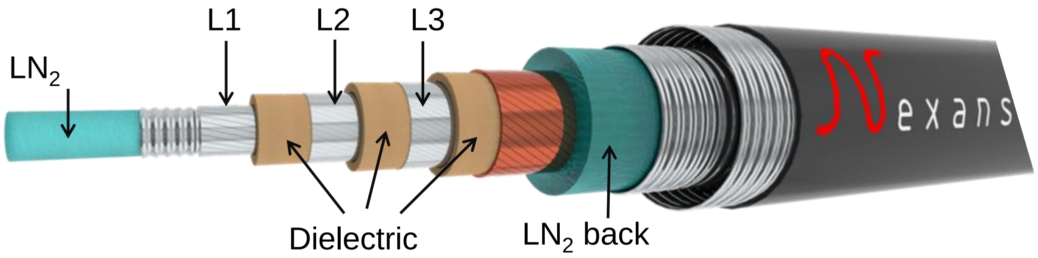
Figure: LS Cable

LS Cable
22.9 kV, 50 MVA, 100 m
BSCCO 2223
Energized 2007
500 m field test with YBCO in 2011

- Since then long term field applications started

Cables

- Objectives
  - Built and test a 40 MVA, 10 kV, 1 km superconducting cable in combination with a fault current limiter
- Project partners
  - Innogy, Nexans, KIT
- Budget
  - 13.5 Mio. €
- Duration
  - Sept. 2011- Feb. 2016



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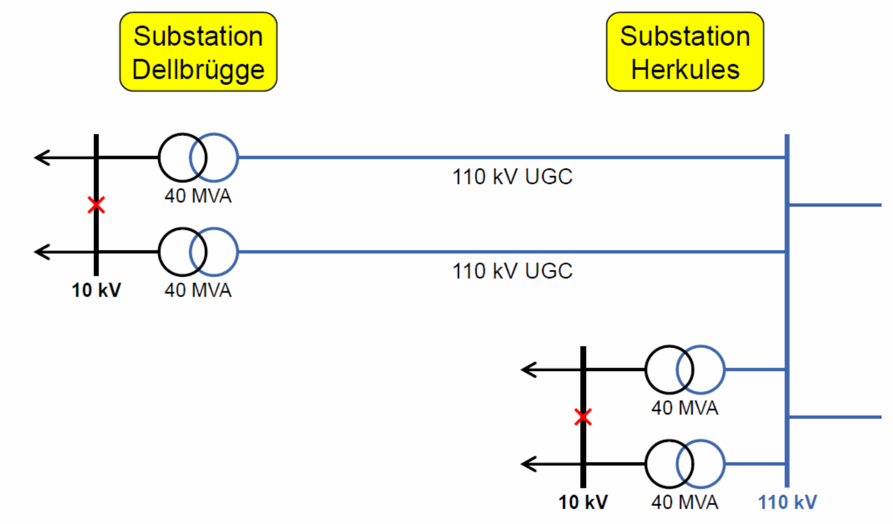
Projektträger Jülich
Forschungszentrum Jülich

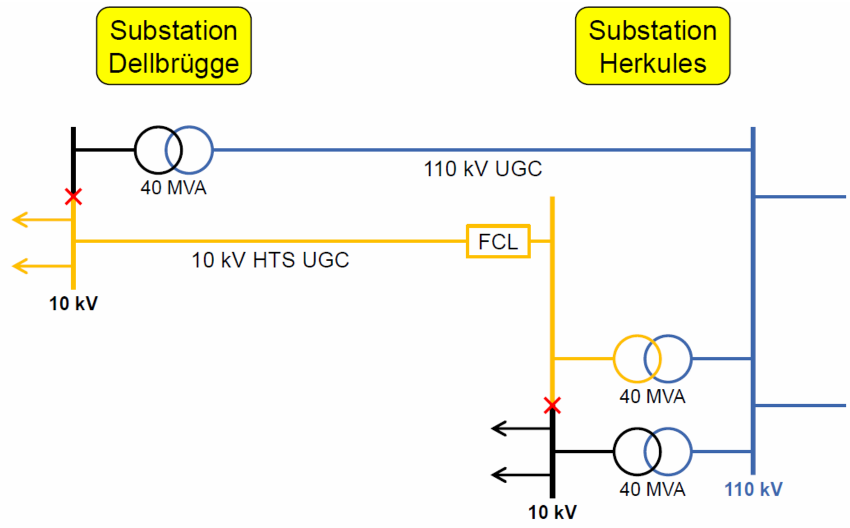
innogy
nexans
KIT Karlsruhe Institute of Technology

Cables

Conventional Situation in Essen

HTS Cable plus FCL Situation in Essen





A transformer and a high voltage cable can be replaced by a medium voltage HTS cable in combination with a fault current limiter.

Cables – Ampacity Cooling Unit

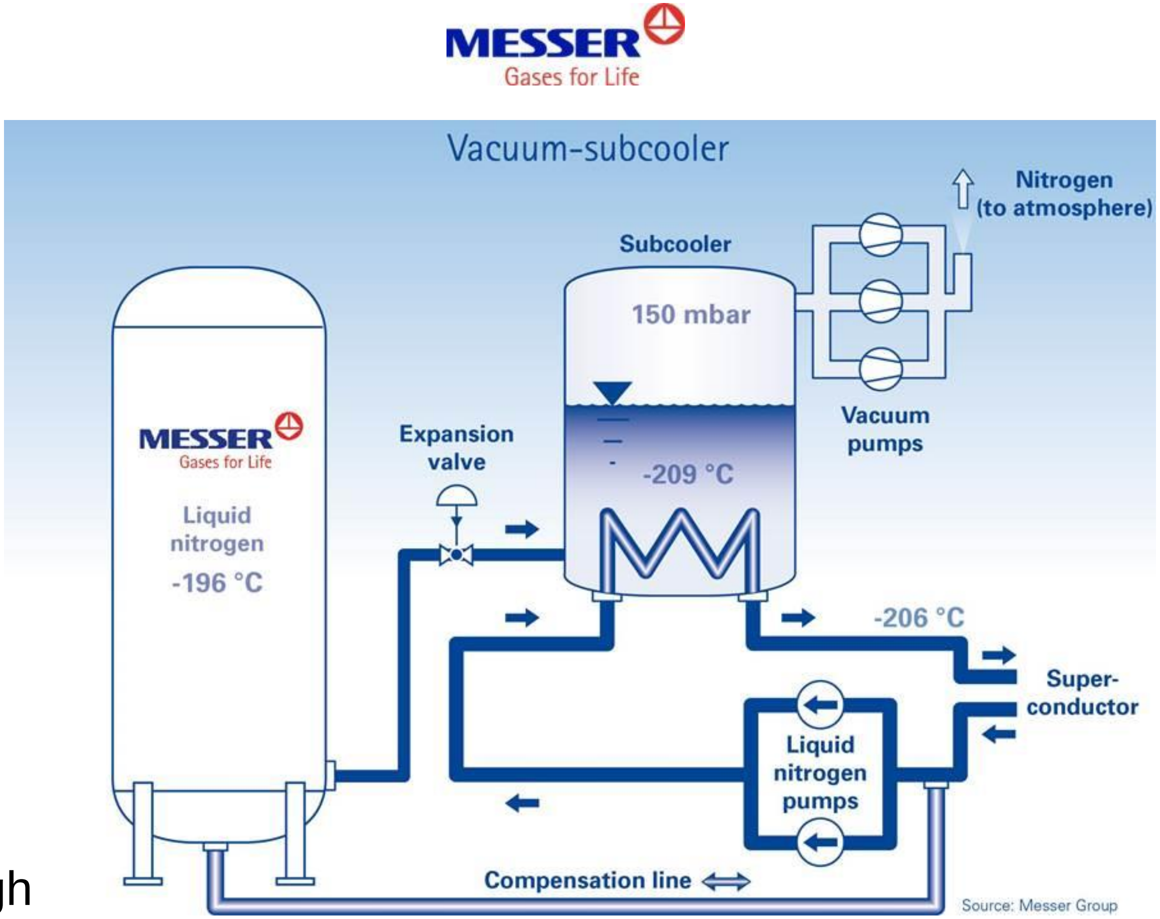
Liquid nitrogen is used
- as heat transfer medium
- as cooling agent

LIN is pumped through the superconducting cable

LIN is recooled in the subcooler (to -206°C)

LIN vaporizes at 150 mbar(a) (forced by vacuum pumps)

LIN temperature decreases to -209°C (expansion through the regulation valve)



Source: F. Herzog, et.al. , „Cooling unit for the AmpaCity project – One year successful operation", Cryogenics Volume 80, Part 2, December 2016, Pages 204-20, DOI: 10.1016/j.cryogenics.2016.04.001

Status Ampacity Project

Major result

- The cable and FCL installation fulfills all technical and operational requirements.

Status

- The operation has been extended. 5 years operation without outage.
- Business cases are under development.

AC Cables

- Several superconducting AC cables up to voltages larger than 100 kV have been tested successfully in the grid.
- First long term or permanent installations are ongoing.
- Some attractive business cases are under development.

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Fault Current Limiters

- Field test experience of resistive type superconducting FCL

Lead Company	Year/Country	Data	Superconductor
ACCEL/NexansSC	D / 2004	12 kV, 600 A	Bi 2212 bulk
Nexans SC	D / 2009	12 kV, 100 A	Bi 2212 bulk
Nexans SC	D / 2009	12 kV, 800 A	Bi 2212 bulk
RSE	I / 2011	9 kV, 250 A	Bi 2223 tape
RSE	I / 2012	9 kV, 1 kA	YBCO tape
KEPRI	Korea / 2011	22.9 kV, 3 kA	YBCO tape
Nexans SC	D / 2011	12 kV, 800 A	YBCO tape
Nexans SC	D / 2013	10 kV, 2.4 kA	YBCO tape
Applied Materials	US /2013	15 kV / 1kA	YBCO tape
Nexans SC	UK /2015	12 kV, 1.6 kA	YBCO tape
Siemens	D / 2016	12 kV, 815 A	YBCO tape
SuperOx	Russia/2019	220 kV, 1 kA	YBCO tape

More than 10 successful field tests of resistive type superconducting fault current limiters at medium voltage level since 2004

Fault Current Limiters

Nexans

Resistive type, YBCO
12 kV, 1600 A
Installed 11/2015

Siemens

Resistive type, YBCO
12 kV, 815 A
Installed 3/2016

Applied Materials

Resistive type, YBCO
115 kV, 550 A
Installed 7/2016

SuperOx SFCL 220 kV project for Moscow grid

- 3 phase device installed in parallel to ACR
- Regulatory procedures underway, to be energized in 1H 2019

Specification	Value
Nominal voltage	220 kV
Maximum operating voltage	252 kV
Lightning impulse withstand voltage	950 kV
Power frequency withstand voltage	440 kV
Nominal frequency	50 Hz
Nominal current	1200 A
Switching current	3400 A
Normal (superconducting) operation active resistance, less than	0,01 Ohm
Current limitation active resistance	40 Ohm
Switching time (superconductor-resistor), less than	2 ms
Location	Outdoor
Dimensions per phase with bushings (Length x Width x Height)	5500 x 2850 x 6500 mm
Weight per phase (dry/with coolant)	16 / 27 ton
Test standard	IEEE C37.302-2015

Fault Current Limiters

- Several medium voltage superconducting fault current limiters have been tested successfully.
- Large companies still struggle with commercialization.
- High voltage superconducting fault current limiters are under development.

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Core ambitions

ecoswing

- Design, develop and manufacture a full scale multi-megawatt direct-drive superconducting wind generator
- Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark (3.6 MW, 15 rpm, 128 m rotor)
- Prove that a superconducting drive train is cost-competitive
- **Have the generator running in 2017.**

Horizon 2020
European Union Funding
for Research & Innovation

Key Project Figures

ecoswing

- **Program:** EU Horizon 2020
- **Reference:** 656024
- **Start Date:** 2015-03-01
- **End Date:** 2019-03-01
- **Total Cost:** EUR 13,846,594
- **EU Contribution:** EUR 10,591,734

Horizon 2020
European Union Funding
for Research & Innovation

"EcoSwing has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 656024." "Herein we reflect only the author's view. The Commission is not responsible for any use that may be made of the information it contains."

Platform for Technology Validation

ecoswing

- The idea is to replace a PM generator with a superconducting generator

- This includes power conversion and refrigeration equipment.

Horizon 2020
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Ecoswing Status April 2019

- 14:00h on 6 December 2018 when Envision's direct drive turbine produced net power to the grid
- Ecoswing is the world's first wind turbine with a grid connected superconducting generator

Turbines of the year 2018: Drivetrains

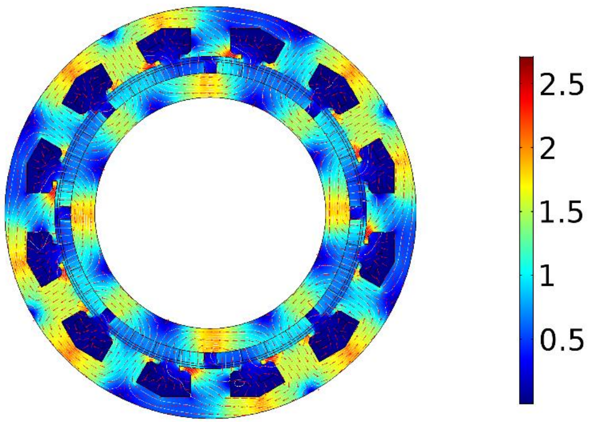
1 January 2019 by Eize de Vries

The sector is adapating to higher-rated turbines and changing grid demands.

The ASUMED Project

- Advanced Superconducting Motor Experimental Demonstrator
- Fully superconducting machine
  - Stator: HTS coils (4 times higher than conventional)
  - Rotor: HTS tape stacks as permanent magnets
- Power density 20 kW/kg
- Prototype:
  - ~1 MW power at 10,000 rpm
  - Thermal loss <0.1%
- http://asumed.oswald.de/

Magnetic flux density norm (T)



Numerical modeling will allow the first detailed AC loss evaluation in a fully superconducting machine

Rotating Machines

- So far, only three field tests of superconducting rotating machines took place
  - 12 MVA Synchronous condenser, 2005, US
  - 4 MVA generator, 2008, Germany
  - 3.5 MW wind generator, 2018, EU
- Several machines for various applications have been built and lab tested up to a rating of 36 MVA.
- A long term test in a real application is still missing.

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Transformer

Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	ABB	Distribution	630 kVA, 18,42 kV/420V	3 Dyn11	1996	Bi 2223
Japan	Fuji Electric	Demonstrator	500 kVA, 6,6 kV/3,3 kV	1	1998	Bi 2223
Germany	Siemens	Demonstrator	100 kVA, 5,5 kV/1,1 kV	1	1999	Bi 2223
USA	Waukesha	Demonstrator	1 MVA, 13,8 kV/6,9 kV	1	-	Bi 2223
USA	Waukesha	Demonstrator	5 MVA, 24,9 kV/4,2 kV	3 Dy	-	Bi 2223
Japan	Fuji Electric	Demonstrator	1 MVA, 22 kV/6,9 kV	1	2001	Bi 2223
Germany	Siemens	Railway	1 MVA, 25 kV/1,4 kV	1	2001	Bi 2223
EU	CNRS	Demonstrator	41 kVA, 2050 V/410 V	1	2003	P-YBCO/S-Bi 2223
Korea	U Seoul	Demonstrator	1 MVA, 22,9 kV/6,6 kV	1	2004	Bi 2223
Japan	Fuji Electric	Railway	4 MVA, 25 kV/1.2 kV	1	2004	Bi 2223
Japan	Kuyshu Uni.	Demonstrator	2 MVA, 66 kV/6.9 kV	1	2004	Bi 2223
China	IEE CAS	Demonstrator	630 kVA, 10.5 kV/400 V	3	2005	Bi 2223
Japan	U Nagoya	Demonstrator	2 MVA, 22 kV/6,6 kV	1	2009	P-Bi 2223/S-YBCO
Japan	Kyushu Uni	Demonstrator	400 kVA, 6.9 kV/2.3 kV	1	2010	YBCO
Germany	KIT	Demonstrator	60 kVA, 1 kV/600 V	1	2010	P-Cu/S-YBCO
USA	Waukesha	Prototype	28 MVA, 69 kV	3	Not completed	YBCO
Australia	Callaghan Innovation	Demonstrator	1 MVA, 11 kV/415 V	3 Dy	2013	YBCO
China	IEE CAS	Demonstrator	1.25 MVA, 10.5 kV/400 V	3 Yyn0	2014	Bi 2223
Germany	KIT/ABB	Demonstrator	577 kVA, 20 kV/1 kV	1	2015	P-Cu/S-YBCO

Transformer

Karlsruher Institut für Technologie

- Development of a three phase 1 MVA HTS Transformer

  Project Partners: Gallaghan Innovation, Wilson Transformers, General Cable …

Parameter	Value
Primary Voltage	11,000 V
Secondary Voltage	415 V
Maximum Op. Temp.	70 K, liquid nitrogen cooling
Target Rating	1 MVA
Primary Connection	Delta
Secondary Connection	Wye
LV Winding	20 turns 15/5 Roebel cable per phase (20 turn single layer solenoid winding)
LV Rated current	1390 A rms
HV Winding	918 turns of 4 mm YBCO wire per phase (24 double pancakes of 38.25 turns each)
HV Rated current	30 A rms

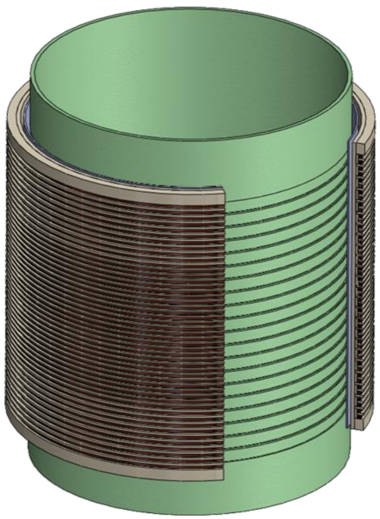
Source: Gallaghan Innovation

First HTS Roebel wire in application test

Transformer

- Development of a three phase 1 MVA HTS Transformer

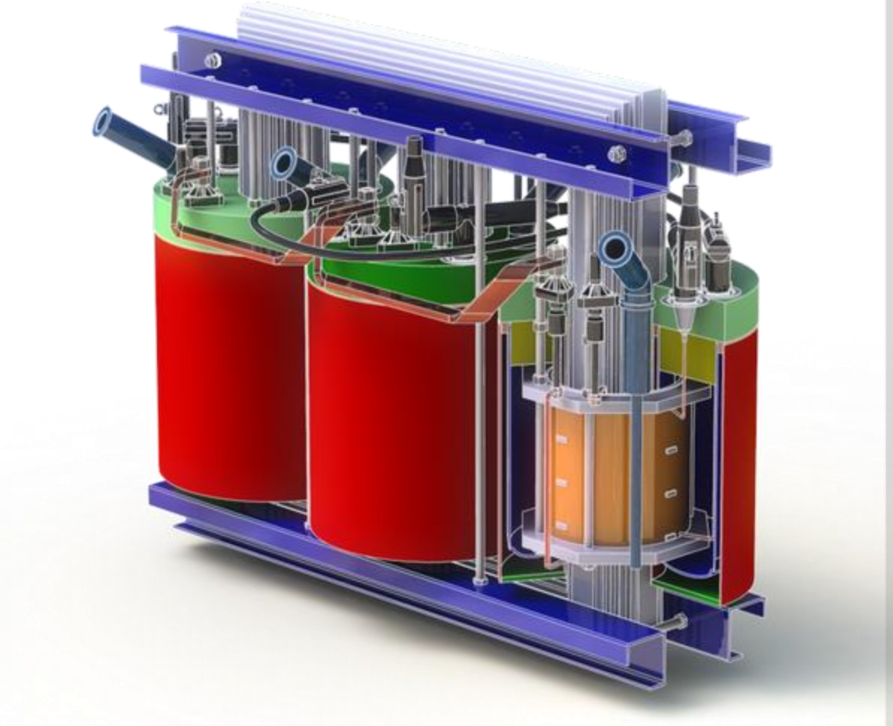
HV Winding



4 mm wide YBCO
I/I_c ~ 25%
Polyimide wrap insulation
24 double pancakes

LV Winding

YBCO Roebel Cable
L = 20 m
15 strands
5 mm width
I_c ~ 1400 A @ 77 K, sf



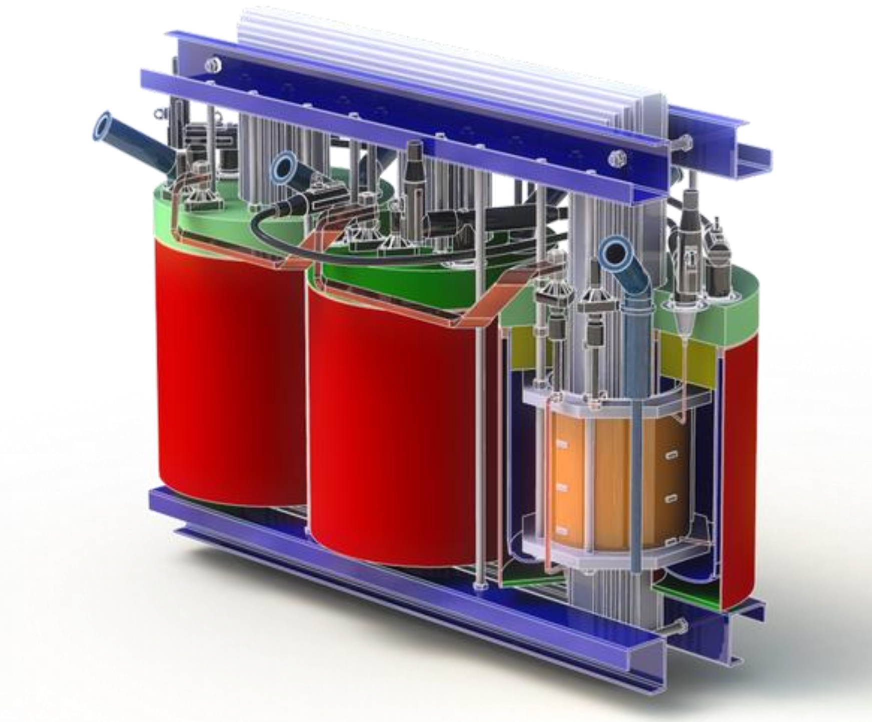
Source: Igallaghan Innovation

More information: Neil D. Glasson, Mike P. Staines, Zhenan Jiang, and Nathan S. Allpress, "Verification Testing for a 1 MVA 3-Phase Demonstration Transformer Using 2G-HTS Roebel Cable", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

Transformer

- Development of a three phase 1 MVA HTS Transformer

Source	Heat load
Cryostat	113 W
Electrical bushing	343 W
AC loss in LV	390 W
AC loss in HV	90 W
Total	**936 W**



Source: Igallaghan Innovation

Efficiency at 100% load: ~ 97%
Efficiency at 50% load 98.5 %

Current standard
Efficiency at 50% 99.27%

More information: Neil D. Glasson, Mike P. Staines, Zhenan Jiang, and Nathan S. Allpress, "Verification Testing for a 1 MVA 3-Phase Demonstration Transformer Using 2G-HTS Roebel Cable", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

Transformer

- Several medium voltage superconducting transformers with a maxium power of a few MW have been developed.
- A long term field test in a public grid is still missing.

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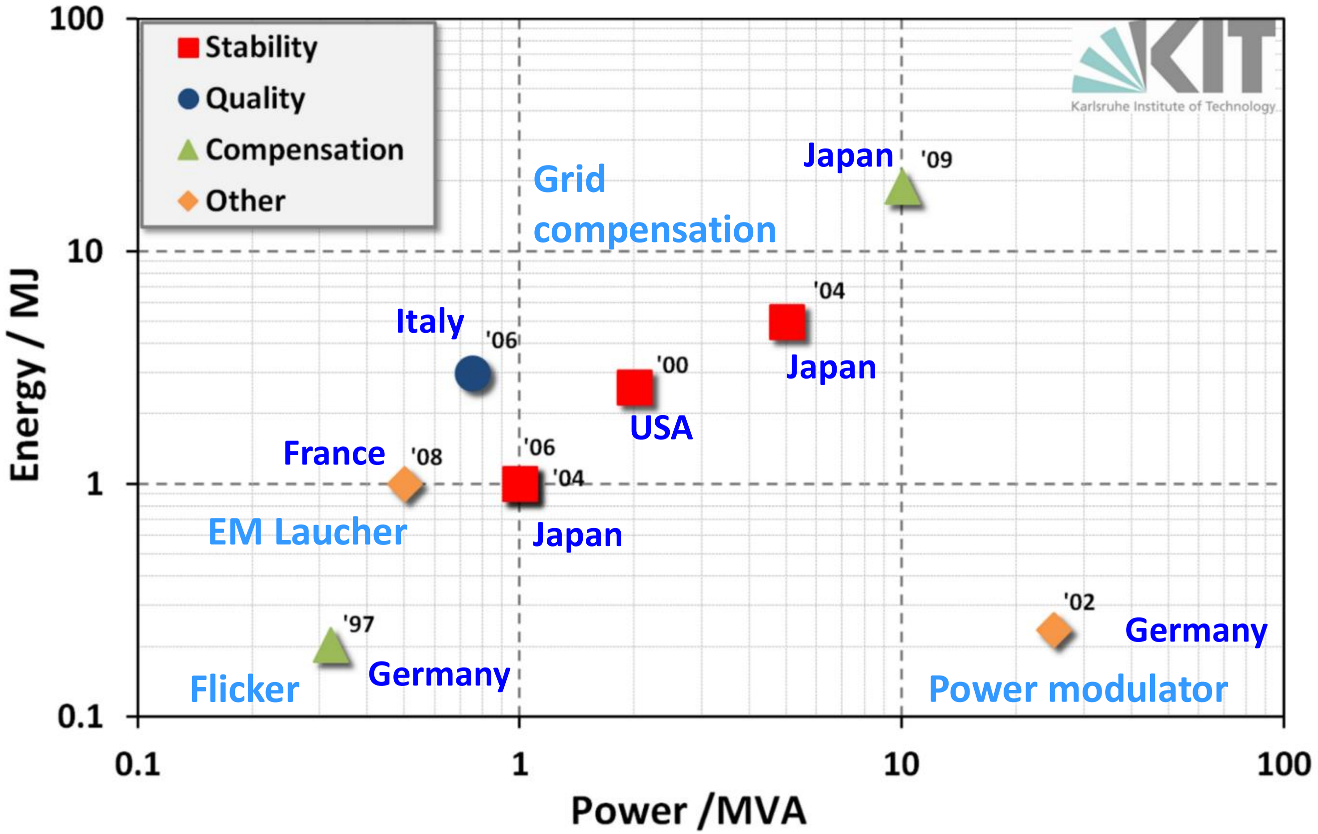
SMES – State of the Art

- More than 10 MJ and 10 MVA have been realized with LTS



The DRYSMES4GRID Project

MISE - Italian Ministry of Economic Development

Competitive call: research project for electric power grid

- Transmission and distribution
- Dispersed generation, active networks and storage
- Renewables (PV and Biomass)
- Energy efficiency in the civil, industry and tertiary sectors
- Exploitation of Solar and ambient heat for air conditioning

Project DRYSMES4GRID funded

- **Budget: 2.7 M€**
- **Time: June 2017 – June 2020 (+1)**
- **develop. of dry-cooled SMES based on MgB_2**
- **500 kJ – 200 kW / full system**

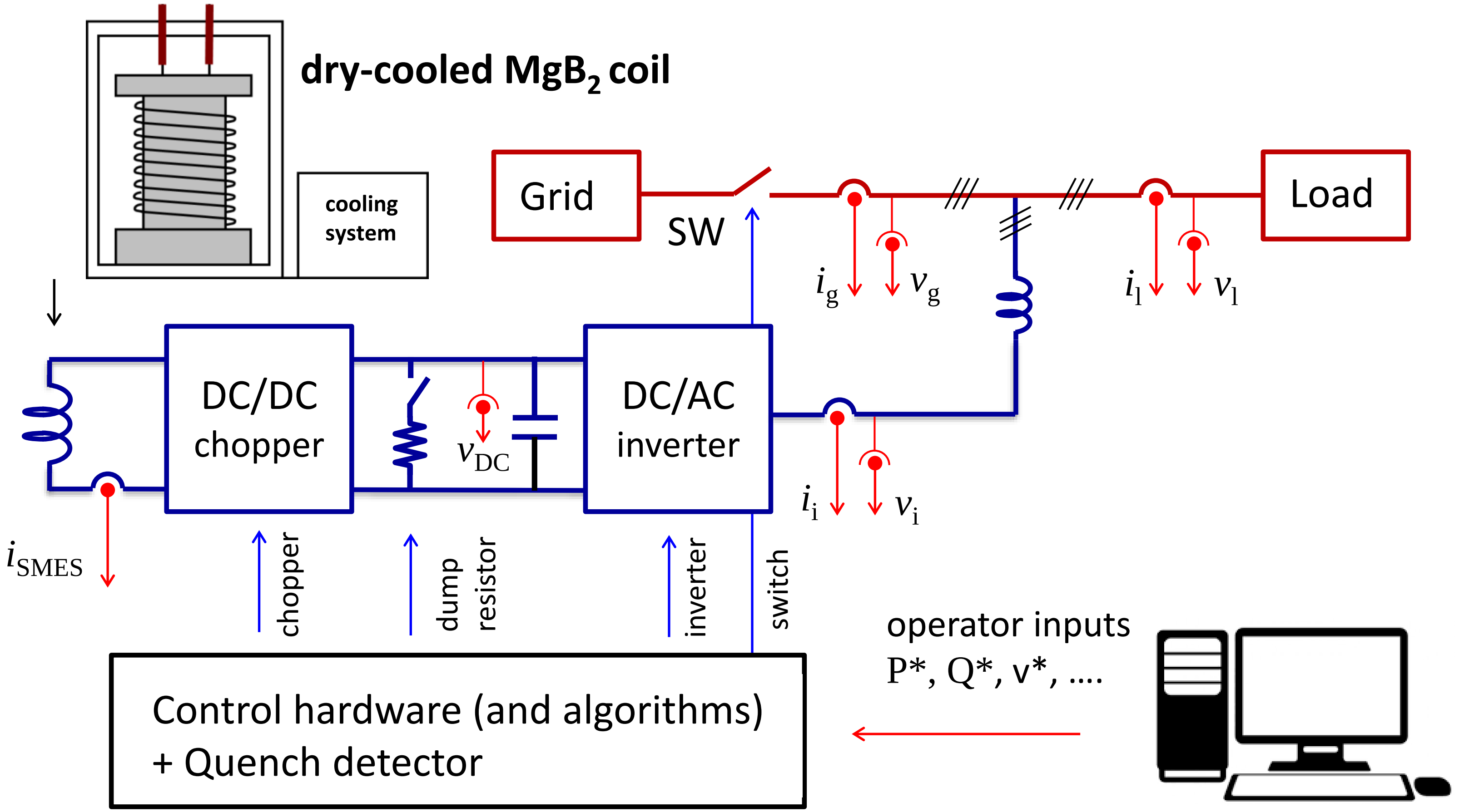
Project Coordinator:

- **Columbus Superconductors SpA, Genova, Italy**

Partners

- **University of Bologna**
- **ICAS - The Italian Consortium for ASC, Frascati (Rome)**
- **RSE S.p.A - Ricerca sul Sistema Energetico, Milan**
- **CNR – SPIN, Genoa**

The DRYSMES4GRID system

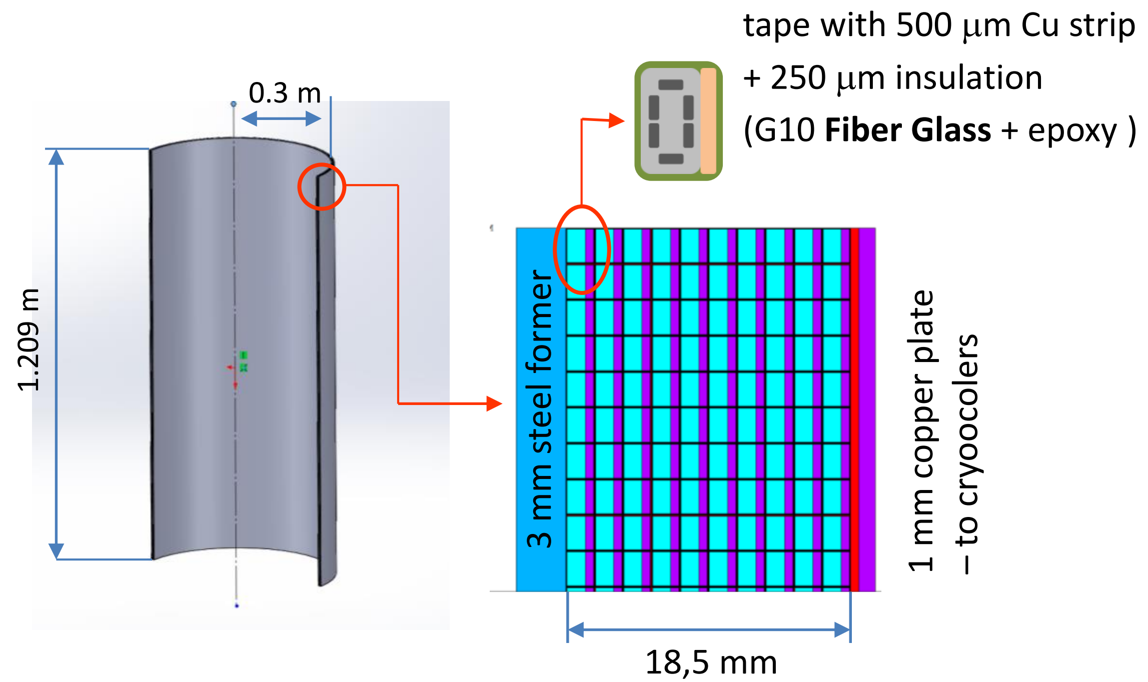


- **Electromagnetic & Mechanical design of the coil completed**
- **Thermal design (connection to cryocooler/s) in progress**
- **Control algorithms (logic, schemes, parameters) defined**

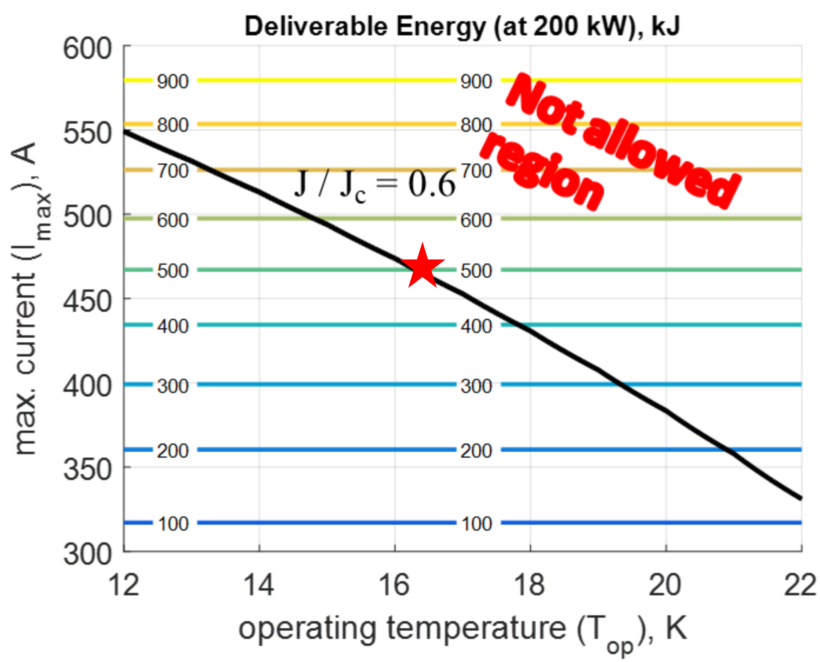
Next
- **Manufacturing of the coil & cooling system**
- **Design and Manufacturing of Power Hardware**

Main characteristics of the designed 500 kJ / 200 kW SMES coil

Inner radius, mm	300
Height, mm	1200.6
Number of layers	10
Number of turns per layer	522
Length of cable, km	10.1
Voltage of the dc bus, V	750
Min Current, A	266.6
Max current, A	467
Field on conductor (at Imax), T	1.63
I/Ic ratio (at Imax)	0.6
Inductance, H	6.80
Total eneregy (at Imax), kJ	741
Deliverable energy, kJ	500.4
Dump resistance, Ω	2,14
Max adiabatic hot spot temp., K	95.6



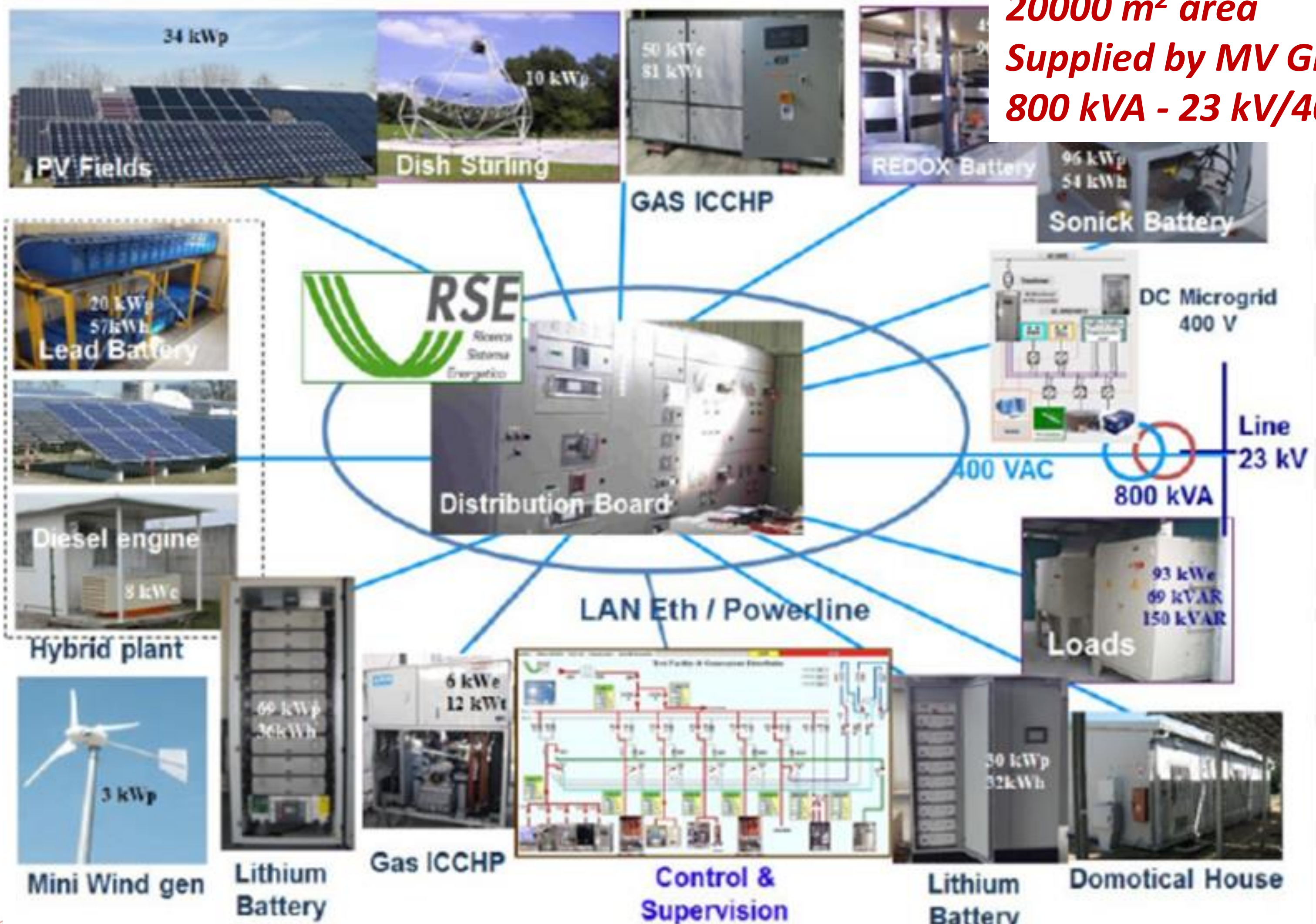
- **The SMES cannot be discharged below I_{min} = 267 A if the power of 200 kW is to be supplied/ absorbed ($I_{min} = P/V_{dc}$)**
- **The designed coil fullfills the specifics (200 kW – 2,5 s) with an operaing temperature T ≤ 16 K and a max. current I_{max} = 467 A**



Test Site: RSE Distributed Energy Resources Test Facility

A real low voltage microgrid that interconnects different generators, storage systems and loads to develop studies and experimentations on DERs and Smart Grid solutions.

20000 m² area
Supplied by MV Grid
800 kVA - 23 kV/400 V transf.



SMES

- A few LTS SMES operate in long term operation up to a rating of about 10 MJ and 10 MW.
- HTS SMES have been developed for research and military purposes only.

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Summary

	TRL 1	TRL2	TRL 3	TRL 4	TRL5	TRL 6	TRL 7	TRL 8	TRL 9
MV AC Cables							X		
HV AC Cables						X			
Resistive type FCL								X	
Wind Generator							X		
Electric Aircraft		X							
Utility Transformer				X					
LTS SMES							X		
HTS SMES				X					
	Low TRL			Medium TRL			High TRL		

- For some applications a high Technology Readiness Level larger than 7 (Test of a prototype in real application) has been reached.
- For this applications future efforts need to be concentrated towards lower cost.