Development, test, installation, and commissioning of the 3 MW superconducing EcoSwing wind power generator

Markus Bauer on behalf of the EcoSwing consortium

Thu-Mo-Or18-01 – MT26, September 26 , 2019, Vancouver, Canada

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Anders Rebsdorf
Anne Bergen
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Carsten Bührer
Cédric Dupont
Christian Broer
Christian Koppe
Christian Kruse
Christian Mehler
Daniel Laloy
David Laurent
Frederick Deneubourg

Hans Kyling
Hendrik Pütz
Hermann Boy
Jan Wiezoreck
Jean-Luc Lepers
Jean-Philippe Francke
Jens Krause
Jesper H.S. Hansen
Jürgen Kellers
Kazu Raiju
Kimon Argyriadis
Konstantin Yagotyntsev
Marc Dhallé
Marcel ter Brake
Markus Bauer
Martin Keller
Martin Pilas
Matthias-Klaus Schwarz

Michael Reckhard
Mogens Christensen
Nathalie Renard
Patrick Brutsaert
Peterson Legerme
Roland Stark
Sander Wessel
Sofiane Bendali
Stephane Eisen
Thomas Hisch
Thomas Skak Lassen
Thorsten Block
Tiemo Winkler
Torben Jersch
Trevor Miller
Vadinho Debrito
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The EcoSwing Story

See
https://www.theva.com/video-zum-abschluss-des-ecoswing-projekts/
Or
https://www.youtube.com/watch?v=NxMkZHyM9UQ

Publications (published):

- Song et al.: Designing and Basic Experimental Validation of the World's First MW-Class Direct-Drive Superconducting Wind Turbine Generator, IEEE Transactions on Energy Conversion DOI: 10.1109/TEC.2019.2927307
- Winkler et al.: The EcoSwing Project, IOP conf. series: Mat. Sc Eng. DOI:10.1088/1757-899X/502/1/012004
- Slides on AC loss calculation (in German): **https://elenia.tubs.de/fileadmin/content/sls/9sls/04_Krause.pdf**

Publications (submitted)

- SUST: Design and in-field testing of world's first ReBCO rotor for a 3.6 MW wind generator
- IEEE TEC:
  Ground Testing of the World's First MW-Class Direct-Drive Superconducting Wind Turbine Generator
- Applied Energy:
  Commissioning of the World's First MW-Class Direct-Drive Superconducting Generator on a Wind Turbine

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Agenda

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- Overview on project
  - Design, component testing, assembly
- Ground testing in Bremerhaven, Germany
- Installation and operation on wind turbine in Thyboron, Denmark
- Summary

Our ambitions

ecoswing

ENVISION
ECO5
JEUMONT Electric
DELTA
DELTA ENERGY SYSTEMS
THEVA
SHI Cryogenics Group
Fraunhofer
UNIVERSITY OF TWENTE.
DNV·GL

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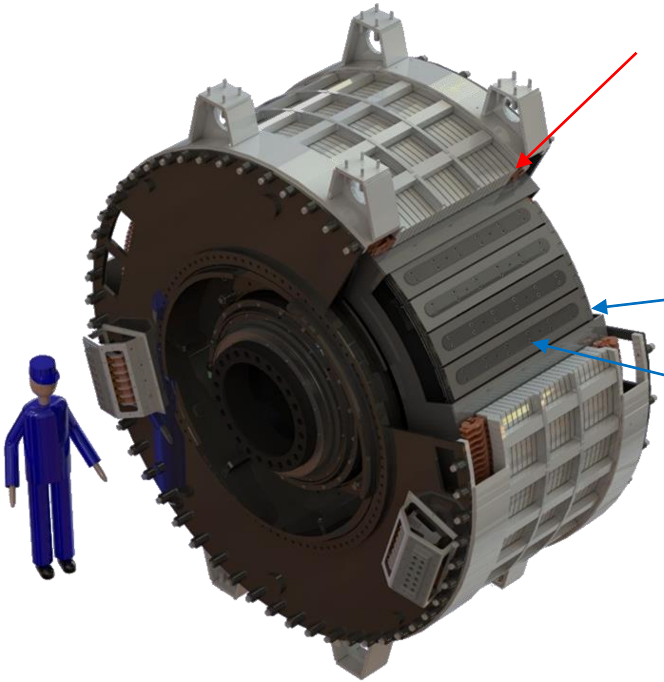
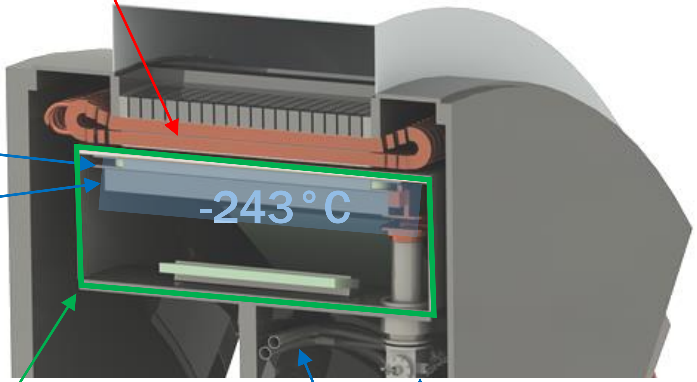
Superconductivity has matured sufficiently that we can follow an ambitious plan:

- Design, develop and manufacture a full-scale multi-megawatt superconducting wind generator
- Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark, replace existing PM generator (3 MW Class, 14 rpm, 128 m rotor)
- Prove that a superconducting drive train is lighter, smaller and cost-competitive.
- Start Date: 2015-03-01
  End Date: 2019-04-30

Elements of the EcoSwing superconductive generator





High power density stator with copper coils

Rotor

Superconductor coils

Cold iron yoke

Self sustaining thermal insulation vacuum

Cryocooling

Coldhead

Working gas pipes

+ compressors in nacelle

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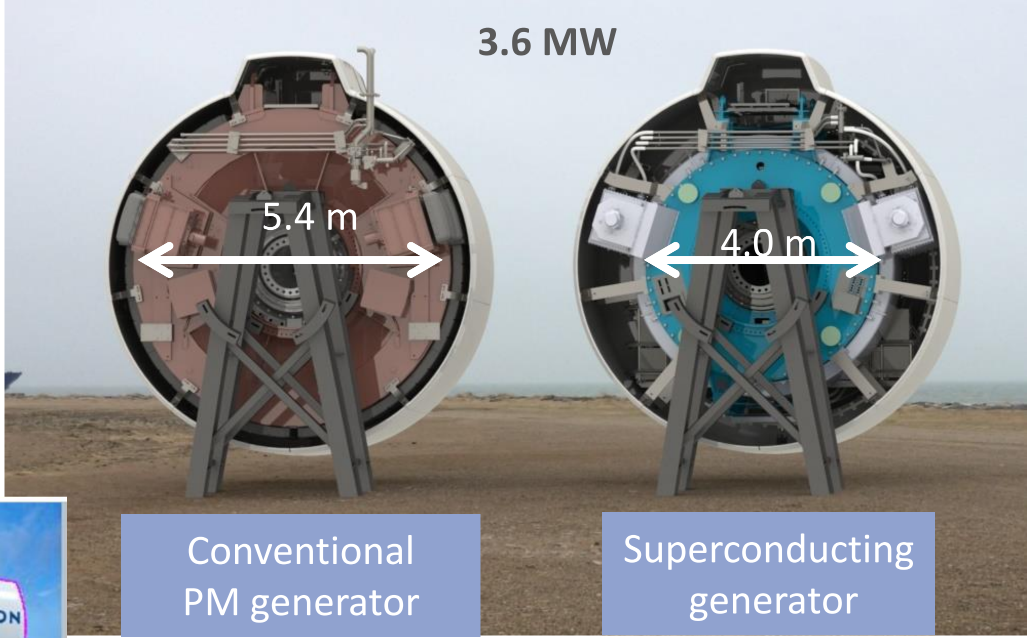
EcoSwing design

- Decreased diameter from 5.4 m (PM generator) to 4 m
- Built **EcoSwing generator**: **25 % weight reduction** compared to PM generator of same diameter
- Commercial design: **40% weight reduction** compared to PM generator.



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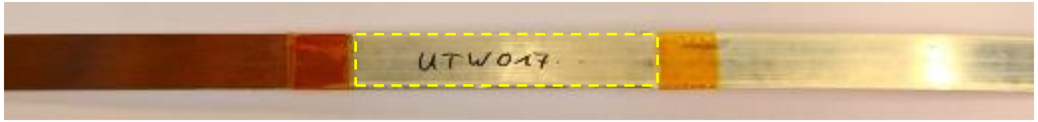
Qualification of Materials and Procedures
Just a few examples…

- Qualification of superconductive joints



- Validation of magnetic properties

- Validation of copper RRR

ECOSWING Copper pieces

Potential measured across 2.5 cm
Measurement current: 1A at low temperatures, 0.1A at 273.15 K
Operator: Jaap Kosse
Measurement date: 14/10/15

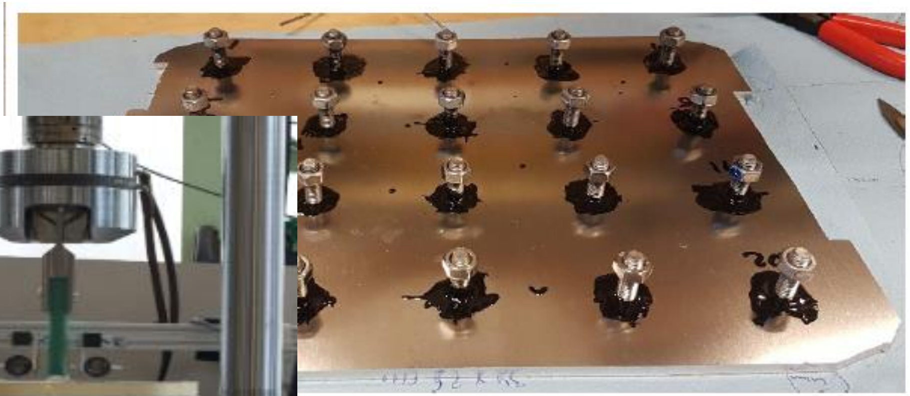
Sample	RRR (273.15/10)	RRR (273.15/30)	R at 273.15K [Ω]	R at 10K [Ω]	R at 30K [Ω]
Piece 2, Electrical connection, #1	124.2	81.6	4.403E-04	3.545E-06	5.395E-06
Piece 2, Electrical connection #2	123.5	81.8	4.575E-04	3.705E-06	5.596E-06
Piece 3, Cooling Plate, #1	78.6	59.0	9.524E-04	1.212E-05	1.613E-05
Piece 3, Cooling Plate, #2	78.7	59.2	9.471E-04	1.203E-05	1.600E-05

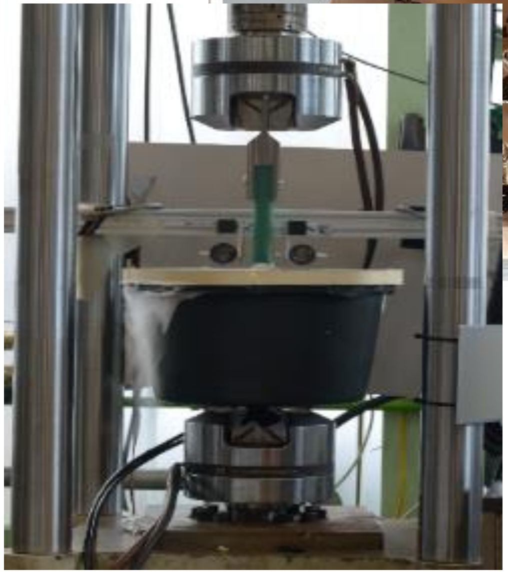
Qualification of Materials and Procedures
Just a few examples…

- Qualification of lubricants and adhesives

- Qualification of structural materials (w/ TNO Delft)

- Qualification of getters, sealants, procedure for affixing MLI…





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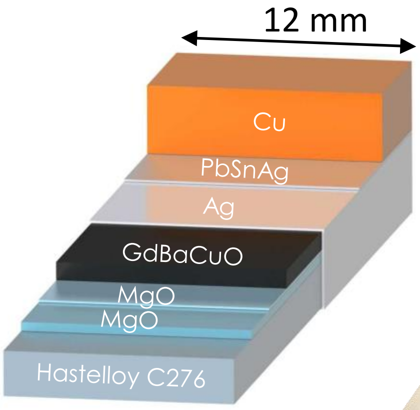
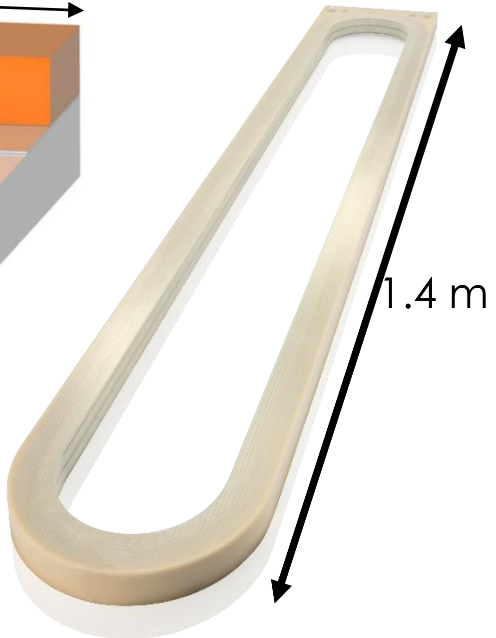
HTS full scale coils

Main characteristics

- Used wire: Standard THEVA Pro-Line HTS conductor with 100 µm Copper lamination
- Each coil contains more than 500 m of HTS wire and has about 200 turns
- Insulated design, 12 µm thin insulation foil
- Coils are 1.4 m long, double pancake
- Potted in resin
- Operating temperature < 30 K, conduction cooled



TPL2100



EcoSwing rotor coil

Type test and routine test of HTS coils

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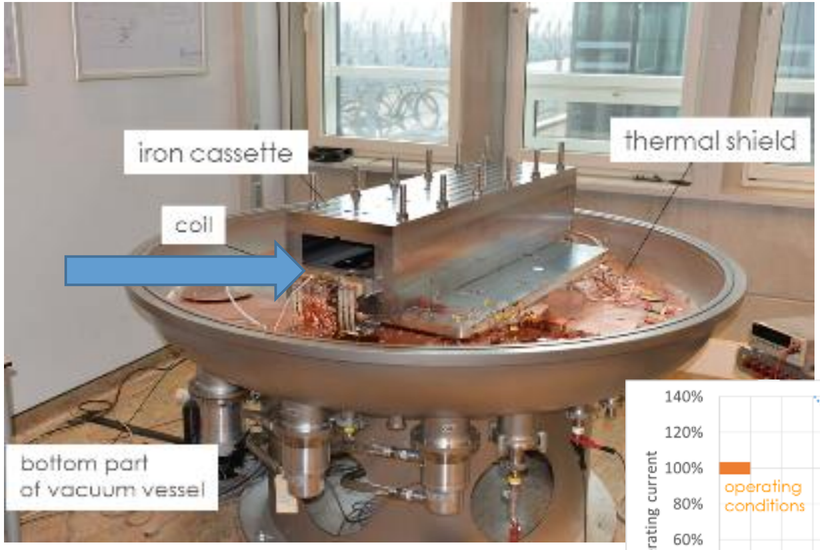
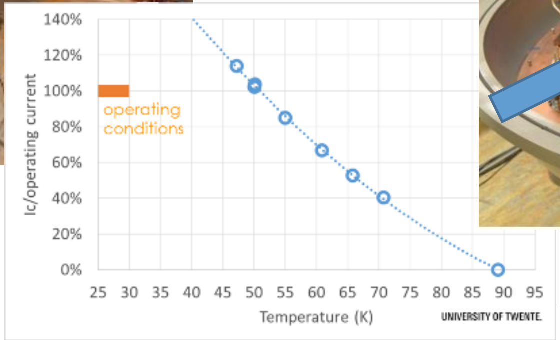
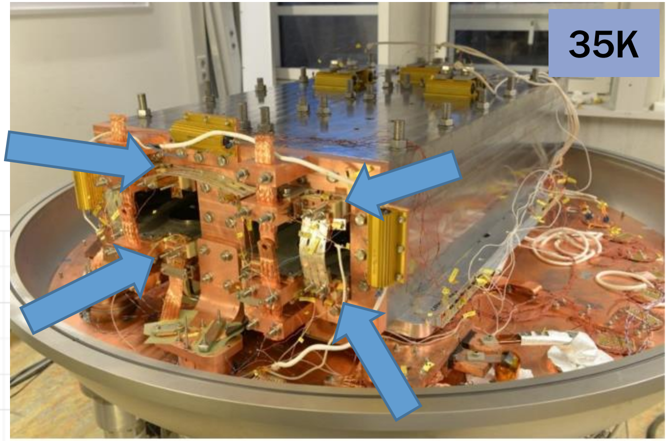
- Performance better than expected
- Nearly linear $I_c(T)$

→ **Type test passed on first attempt**



Type testing first coil





Routine testing with 4 coils

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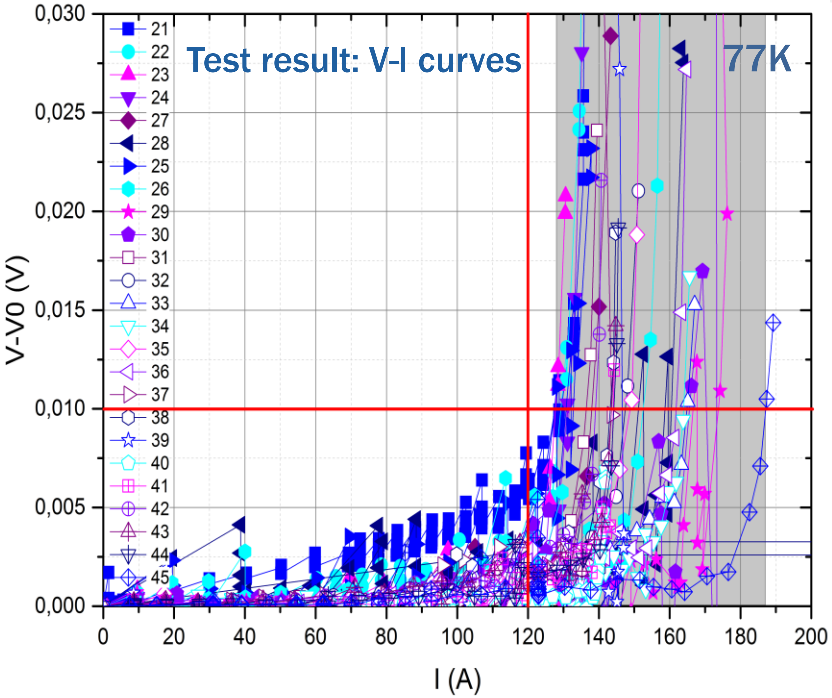
77K routine testing of coils

Simple setup
to test in liquid nitrogen



- Fast and efficient series testing in liquid nitrogen (77K, -196°C)
- All coils exceeded performance criteria (120 A)
- Coil production yield:
  - Overall 89% (45)
  - Second half: 100% (20)

Successful small series production of HTS coils!

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THEVA

Assembly of a superconducting generator

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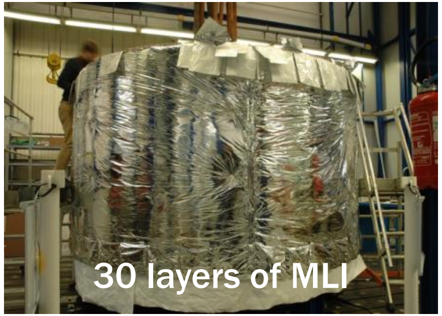

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JEUMONT Electric

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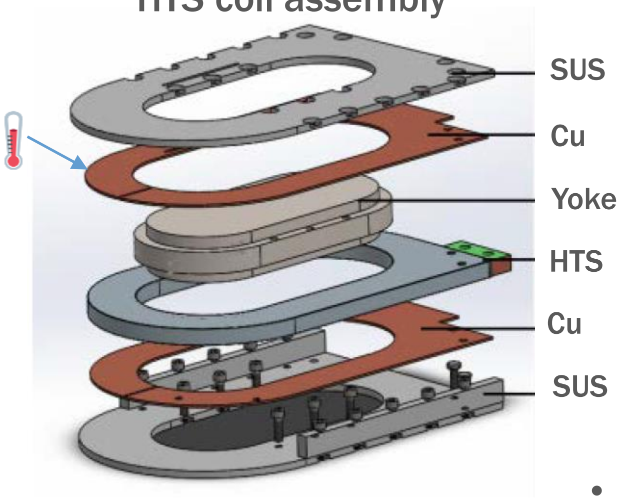
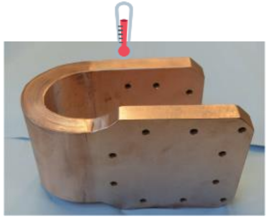
Main components of cooling system on rotor

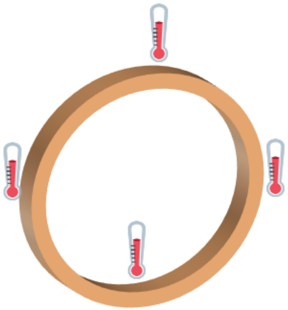
HTS coil assembly



Flexible connections



Cu cold bus



Cryocooler

- Pure conduction cooling concept
- Cu-OFE with defined and tested RRR value
- Contacts with tested heat flow resistance
- Monitoring of temperatures: 90 sensors (rotor alone)

T sensor

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Cooling system

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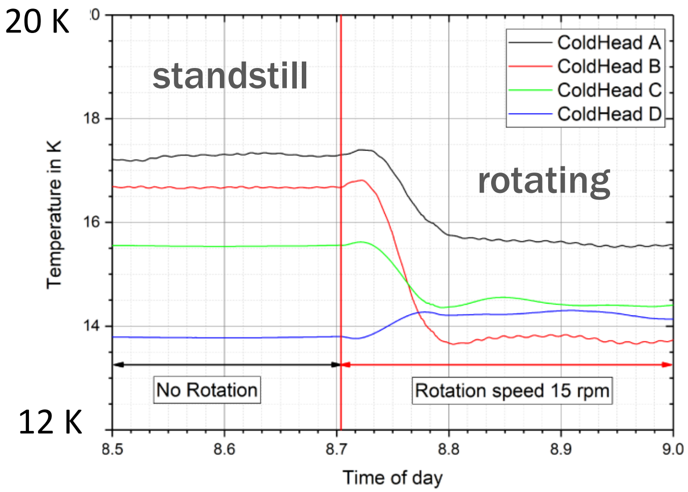
Concept:

- Conduction cooling with rotating GM cryocoolers
- Tested off the shelf components
- New: rotational He gas (warm) feedthrough
  solution to exchange cold heads with cold rotor

- SRDK-500B cryocoolers
- F-70 compressors.

30K	80/95 W
Power (50/60Hz)	7.5/9.0 kW
Maintenance	expected every 18.000 hrs
Orientational Dependence	<30%



- At standstill orientational dependence of cryocooling is detectable
- Rotation leads to homogenization of temperatures

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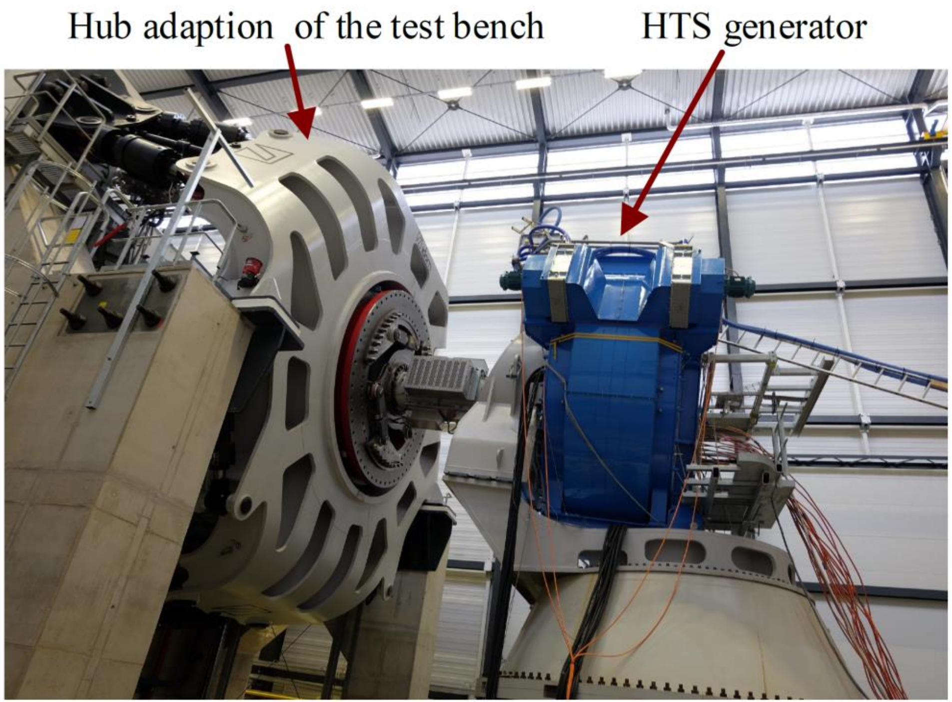
SHI Cryogenics Group

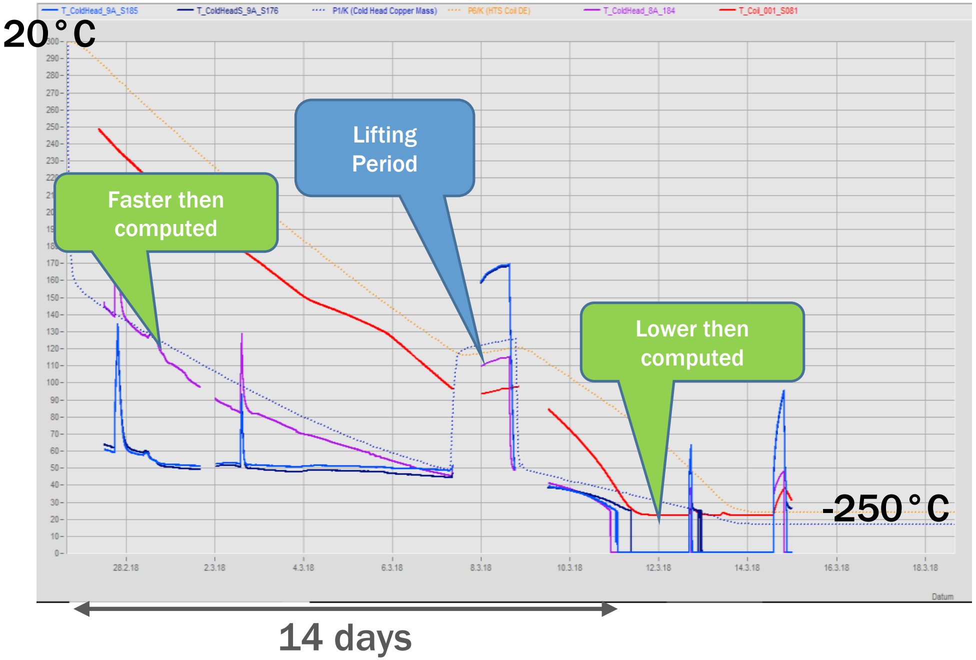
Ground testing at IWES

Steps during ground testing at DyNaLab of IWES in Bremerhaven:

- Mounting hub adaptation and generator
- Rotor cool down
- Excitation of the rotor at standstill
- Rotation
- Short circuit test
- No load test
- Power generation



1st cool down before ground test



Cooling down period faster then calculated 14 days compared to 18 days

- Cooling power exceeds expectations

Overall temperature level was lower than anticipated

- Thermal design conservative

Cryostat vacuum better then expected

- $2.7 \cdot 10^{-10}$ bar and self-sustaining
- No pump required during operation

Cryogenic system fulfilled all specifications!

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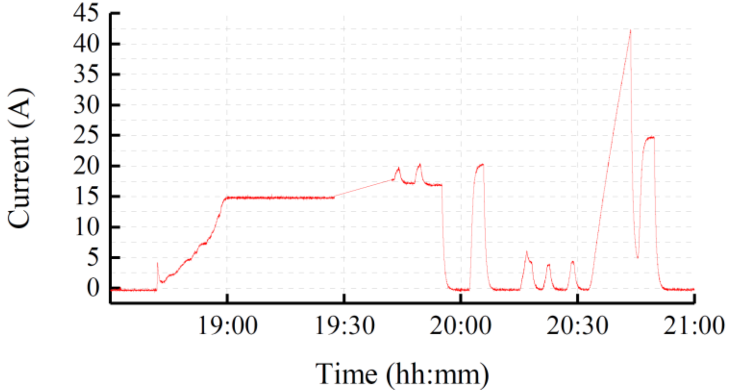
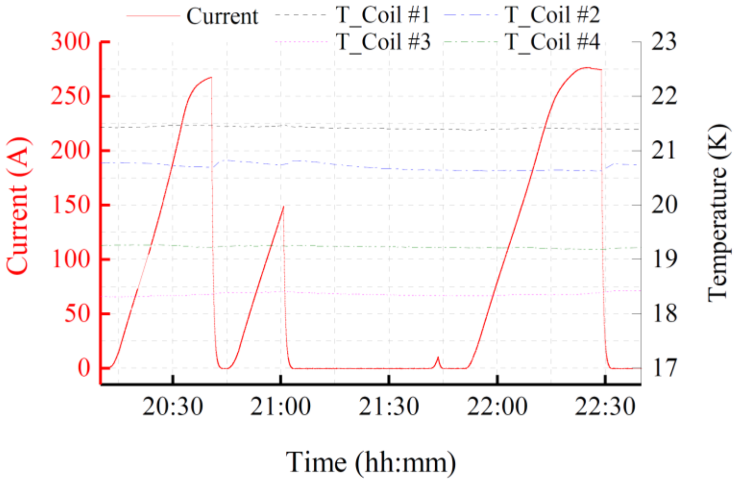
Excitation of HTS field windings

First excitation of HTS field winding at standstill in Bremerhaven





- Debugging of control and QD system
- Optimization of filter constants and threshold values
- Test of shutoff safety chain

Excitation up to 275 A

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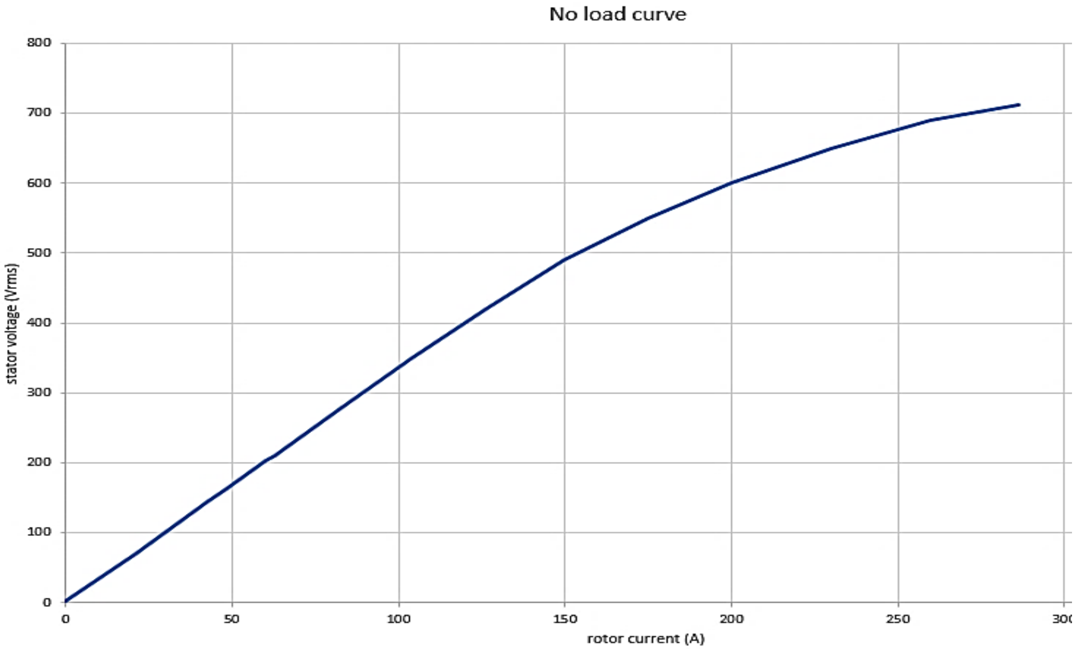
Some detail findings
No load tests

- Stator voltage reached nominal at 260 A rotor current
- The no-load curve does not show any unexpected behavior and is better than the 2D-FEM calculated one.
- With full 3D FEM including end windings no-load curve was fully reproduced.



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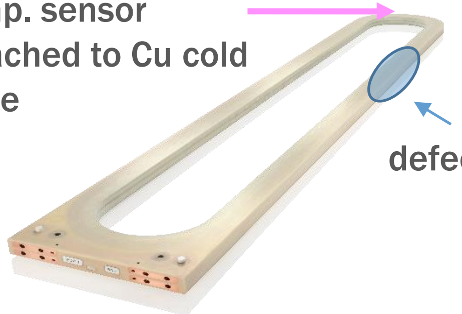
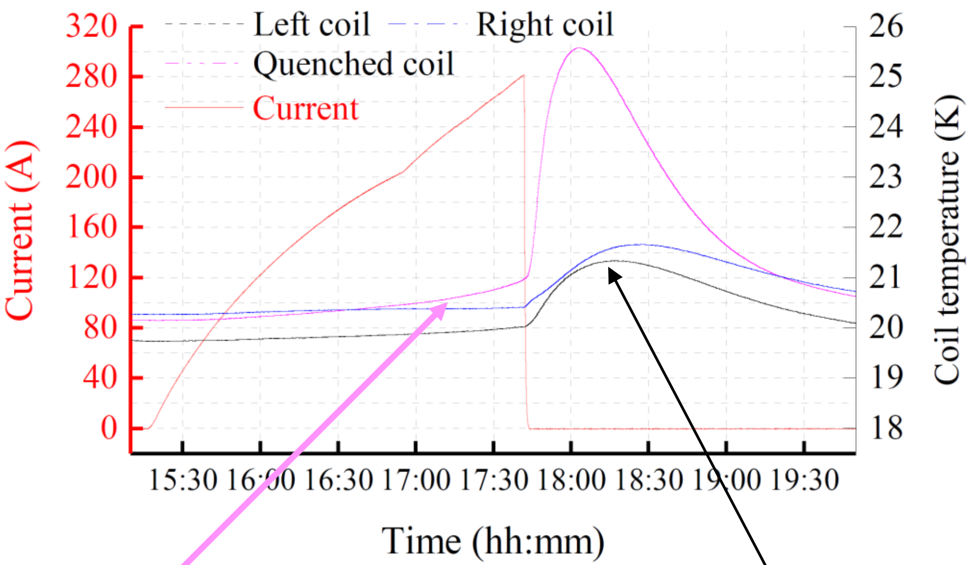
But not everything went as expected…….

Quench of one coil

During further increase of excitation current one coil quenched

- voltage rise detected by QD system
- automatic shut down
- temperature rise in quenched coil of up to 4.5 K





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Analysis of quench

Detailed analysis of temperatures and voltages

→ Only one coil with defect already before the quench

After the quench

→ higher resistance in quenched coil (1.7 mΩ)

No damage to other coils

→ QD system prevented further damage

Possible reasons:

- Coil only tested in LN2
  → conditions (T, B) differ from final operation conditions
  →Damaged wire with local I_c drop not detected
- Insulation failure leading to local heating
- Damage of coil after the QC test

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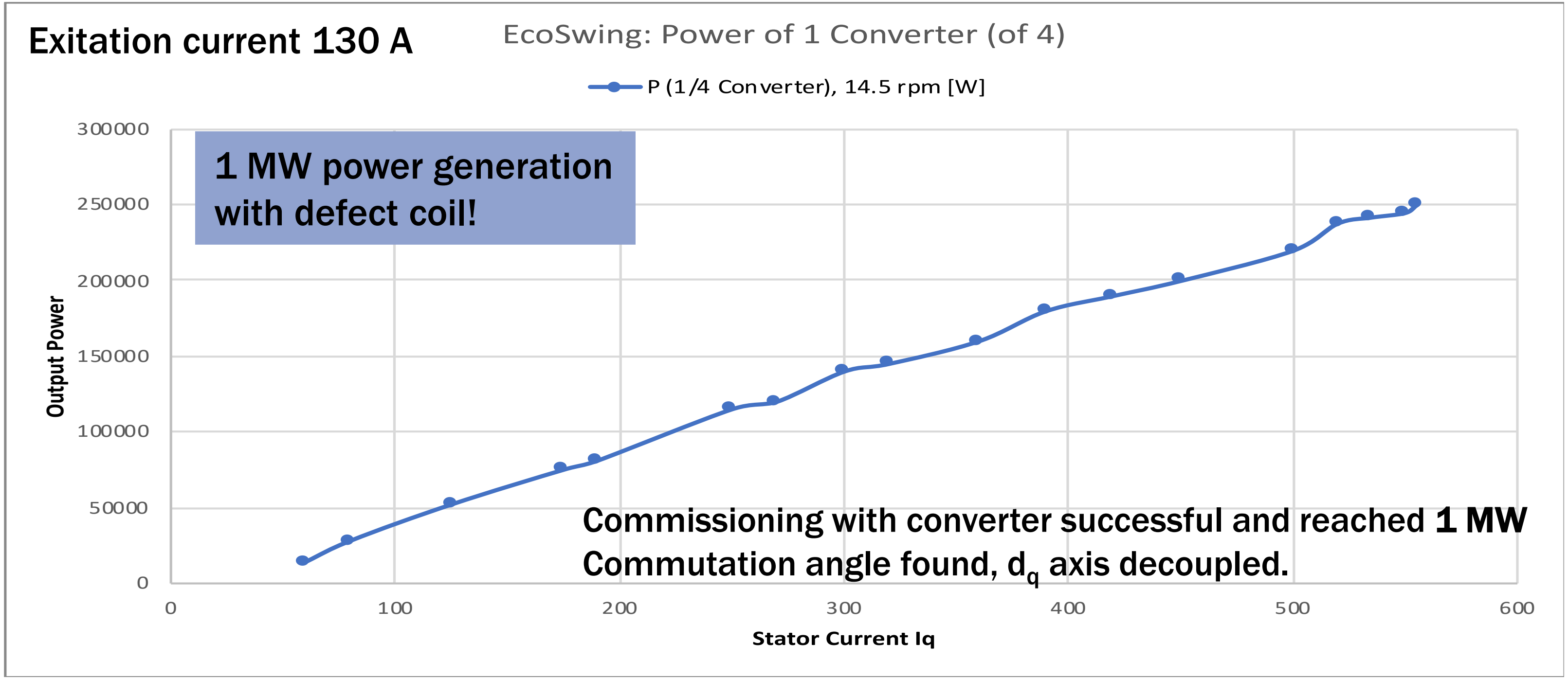
Some detail findings
Partial power test with defect coil



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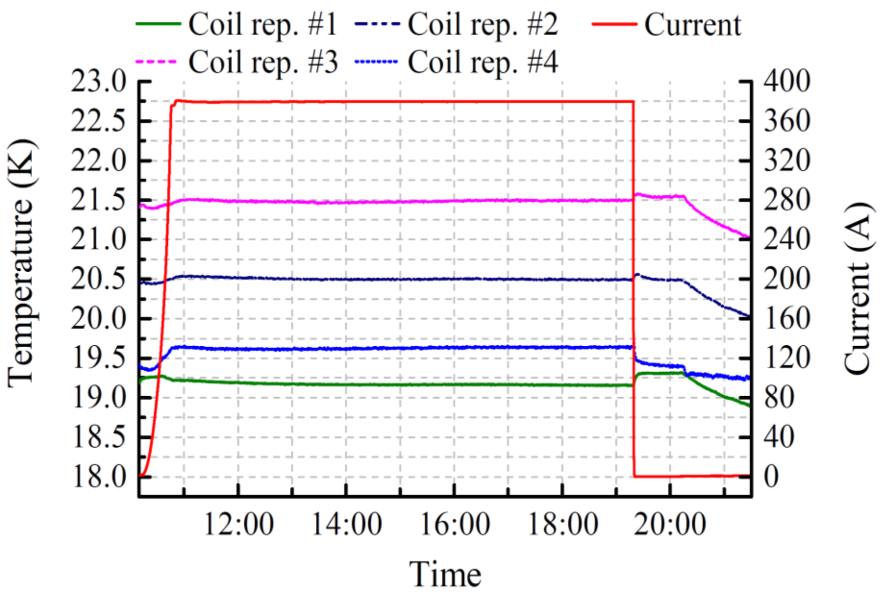
Repair of the rotor

Repair steps

- Transport of the generator to suitable place (cranes, welding..)
- rotor and stator separated
- vacuum recipient opened by cutting open the welding seam
- coil exchanged
    - MLI, el. + thermal connections, screws…
- Reassemble, re-weld, evacuation



Excitation test at standstill: 380 A (8h) ✓

Excitation for operation: 330 A ✓

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But not everything went as expected.......

But did we learn something?

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Learnings

Positive findings

- QD system worked correctly
- Operation with derated excitation (39%) is possible even with a defect HTS coil
- HTS rotors can be repaired

Improvements in QC

- QC testing should mimic the operational stress level as good as possible
  → HTS tape should be tested with similar I/Ic even if at different T and B conditions
- Insulation (turn to turn, layer to layer, coil to ground) has to be included in QC even if there is very little voltage drop at normal conditions

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Commissioning on turbine in Thyborøn, Denmark

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Commissioning on the wind turbine:

- Preinstallation of components
- Mounting of generator, converter, water cooling, DAQ, …
- Connection to PLC of wind turbine
- Safety testing
- Rotor cool down
- Excitation of the rotor
- No load rotation
- Stepwise increase to full power production

"Anything that is not ready when the crane is there will have to be done by partners in the air."

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2_{nd} cool down on turbine

300 K

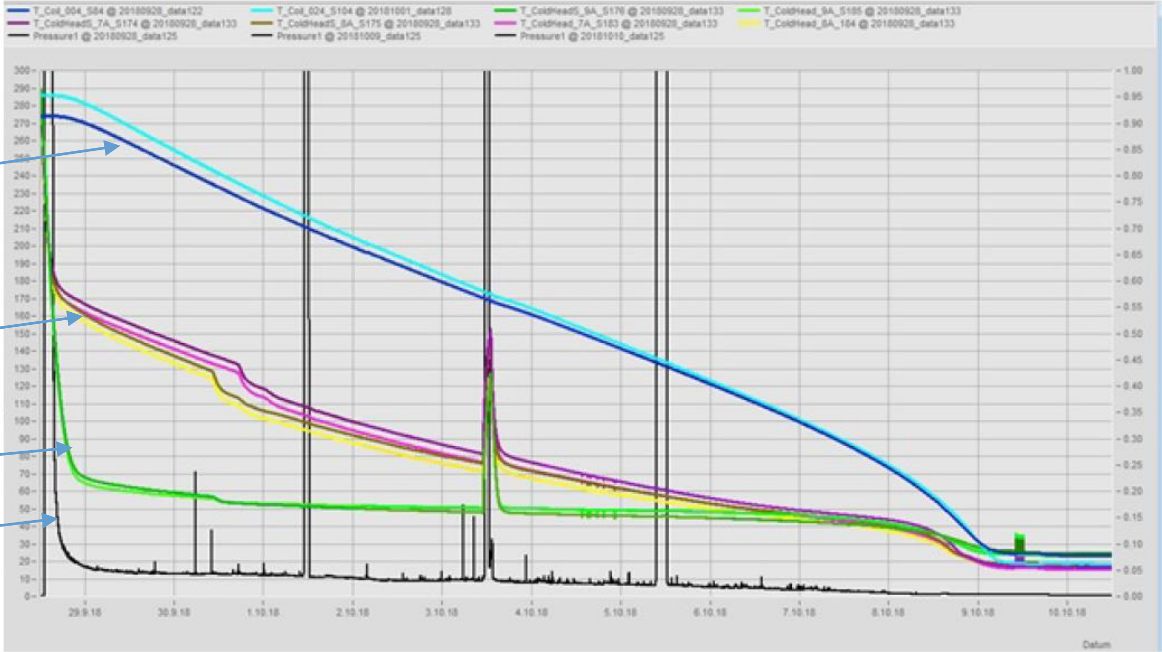
HTS coils

Cold heads

Cold head
at current
feed trough

pressure

0 K



~20 K

12 days from 28.9.2018 until 9.10.2018

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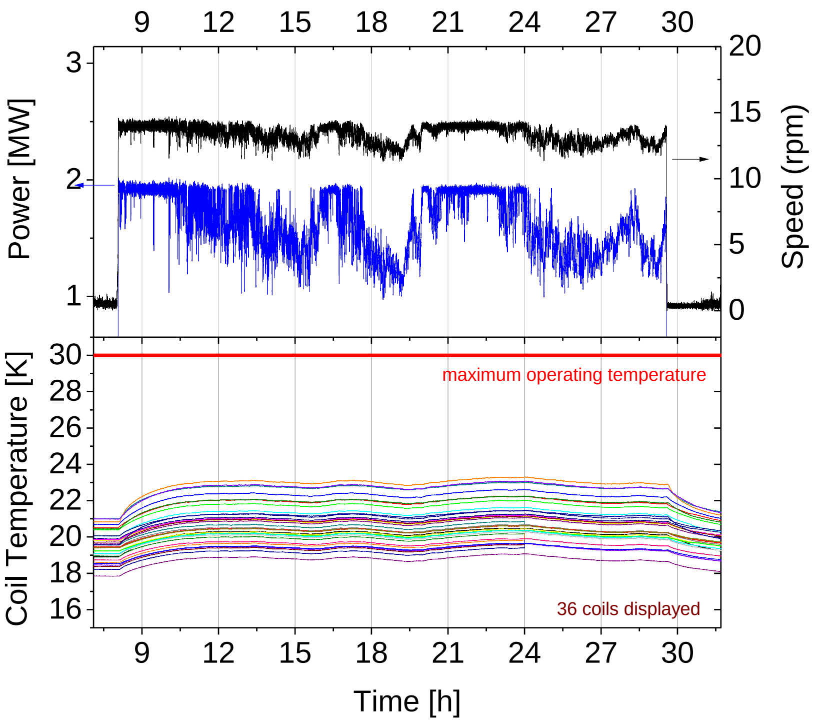
Power generation and cooling

2 MW test run
255 A excitation

Installed on wind turbine



Experience with cooling system

- Off the shelf components worked as specified
- Rotation of cryocoolers is no problem (15 rpm)
- Conduction cooling is reliable
- Influence of power generation on temperatures is small

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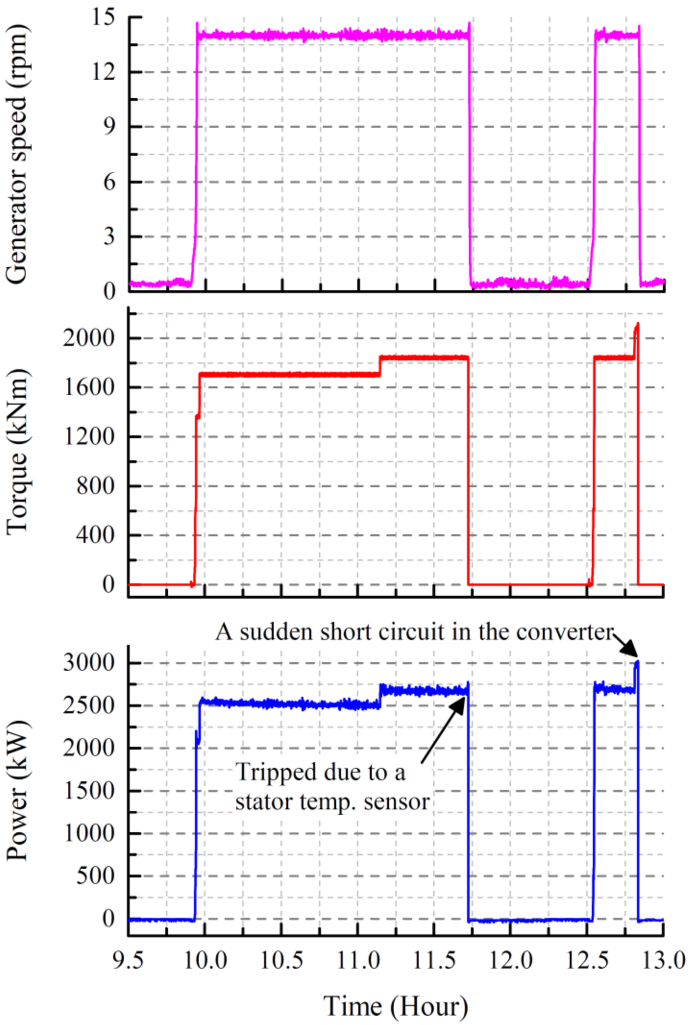
Power production



- Stable operation at 2 MW power level in unattended mode
- 2 weeks of continuous operation (remotely monitored)
- Short circuit in the converter system at 3 MW prevented reaching final 3.6 MW
  - Resonance in generator-tower cables-inverter - conventional technology
  - No problems in the rotor, no doubt that 3.6 MW are possible

In total power was fed into the grid for 650h!
Many Danish households could claim
"powered by superconductivity".

3 MW test run
330 A excitation

Conclusions

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- The world's first superconducting generator was successfully built and operated on a wind turbine.
- This in general demonstrates
  - **compact and simple** use of superconductors,
  - superconductor technology and cryocooling **is stable and robust.**
- Superconducting generators can be
  - **much smaller** than present day "state of the art" generator (Ecoswing: 5.4 m → 4 m)
  - **much lighter** than present day "state of the art" generator (- 50 %)
- The same technology can be applied to other slow rotating machines
  - Motors and generators for ship propulsion
  - Hydro power generators

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Thank you!

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