Status of the Ecoswing project
EUCAS 2017, Geneva

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“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.”
Core ambitions

• 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.
The idea is to replace a PM generator with a superconducting generator.

This includes power conversion and refrigeration equipment.
Key technical figures

- **Generator:** Synchronous
- **Drive Train:** Direct Drive
- **Superconductor:** 2G Coated Conductor
- **Refrigeration:** Gifford-McMahon
- **Power Converter:** 4Q-IGBT
- **Turbine:** 2 Bladed, On-shore.
Key project figures

- 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
Integrated consortium

- 9 Partners from 5 countries working for a common goal

- Project web site: www.ecoswing.eu
Topics of the project

Specs
Design
Materials
Components
Assembly
Testing
Installation

Regulatory Oversight
Topics for this presentation

- Specs
- Design
- Materials
- Components
- Assembly
- Testing
- Installation

Regulatory Oversight

Horizon 2020
European Union Funding for Research & Innovation
General requirements

- Design according to IEC61400 and IEC60034 series
- 3.600 kW, 2.460 kNm, 690 V, 50 Hz
- Insulation class F
- Max temperature rise class B
- Temperature, external: -20 °C +30 °C
- Altitude: 2000 m
- Humidity <95%, 100% for 10% of life
- Turbine system mechanical load
- Vibrations (Fore-aft, Side-side, Roll, Nod, Yaw)
- Restricted space request for compact design
- Serviceable wear parts
- Service interval minimum 1 year
- Lightning protection IEC61400-24

Same as for conventional generators
Unique requirements

• Stability of superconductor supply
• Reliable Coil winding
• Robust and proven cryogenics (incremental innovation)
• Risk mitigation through testing of sub components.

Unique for superconductive generators
Main design goals

- **40% lower weight**

- **All roads capability:** diameter limited to < 4 m

- **Low cost design:** Commercial components for superconductors as much as possible

- **Low weight design:** Optimized for low top head mass

- **Mainstream markets:** 3.6 MW for on-shore and off-shore.
## EcoSwing generator
### Design specifications

<table>
<thead>
<tr>
<th>Design Specification</th>
<th>3.6 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator terminal power</td>
<td>4,000 mm</td>
</tr>
<tr>
<td>oD generator frame</td>
<td>15.0 rpm</td>
</tr>
<tr>
<td>Rated speed</td>
<td>With iron core sheets</td>
</tr>
<tr>
<td>Stator type</td>
<td>Radial air cooling</td>
</tr>
<tr>
<td>Stator voltage</td>
<td>710 V</td>
</tr>
<tr>
<td>Axial core length</td>
<td>1,142 mm</td>
</tr>
<tr>
<td>Stator coils</td>
<td>Form wound copper coils, mica insulation system, VPI, class F</td>
</tr>
<tr>
<td>Bearings</td>
<td>2 main</td>
</tr>
<tr>
<td>Free mechanical air gap</td>
<td>13 mm</td>
</tr>
<tr>
<td>HTS wire dimensions, bare</td>
<td>12 x 0.2 mm$^2$</td>
</tr>
<tr>
<td>Current density in HTS pack</td>
<td>~ 100 A/mm$^2$</td>
</tr>
<tr>
<td>Efficiency (rated)</td>
<td>~ 92%</td>
</tr>
<tr>
<td>Current loading</td>
<td>132 kA/m</td>
</tr>
<tr>
<td>Cogging torque</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Load torque ripple</td>
<td>&lt; 1.5%</td>
</tr>
<tr>
<td>THD stator voltage</td>
<td>~ 1%</td>
</tr>
</tbody>
</table>

**EcoSwing**

**Horizon 2020**

**European Union Funding for Research & Innovation**

**ECO5**

**JEUMONT Electric**
A short circuit event in the power converter is not very likely—but a potentially disastrous event:

- It can break the generator as well as the hub and the blades.
- In the example (right) it amounts to 4x nominal torque.

Torque-limiting measures needed:

- Overrating for high torque in short circuit events counters the thermal efficiency of the HTS rotor.
Computation of the short circuit torque is required
  - Makes calculation of entire ring necessary (not just one pole)
  - Must include inertia of rotor and shaft as torsional spring
  - Must include stator and rotor

Example shown (right)

Mechanical design was made such that it sustains this short circuit, and the resulting torque levels.
Dual use vacuum chamber

• Cryostat serves two purposes:
  • Thermal insulation
  • Force transmission from shaft to the HTS poles

• Here the cryostat constitutes also the inner structure
  • One piece
  • Lower cost
  • Can be made of low cost steel.
Pole connectors

• HTS coils are all the same (no difference in N and S Pole)

• Connectors are designed such the NSNS Pole arrangement is achieved.
• Commercially available current feed throughs were considered inadequate for use in vibrating wind power environment.

• A robust system was developed allowing high current, industrial metal seals, no ceramic soldered to metal and a large cross-section allowing a small thermal gradient.
THEVA Pro-Line™

• High performance 2G HTS tape
• Simple layer architecture
• Contains 20 years of R&D
• Unique approach – all IP owned by THEVA

THEVA Pro-Line - Substrate (Hastelloy C276)
90 – 100 µm

Silver contact layer (surround) ~ 1.5 µm

HTS film
(GdBα₂Cu₃O₇₋₋ₓ)
3 – 5 µm

MgO cap layer
0.3 – 0.5 µm

ISD-MgO
~ 3 µm

MgO cap layer
0.3 – 0.5 µm

Substrate (Hastelloy C276)
90 – 100 µm
HTS Tape production

PRODUCTION FEATURES
• Built 2012-2014, commissioned end of 2015
• Maximum production capacity: 150 km/yr (@ 12 mm-width)
• Production tape length: 300 m, up to 600 m demonstrated!

GOALS
• Cost efficient production
• Robust process allowing high yield
• Implementation of industrial standards
• Proof of production: high quality tape

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Production sequence

Modular
Continuous vacuum tape locking
Roll-on with in-line quality control
Physical vapor deposition with electron beam evaporation
Pay-off (back side)
HTS tape design

Example of adiabatic quench temperature simulation

THEVA TPL2100 Pro-Line HTS tape

HTS wire with thick copper stabilization for superior electrical stability and high mechanical robustness

HTS tape designed according to needs!
Characterization of HTS tapes

Magnetic field performance - $I_c(B,T)$

Patterned bridges 1-2 mm wide

Reliable lift factor as prerequisite for stable production

15 samples taken out of production over about 1a:
LF(1.5 T, 30K) = 2.2 ± 0.4

**Reliable lift factor as prerequisite for stable production**
Critical current measurement using Tapestar hall scanning

Optical width measurement after lamination

Other parameters to be controlled: Lamination strength, bending radius, thickness

Quality control is considered crucial for successful manufacturing of the HTS coils
Qualification of superconductive joints

Validation of magnetic properties

Validation of copper RRR
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...
Components

Specs
Design
Materials
Assembly
Testing
Installation

Regulatory Oversight

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Subscale coil test

Test coil #1
- single layer
- 10 turns

LN₂ test

Pole assembly test
- magnetic pole piece
- non magnetic mechanical support
- conduction cooling
A very straightforward thermal model, combined with non-linear self-heating ...

\[ P(T) = I_0 V(T) = I_0 V_c \left[ \frac{l_0}{I_c(T)} \right]^n \]

... yields a non-linear 1\textsuperscript{st} order differential equation for the temperature-time response:

\[ \frac{d\theta}{d\tau} = \frac{1}{(1 - \theta)^n} - \alpha \theta \]

\[ r = \frac{t}{\Delta t_0} = \frac{P(T_0)}{C \Delta T_0} \tau \] and \[ \alpha = \frac{k \Delta T_0}{P(T_0)} \]

\[ \theta = \frac{T - T_0}{\Delta T_0} \]
**HTS full scale coils**

**Main characteristics**

- Each coil contains more than 500 m of HTS wire and has about 200 turns
- Coils are 1.4 m long, double pancake
- Potted in resin
- Used wire: Standard THEVA Pro-Line HTS conductor with Copper lamination
- Operating temperature < 30 K, conduction cooled
- Pole assembly containing only few parts for fast assembly
Winding of type-test coil

Start of coil winding

First layer nearly finished

Soldering of joints
Type-testing of HTS coils

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

Type test passed on first attempt

![Graph showing $I_c$ vs. Temperature](image)

UNIVERSITY OF TWENTE.
Acceptance tests at 35 K

Test rig for testing of 4 coils mounted in the coil assemblies

- Cooling via Cu coldbus identical to rotor situation
- Similar forces as in the rotor
- Overcurrent and overheat conditions to pass the test
- Focus on testing of basic functionality, only few “scientific“ measurements
Acceptance tests in LN2

LN2 test of coils

• Cooling by slow submersion in LN$_2$

• Test if
  • coil is superconducting,
  • resistance of joints is low and
  • $I_c$ is as designed

• Can be done easily at different locations without special requirements

A fast and easy test suitable for economic quality control in a series production
- SHI Cryogenics Group provides commercial grade cryogenic equipment
  - SRDK-500B cryocoolers
  - F-70 compressors.
SRDK-500B coldhead

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>25 kg</td>
</tr>
<tr>
<td>Compressor</td>
<td>F-70H</td>
</tr>
<tr>
<td>Power (50/60Hz)</td>
<td>7.5/9.0 kW</td>
</tr>
<tr>
<td>Maintenance</td>
<td>expected every 18,000 hrs</td>
</tr>
<tr>
<td>Orientational Dependence</td>
<td>&lt;30%</td>
</tr>
<tr>
<td>Regulatory</td>
<td>UL/CE</td>
</tr>
<tr>
<td>Noise</td>
<td>70 dBA</td>
</tr>
</tbody>
</table>
Orientation Dependence
@ 40W Heat Load

Temperature (K)

Angle (deg.)

Sample N=1
Power conversion

- DELTA provides the power converter
  - Latest IGBT technology
  - Assembled power stack shown on the left
- Power rating up to 1000 kVA
  - High power density design
  - Cost effective standard liquid cooling
- DELTA also provides
  - Quench protection / DAQ
  - Exciter.

Power Stack
Assembly

Specs

Design

Materials

Components

Testing

Installation

Regulatory Oversight

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Main shaft
Raw cast at foundry
Rotor yoke
With coils ready for mounting
Stator assembly
Conventional with iron core sheets
Stator coils
Form wound copper, mica insulation, VPI, class F
Stator flanges
Drive end side and non-drive end side
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“EcoSwing aims at nothing less than world's first superconducting low-cost, lightweight drive-train demonstrated on a large-scale modern wind turbine”
THANK YOU!