HTS field coils with robust design for a superconducting wind turbine generator

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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 MW Class, 15 rpm, 128 m rotor)
- Prove that a superconducting drive train is cost-competitive
- Have the generator running in 2017.
Turbine integration

Envision GC-1 Turbine

Generator in rear module

Rear module with existing Permanent Magnet Generator is replaced by more compact HTS Generator.

Outer diameter is reduced from 5.4 m down to 4 m and torque capability is unchanged.
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
- EcoSwing completed design stage, generator is in assembly.
Key project figures

For a full overview on our project: Plenary talk on Thursday 16h by Jürgen Kellers

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Integrated consortium

• 9 Partners from 5 countries working for a common goal

- Envision
- ECO
- Jeumont Electric
- Delta Energy Systems
- Theva
- SHI Cryogenics Group
- Fraunhofer
- University of Twente
- DNV-GL

• Project web site: www.ecoswing.eu
HTS coils are the heart of the HTS generator!
Agenda

- Requirements
- Tape design and characterization
- Development using sub-scale test coils
- Theory on thermal stability of coils
- Manufacturing of full size HTS Coils
- Type Test
- Routine Tests
A list of requirements that were defined in the beginning:
- Use 2G HTS wire with suitable stabilization
- Double pancake coils
- Size in the beginning not fixed but between 1.0 m and 1.4 m in length
- Number of turns: around 200
- Conduction cooled
- Operation temperature around 30 K
- Cold iron yoke
- Operating field 1-2 T (at the coil)
- Simple to manufacture and simple to mount
- Nothing fancy! Off the shelf if available!
THEVA TPL2100 Pro-Line HTS tape
HTS wire with thick copper stabilization for superior electrical stability and high mechanical robustness

Example of adiabatic quench temperature simulation

More Information on tapes today afternoon 16h TUE-Af-Or17
Characterization of HTS tapes

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

Patterned bridges 1-2 mm wide

Full width samples 12 mm, up to 80 mm long

Measurement of 15 samples taken out of production over about 1 year:
$LF(1.5 \, T, \, 30 \, K) = 2.2 \pm 0.4$

Robinson Research Institute

30 K

$30 \, K$

$LF(B) = LF(B=1T) \times B^{-\alpha}$ with
$LF(1T) = 2.72$ and $\alpha = 0.49$

Horizon 2020 European Union Funding for Research & Innovation
Development of highly reproducible joints

- 10 cm long lap joints (12 mm)
- Solder: In97Ag3
- Highly reproducible
- Typical: 4.8 nΩ or 60 nΩ cm² @ 77 K
Joint resistance at operating conditions

R(B,T) measurements of joints

- Mean joint resistance 36 nΩ cm²
- No significant dependence on magnetic field or temperature

→ Joints can be accepted in the coils
Sub-scale HTS coils

General characteristics

• Pancake coils
• Mechanically robust: tape is fixed and protected by resin
• Well defined shape and surface by using a mould
• Current connection mechanically fixed within cast coil

Sub-scale test coils

• Design similar to full-size coils, but shorter
• 4 single and one double layer coil
• 10 turns ... 2 x 87 turns of HTS wire

THEVA booth
Example of coil

10 turns
300 mm
double layer test coil

2 x 87 turns
single layer test coil
first sub-scale test coil manufacturing

General characteristics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Coil number</strong></td>
<td>1</td>
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<tr>
<td><strong>Geometry</strong></td>
<td>Single pancake</td>
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<tr>
<td><strong>Number of turns</strong></td>
<td>10</td>
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<tr>
<td><strong>Number of HTS tapes</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Number of joints</strong></td>
<td>none</td>
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</tbody>
</table>
First sub-scale test coil LN$_2$-testing

$\mathbf{I_c}$ measurement in LN$_2$

- Critical current at 77 K as expected from tape data and self field of the coil
- No degradation after several thermal cycling runs
First sub-scale HTS coil – test of mechanical robustness

- Mechanical deformation in LN$_2$ with screw up to 3 mm deformation
- Monitoring of $I_c$ during the test
- Coil was plastically deformed afterwards
- No influence on $I_c$
- No cracks in resin

→ Mechanically robust coil system
First sub-scale HTS coil – pole assembly

- Current connection to innermost layer (only for single layer coils)
- Iron pole
- SUS cassette
- Cu cooling plates
- Current connection
First sub-scale HTS coil full pole assembly

Test of full pole assembly in test rig

Testcoil #1

- Temp-Zykl1
- Temp-Zykl3
- Temp-Zykl5
- Temp-Zykl6: UTwente 77K, sf

- Voltage [μV]
- Current [A]

77K, 10 turns

- $I_c$: 216 A in LN$_2$
- $I_c$: 215 A conduction cooled
- $n$: 37
- $n$: 44

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First sub-scale HTS coil test rig measurements

At 30K: \( I_c \) of about 1000 A (800 \( \mu \)V)
Double layer sub-scale test coil

**General characteristics**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil number</td>
<td>4</td>
</tr>
<tr>
<td>Geometry</td>
<td>2, “double pancake”</td>
</tr>
<tr>
<td>Number of turns</td>
<td>$2 \times 87 = 174$</td>
</tr>
<tr>
<td>Number of HTS tapes</td>
<td>10</td>
</tr>
<tr>
<td>Number of joints</td>
<td>11</td>
</tr>
</tbody>
</table>

Double layer Sub-scale test coil in stainless steel cassette

**Testcoil #4 n=174**

![Graph showing voltage vs. current](image)

Voltage taps

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Double layer sub-scale test coil

Test rig

Double layer test coil mounted in test rig

Mounted in test rig including MLI blanket.

Copper cooling plate

Current connection

Design validation: $I_c$, joint & interconnect resistance, inductance, temperature distribution, quench behaviour, ...

First cool-down

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Subscale HTS coil $I_c(T)$ measurements

- **Ic criterion**
- 2 x 87 turns

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**Legend for Voltage (V) graph**:
- Red: 80K
- Orange: 77K
- Yellow: 70K
- Green: 60K
- Cyan: 50K
- Blue: 40K
- Purple: 35K

**Legend for Critical Current (A) graph**:
- Red: Critical Current
- Black: Fitted $I_c$ ($R^2=0.998$)
- Red square: n-value

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Some theory.......
Measurements of the sub scale test coils showed:

- Small changes in current have huge effect on voltage development at quench
- Similar shape of $U(t)$ curve

$\Rightarrow$ Development of thermal model

More information
Anne Bergen
Mon-Af-Or9
A very straightforward thermal model, combined with non-linear self-heating...

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

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

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

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

\[ \theta = \frac{T - T_0}{\Delta T_0} \]
Stability & thermal drift

The time-scale depends on coil enthalpy and on initial heating level, but typically turns out to be minutes - hours.
Now back to engineering ...
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

1,4 m
coil
pole assembly
Winding of type-test coil

Start of coil winding

First layer nearly finished

Soldering of joints
Potting of type-test coil

- Casting mould
- Potting
- Coil after potting still in mould
- Final coil
Type-testing of HTS coils

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

$\Rightarrow$ Type test passed on first attempt

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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

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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
• A robust HTS coil technology was developed using standard industrial coil manufacturing equipment

• Sub-scale test coils for fast development the technology proved to be successful

• HTS conduction cooled coils show well tempered thermal behavior, i.e. slow thermal drift when overloaded → important for quench protection

• Full size HTS coil passed the type test at overcurrent and overtemperature conditions

• Acceptance tests at 35 K and 77 K were developed and are used now for the quality control of the ongoing production of the coils
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