Development of a Superconductive Wind Power Generator within the EcoSwing Project

"Energy Cost Optimization using Superconducting Wind Generators"

"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."
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:** PVD CC (GdBaCuO)
- **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](http://www.ecoswing.eu)
Topics for this presentation

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

Regulatory Oversight
• As power sizes go up Permanent Magnet Generator (PMG) beat Doubly Fed Induction Generator with gearboxes (DFIG)
  • Large DFIG becomes too heavy and too costly to maintain
  • Direct Drive (DD) have less maintenance, higher part load efficiency, better scalability
  • The future of wind turbine drivetrains belongs to DD machines i.e. without gearboxes

• Future wind turbines are on floating platforms i.e. top mass must go down
  • Future drivetrains must be significantly lighter relative to existing DD solutions
  • High power density, low costs and low weight are the benchmarks for the future
  • PMG technology is at the moment the only candidate.

Superconductor Generators shows bigger potential than PMG as the wind turbines grows in power
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
- Robust and proven cryogenics (incremental innovation)
- Risk mitigation through testing of sub components.
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>
</tr>
</thead>
<tbody>
<tr>
<td>Generator terminal power</td>
</tr>
<tr>
<td>oD generator frame</td>
</tr>
<tr>
<td>Rated speed</td>
</tr>
<tr>
<td>Stator type</td>
</tr>
<tr>
<td>Stator primary cooling</td>
</tr>
<tr>
<td>Stator voltage</td>
</tr>
<tr>
<td>Axial core length</td>
</tr>
<tr>
<td>Stator coils</td>
</tr>
<tr>
<td>Bearings</td>
</tr>
<tr>
<td>Free mechanical air gap</td>
</tr>
<tr>
<td>HTS wire dimensions, bare</td>
</tr>
<tr>
<td>Current density in HTS pack</td>
</tr>
<tr>
<td>Efficiency (rated)</td>
</tr>
<tr>
<td>Current loading</td>
</tr>
<tr>
<td>Cogging torque</td>
</tr>
<tr>
<td>Load torque ripple</td>
</tr>
<tr>
<td>THD stator voltage</td>
</tr>
<tr>
<td>3.6 MW</td>
</tr>
<tr>
<td>4,000 mm</td>
</tr>
<tr>
<td>15.0 rpm</td>
</tr>
<tr>
<td>With iron core sheets</td>
</tr>
<tr>
<td>Radial air cooling</td>
</tr>
<tr>
<td>710 V</td>
</tr>
<tr>
<td>1,142 mm</td>
</tr>
<tr>
<td>Form wound copper coils, mica insulation system, VPI, class F</td>
</tr>
<tr>
<td>2 main</td>
</tr>
<tr>
<td>13 mm</td>
</tr>
<tr>
<td>12 x 0.2 mm²</td>
</tr>
<tr>
<td>~ 100 A/mm²</td>
</tr>
<tr>
<td>~ 92%</td>
</tr>
<tr>
<td>132 kA/m</td>
</tr>
<tr>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>&lt; 1.5%</td>
</tr>
<tr>
<td>~ 1%</td>
</tr>
</tbody>
</table>
Starting Point: Established methods have deficits in simulating DC and slow AC
  - Coil charging, load changes, short circuits...
  - Compare V. Zermeno et al, “Calculation of alternation current losses in stacks and coils ...”, JAP 114, 2013

Goal: Develop method to calculate dynamic behavior upon transients in 2G HTS

Approach:
  - Use perpendicular components of vector potential as unknown
  - Use HTS current density as unknown
  - Use non-linear E(j) as a constraint

Status:
  - “Physics Module” integrated into Comsol Multiphysics
  - For 2G wires without simplifications, including copper stabilization
  - Applicable to DC and slow AC, also to magnetizing currents
  - Works for complex applications, faster and memory efficient.

Improved AC loss computation method in HTS wire

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.
Dynamic modelling of turbine

• Mechanical and electromechanical computations for entire system
  • Site data (wind turbulence) by WindPro
  • Mechanical turbine response by BLADED
  • Generator electromechanical (and thermal) response by COMSOL

• We detected neither prohibitive resonance, nor prohibitive ac loss

• Statistical time series data will be tested during ground based test.
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.
• 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.
Pole connectors

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

upper layer connection

lower layer connection

• Connectors are designed such the NSNS Pole arrangement is achieved.
• CAD model feeds bill-of-materials
  • Provides master list for procurement
  • Provides cost estimate under series manufacturing.
HTS tape
THEVA TPL2100 Pro-Line

<table>
<thead>
<tr>
<th>Architecture</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Hastelloy™ C-276, non-magnetic</td>
</tr>
<tr>
<td>Buffer layer</td>
<td>MgO</td>
</tr>
<tr>
<td>HTS layer</td>
<td>GdBa₂Cu₃O₇</td>
</tr>
<tr>
<td>Metallization</td>
<td>~ 1 μm Silver surround</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>100 μm Copper on HTS side</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.20 - 0.23 mm</td>
</tr>
<tr>
<td>Width</td>
<td>12.0 - 12.5 mm</td>
</tr>
<tr>
<td>Minimum double bend diameter (RT)</td>
<td>60 mm</td>
</tr>
<tr>
<td>Recommended maximum handling force</td>
<td>150 N (15 kg)</td>
</tr>
<tr>
<td>Maximum rated stress</td>
<td>340 MPa at room temperature</td>
</tr>
<tr>
<td>Maximum rated tensile strain</td>
<td>0.3% at 77K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum critical current $I_c$ (77 K, self-field)</td>
<td>360 A, other current ratings upon request</td>
</tr>
</tbody>
</table>

HTS wire with thick copper stabilization for superior electrical stability and high mechanical robustness
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 1st order differential equation for the temperature-time response:

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

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

$$\theta = \frac{T - T_0}{\Delta T_0}$$
Qualification of Materials and Procedures

Just a few examples...

- Qualification of superconductive joints
- Validation of magnetic properties
- Validation of copper RRR

ECOSWING Copper pieces

<table>
<thead>
<tr>
<th>Sample</th>
<th>RRR (273.15/10)</th>
<th>RRR (273.15/30)</th>
<th>R at 273.15K [Ω]</th>
<th>R at 10K [Ω]</th>
<th>R at 30K [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piece 2, Electrical connection, #1</td>
<td>124.2</td>
<td>81.6</td>
<td>4.403E-04</td>
<td>3.545E-06</td>
<td>5.395E-06</td>
</tr>
<tr>
<td>Piece 2, Electrical connection #2</td>
<td>123.9</td>
<td>81.8</td>
<td>4.575E-04</td>
<td>3.705E-06</td>
<td>5.596E-06</td>
</tr>
<tr>
<td>Piece 3, Cooling Plate, #1</td>
<td>78.6</td>
<td>59.0</td>
<td>9.524E-04</td>
<td>1.212E-05</td>
<td>1.613E-05</td>
</tr>
<tr>
<td>Piece 3, Cooling Plate, #2</td>
<td>78.7</td>
<td>59.2</td>
<td>9.471E-04</td>
<td>1.203E-05</td>
<td>1.600E-05</td>
</tr>
</tbody>
</table>
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

Components
Subscale coil test

Test coil #1
- single layer
- 10 turns

LN₂ test

Pole assembly
- magnetic pole piece
- non magnetic mechanical support
- conduction cooling

Markus Bauer et al.
TUE-MO-OR14-01
HTS coil specifications

• ~ 200 turns with 500 m of copper laminated HTS wire

• Double pancake, insulated design, potted using commercial resin, glass fiber reinforced

• Use of casting mold for smooth surface
  • optimum mechanical and thermal contact

• Operating temperature < 30 K, conduction cooled with cold heads.
Type testing of HTS coils

Operating conditions

Temperature (K)

Ic/operating current

UNIVERSITY OF TWENTE
• SHI Cryogenics Group provides commercial grade cryogenic equipment
  • SRDK-500B cryocoolers
  • F-70 compressors.
SRDK-500B coldhead

- Weight: 25 kg
- Dimensions: 325mm x 570mm

Specifications:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<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 expected</td>
<td>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>
<tr>
<td>20K</td>
<td>40/50 W</td>
</tr>
<tr>
<td>30K</td>
<td>80/95 W</td>
</tr>
</tbody>
</table>
SRDK-500B
Orientation dependence

Orientation Dependence
@ 40W Heat Load

Temperature (K)

Sample N=1

50Hz
60Hz
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 conversion
Stack Detail

- Metallic holder with mounted electronics, such as current and voltage transducer and the Control Board (1)

- DC link bus with DC link capacitors (2)

- Cooling plate with IGBT modules (3).
Quench protection / DAQ

- Quench protection / DAQ system
  - Contains voltage and temperature measurement cards
  - Voltage drop increase will immediately be recognized and excitation will be stopped
  - Sensor data will be stored in data acquisition system.
• Powering the superconducting rotor coils
• Mounted in rotating frame
• Steady state voltage drop only determined because of voltage drop over copper connections
• Exciter control by microcontroller
• Communication via Ethernet
• Error detection:
  • Ground fault
  • Overcurrent
  • Communication fault
  • Over temperature
  • Quench.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Slip ring current</td>
<td>50 A</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Rotor Inductance</td>
<td>4 – 16 H</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>0.2 mΩ</td>
</tr>
<tr>
<td>Output Current</td>
<td>0 – 600 A</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>0 – 15 V</td>
</tr>
<tr>
<td>Maximum charging rate</td>
<td>1 A/s</td>
</tr>
<tr>
<td>Maximum discharging rate</td>
<td>10 A/s</td>
</tr>
<tr>
<td>Maximum induced voltage</td>
<td>200 V</td>
</tr>
<tr>
<td>Ground fault detection</td>
<td>DC output</td>
</tr>
<tr>
<td>Lightning protection</td>
<td>AC input</td>
</tr>
<tr>
<td>Safety Chain</td>
<td></td>
</tr>
<tr>
<td>Shielded signal wires</td>
<td>-</td>
</tr>
<tr>
<td>Communication</td>
<td>Ethernet</td>
</tr>
</tbody>
</table>
Converter container

- Converter mounted into standard 20’ container
- Main water cooling system for converter with 2 heat exchanger
- Air conditioning for container
- Cooling systems can handle losses of 120 kW.
Stator coils
Form wound copper, mica insulation, VPI, class F
Stator assembly
Conventional with iron core sheets
Rotor yoke
With coils ready for mounting
Stator flanges
Drive end side and non-drive end side
Stator air ducts
Main shaft
Raw cast at foundry
Testing
Ground based test at Dynamic Nacelle Laboratory

- Fraunhofer IWES will execute tests in its DyNaLab facility
  - Nacelle testing lab
  - Max torque 13 MNm
  - Max power 15 MW.
Key features of nacelle test rig

Hydraulic load application system
- Simulation of wind loads
- 1.2 MW ~2.1m³/min @315bar
- Thrust: ± 1900 kN, Radial: ± 2000 kN
- Bending: ± 20000 kNm (rotating y-, z-axis)
- Dynamic: 0-2 Hz (30% of max. load)
- 0-g unit for weight compensation (150 to)

Drive
- 5° inclined drive train
- 10/15 MW (nominal/peak) - Twin Synchronous Direct Drive
- 8.6/13 MNm (nominal/peak)
- Flexible coupling
- Hydraulic safety coupling (adjustable 8-15 MNm)

Grid simulation
- 10/20/36 kV tappings
- 44 MVA installed converter capacity
- LVRT & HVRT simulation
- < 2% THD @ 50 Hz
Ecoswing test setup
Regulatory Oversight
Future accreditation considered from the start

• DNV GL Renewables Certification is accredited Certification Body according to DIN EN ISO/IEC 17065:2013

• DNV GL has long history – developing guidelines for wind turbines (1986 1st guideline for certification of onshore wind turbines published).
Tasks of DNV GL in EcoSwing

- Monitoring of development and tests
- Focus on critical aspects as well as certification aspects
- Participation in type testing at Fraunhofer IWES in Bremerhaven and on-site tests in Thyborøn
- Development of “DNV GL Recommended Practice for superconducting drive trains of wind turbines”
  - Currently there are no relevant standards or guidelines covering critical aspects of superconductors inside generators for wind turbines
  - DNV GL wants to change this.
There are no superconductor requirements in relevant standards

- IEC 61400-1 for wind turbines
- IEC 60034 for generators
- IEC 62477 for converter

This will be considered in the new Recommended Practice as well as additional requirements for cryogenic cooling equipment

- Provides principles, technical requirements and guidance for design of superconducting drive trains for wind turbines
- Will be the technical basis for future DNV GL certification processes of superconductive drive trains.
• Superconducting drive trains in wind turbines are “development projects”
  • Suppliers need to meet industrial market standards

• For commercialization, the following aspects need to be accomplished
  • Sufficient availability of superconductor wire and coils in good quality at low costs
  • Operational safety in normal or faulted operation
  • Demonstration of expected lifetimes
  • High reliability under extremely challenging environmental conditions of wind turbines installed onshore as well as offshore (e.g. temperature range incl. minimum and maximum temperature, vibration, shock, marine environment, etc.)
  • “Simple” and “easy” maintenance of the superconductor components.
The GC-1 wind turbine

- Two bladed turbine with partial pitch
  - Innovative design
  - Typhoon safe
  - In operation since 2013
- More info [www.project-gc1.com](http://www.project-gc1.com)
- Ideally suited for generator exchange.
The GC-1 wind turbine

Foundation Loads during a 360 degree change in wind direction

- Moment caused by wind
- Two bladed profile
- Three bladed profile

PP-2B technology has a significant potential for CAPEX reduction
Turbine integration

• Generator in rear module

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

• Outer diameter is reduced from 5.4m down to 4m and torque capability is unchanged.
Placement of power conversion container

- Location at bottom of tower
- Replaces existing power conversion container
- Grid connection container on the other side of the tower.
“EcoSwing aims at nothing less than world's first superconducting low-cost, lightweight drive-train demonstrated on a large-scale modern wind turbine”
Acknowledgements to the Team

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Christian Koppe
Christian Kruse
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Peterson Legerme
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