Development and Optimization of Large Direct Drive Superconducting Generators for Off-Shore Wind Farms

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Oct. 29th, 2013
Houston, TX

Outline

- Introduction
- Superconducting generators
- HTS conductor choice
- Fully Superconducting Generator - DOE
- Partially Superconducting Generator - ARPA-e
- Conclusion
• Introduction
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• Partially Superconducting Generator - ARPA-e
• Conclusion
Global Energy – A “Hungry” Market

• Existing and expanding global economies have a large appetite for Energy...

...with no signs of letting up!

“\textbf{In order to meet the 45\% increase in projected demand, an investment of over $26 \text{ trillion} \text{ will be required ...}”}

Sources: 
Global Offshore Wind Market

> 80 GWatts of new installations (>8,000 ea 10 MWatt Turbines)

Source: IHS Emerging Energy Research
Price Range of Renewable Electricity (2008)

*Average cost will vary according to financing used and the quality of the renewable energy resource available.

Sources: Idaho National Laboratory, Carbon Trust, Simmons Energy Monthly, U.S. DOE-EERE, IEA, Solarbuzz LLC, REN21, LBNL
Attaining Cost Of Energy Goals for Wind

- 10 GW @ 10c/kWh by 2020, 54 GW @ 7c/kWh by 2030...today at 27c/kWh
Wind Generators – Requirements

- Large power output (less generators)
- High reliability; high availability
- Low capital cost (CAPEX)
- Ease of manufacture and assembly
- Ease of maintenance
- High efficiency

How costs compare

<table>
<thead>
<tr>
<th></th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine &amp; installation</td>
<td>65%</td>
<td>45%</td>
</tr>
<tr>
<td>Electrical Infrastructure, foundations &amp; other</td>
<td>14%</td>
<td>14%</td>
</tr>
<tr>
<td>OPEX</td>
<td>21%</td>
<td>24%</td>
</tr>
</tbody>
</table>

http://www.windpowerengineering.com/design/mechanical/understanding-costs-for-large-wind-turbine-drivetrains/
HTS Generators – Value Proposition

- Generator mass reduction
  - Some impact on LCOE
- High reliability; high availability
  - No gear box
  - No thermal cycling
  - Sealed system
    - Long maintenance time if problem in cryostat
    - No failure allowed at cryogenic temperature
- Low capital cost (CAPEX)
  - Driven by cost of conductor and cooling system
  - Expected to be competitive for large systems
- Ease of manufacture and assembly
- Ease of maintenance
  - Less reliable components can be located outside of the cryostat
  - Modular approach can be used (individual cryostats...)
- High efficiency
  - Low losses, high efficiency at fractional power output

HTS Machine Possible Configurations

- **Back Iron**
  - Low mass
  - Large number of poles
  - Low $x_d$
  - High short circuit current and torque
  - High peak field
  - Large quantity of HTS conductor
  - Low cooling requirements

- **Ironless All-Cryo**
  - Low mass
  - Low number of poles
  - Low $x_d$
  - **Fault current limitation**
    - High peak field
    - Very large quantity of HTS conductor
    - AC losses
    - High cooling requirements

- **Salient Iron**
  - Heavy
  - Reg. $x_d$
  - Low peak field (if not saturated)
  - Low quantity of HTS conductor
  - Low cooling requirements
  - Modular cryostat possible

* Courtesy of C. Oberly, AFRL

Field Windings: 
Armature Windings: 
Iron: 
Eddy Current Shield: 
Cyrogenic region: 
Output Terminals:
Design Requirements

• Economic
  – Low cost conductors
  – Low cost cryocoolers
  – Superconductor availability
  – Cost effective manufacturing

• Mechanical
  – Torque transmission/torque tube
    • Composite - steel
  – Large Lorentz forces (peak field >4 T)
  – Torque and forces applied on conductors

• Thermal
  – Heat leaks need to be minimized
    • Conduction through shaft
    • Current leads
    • Splices
  – AC losses
    • Multifilament conductors

• Stability
  – Quench detection/protection
  – Fault current/torque

![MgB2 conductor](image1)
![2G conductor](image2)
![Carbon fiber composite thermal conductivity](image3)
Partially and Fully Superconducting Machines

**Fully Superconducting (FSG)**

- Stator
  - Thermal Shield
  - Armature Wdg.
  - Field Wdg.
  - Shaft

- Rotor
  - Field Wdg.
  - Shaft
  - Thermal Shield
  - EM Shield
  - Armature Wdg.

**Partially Superconducting (PSG)**

**Apparent Power output of an electrical generator:**

\[
S = B_r^0 K_s \pi r_0^2 L_a \frac{\omega}{p}
\]

- \(S\) = apparent power (VA)
- \(B_r^0\) = no-load excitation field (T)
- \(K_s\) = electrical loading (A/m)
- \(R_0\) = average radius of armature winding (m)
- \(L_a\) = active length (m)
- \(\omega\) = angular frequency (rd/s)
- \(p\) = number of pole pairs

**Rotor contribution**
- Limited by conductor performance.
- More conductor needed in PSG because of the large air gap.

**Active volume**
- Larger radius needed for PSG because of the limited electrical loading.

**Stator contribution**
- Much higher values obtained in FSG because of high current density in superconductor.

**Rotation speed**
- Frequency needs to be kept low in FSG to limit AC losses.
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Choice of Conductor

- The conductor defines the operating temperature of the system

- Key conductor parameters:
  - Engineering critical current density @ operating field
  - Filament size (AC applications)
  - Ratio superconductor/ non superconductor
  - Minimum quench energy
  - Normal zone propagation velocity
  - Minimum bending radius
  - Cost

BiSrCaCuO conductors

MgB2 conductors

YBCO conductors
### High Level Conductors Comparison

<table>
<thead>
<tr>
<th>Superconductors</th>
<th>Cost</th>
<th>Bending radius</th>
<th>“SC” Splice</th>
<th>Small Filaments</th>
<th>Quench Detection</th>
<th>Isotropic Field Dependence</th>
<th>Critical Temp ($T_c$)</th>
<th>Operating Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1G (BSCCO)</strong></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>110K</td>
<td>~30K</td>
</tr>
<tr>
<td><strong>2G (YBCO)</strong></td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>92K</td>
<td>50-77K</td>
</tr>
<tr>
<td><strong>MgB2</strong></td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>39K</td>
<td>15-20K</td>
</tr>
</tbody>
</table>

- The choice of conductor is done at the system level considering the total cost of system conductor-cooling system.
- MgB2 is very promising:
  - Price point of MgB2 moving towards $10/kAm @ 2T, 20 K
  - Development of high filament count conductors (~10 mm)

- 2G (YBCO) is improving fast:
  - Current price point of YBCO at $400/kAm @ 2T, 60 K
  - Active development towards cost reduction and multi-filaments
    - 4X performance increase
Current Cost of Conductors at 2 T (2012)

Cost of conductor

- YBCO-$/kAm
- MgB2-$/kAm

4x improvement expected (UH – ARPA-e)

2x improvement expected (mass production, higher Jc) (DOE/NASA)
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Large Wind Turbine Generators

Department of Energy Awards Nearly $7.5 Million to Help Develop Next Generation Wind Turbines

June 28, 2011

U.S. Energy Secretary Steven Chu today announced that six projects in four states—California, Colorado, Florida, and New York—have been selected to receive nearly $7.5 million over two years to advance next-generation designs for wind turbine drivetrains. Drivetrains, which include a turbine's gearbox and generator, are at the heart of the turbine and are responsible for producing electricity from the rotation of the blades. The advances in drivetrain technologies and configurations supported through these research and development projects will help the United States maintain its position as a global leader in wind energy technologies, support thousands of American manufacturing, construction and planning jobs in a key renewable energy market, and reduce the cost of wind energy in the future. The projects selected today will also help promote and accelerate the deployment of advanced turbines for offshore wind energy in the United States.

"Developing innovative drivetrain technologies will allow U.S. manufacturers to build larger, more cost-effective, and more efficient wind turbines than any in operation today," said Secretary Chu. "The projects announced today will help the United States lead the global wind energy industry in this critical technology area, diversify our domestic energy portfolio, and create new jobs for American workers."

These early research and development projects will focus on reducing the cost of wind energy by increasing component reliability or redesigning drivetrains to eliminate gearbox, which reduces weight, operations and maintenance costs. Wind energy drivetrains can produce an overwhelming number of components that make up a drivetrain.

Each project has been selected to receive a Phase I award, which is the six-month Phase I funding period. Each project is expected to need 18 months. Projects selected for Phase II funding will each receive a total of $3.5 million. Below is a list of the projects selected for awards:

- **Advanced Magnet Lab (Palm Bay, Florida)** will develop an innovative superconducting direct-drive generator for large wind turbines. The project will employ a new technology for the drivetrain coil configuration to address technical challenges of large torque electric machines.

- **Boulder Wind Power (Boulder, Colorado)** will test an innovative permanent magnet-based direct-drive generator to validate performance and reliability of a large utility-scale turbine. Design requirements and optimization will also be documented for turbines up to 10 megawatts and for turbines deployed in offshore applications. The proposed generator design may operate at higher efficiencies than other permanent magnet generators.

- **Clipper Windpower (Carpinteria, California)** will develop and test a unique drivetrain design that enables increased serviceability over conventional gearboxes and is scalable to large capacity turbines.

- **Eaton Corporation (Cleveland, Ohio)** will design and test components of an innovative hydrostatic direct-drive concept, which uses a fluid transmission instead of a mechanical gearbox. The proposed drivetrain configuration eliminates many high risk components, this design also allows for reconfiguration of the drivetrain so that many of the high risk components are accessible/serviceable at the base of the turbine.

- **GE Global Research (Niskayuna, New York)** will design and perform component testing for a 10 megawatt direct-drive generator employing low-temperature superconductivity technology. The proposed generator employs a unique stationary superconducting component design that reduces the risk of fluid leakage.

- **National Renewable Energy Laboratory (Golden, Colorado)** will optimize and test a hybrid design that combines the advantages of geared and direct-drives through an improved single-stage gearbox and a non-permanent magnet generator that reduces the need for rare earth materials. The technology developed will be scalable to 10 megawatts, and may be used to retrofit currently deployed 1.5 megawatt turbines.
Fully Superconducting Generator (MgB2)

Turbine hub support and bearings

Fully Superconducting Generator

Approximate Specifications:
- Diameter: 3.5 m [140 in]
- Length: 7.6 m [300 in]
- Mass: 140 t [319,000 lbs]

Power Converters
Fully Superconducting Rotating Machine

- 10 MW, Direct Drive, Fully Superconducting Generator
  - Detailed Conceptual Design ✓
  - Cost of Energy Analysis ✓
  - De-risking Program Development: 2012-2014
    - Mechanical components
    - Manufacturing
    - Detailed LCOE
    - MgB2 Conductor development
    - Fault conditions
    - AC losses (modeling/experimental)
Fully Superconducting Generator (FSG) Block Diagram

- **Back Iron**
- **Stator Cryostat (@ 15-20K)**
  - Stator (Superconducting)
  - Heat Exchange
  - Rotor (Superconducting)
  - Heat Exchange
  - Cryocooling System (gas Helium)
  - Rotor Excitation (DC Power)
- **System Controls**
- **Power In**
- **Main Shaft (10 RPM)**
- **Rotor Cryostat (@15-20K)**
- **Current Leads**
- **Power Conversion (AC-DC-AC)**
- **Power Out**
FSG Design - High Fidelity Sizing Models

Proprietary Sizing Model is applied to obtain Superconducting Generator Design

1. **Primary inputs** ➔ Power requirement and RPM

2. **High fidelity analytical sizing** is performed from first principles based on a simplified geometry

3. **Primary outputs** ➔ Generator parameters
   - Electromagnetic
   - Thermal
   - Structural

2. **Optimization** is performed for minimum mass with constraints on the AC losses

3. **Final Outputs:**
   - Active length of coils
   - Overall principal dimensions
   - Rotor and stator field requirements
   - Key machine parameters

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   - Key machine parameters

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**Wdg. Parameters**
- Avg. r₀
- Number of Layers
- Air gap Length: d
- Wdg. Parameters

**ARMATURE SIZING**
- EM, electrical param.
- K_s, thickness, J
- Backiron thickness
- weight

**ROTOR SIZING**
- Rotor
- Thickness, J
- weight

**SOLVER**
- Torque- Power- Weight- Efficiency...

**DESIGN**
AC Losses and Machine Mass Trade-Off

- AC losses can be reduced at the expense of additional weight
- Cryocooler represents a small fraction of the total weight
3D FEA Models

**Electromagnetic**

**Structural**

- FEA models for generator design and optimization

**Electro-thermal**

**Thermal**

Temperature gradient $\sim 3.5 \text{ K}$

Flow of GHe $\sim 4.7 \text{ l/s}$

Heat pulse
Stator Current Limitation

• **The superconducting stator acts as fault current limiter**
  - ✓ Provides lower short circuit torque
  - ✓ Provides lower short circuit power without impacting dynamics

• **Fault Sequence:**
  1. Short circuit occurs and phase current rises
  2. Current level exceeds $I_c$ (MgB$_2$ critical current)
  3. Stator current diffuses from the superconductor to the matrix material throughout entire coil
  4. Coil impedance changes from inductive to resistive
  5. Single phase impedance rises from $\sim 4 \Omega$ to $>600 \Omega$
  6. Fault current drops from $>1,000$ A to $\sim 6$ A (dissipating $\sim 22$ kW)
  7. Phase imbalance is detected
  8. Temperature rise in windings has to be limited to less then 60K

*Phase current vs. time*
• Accomplishments
  – Design and detailed CAD drawings
  – Manufacturing plan
  – Detailed LCOE model
• Ongoing work
  – De-risking tasks (structural material, multi-filamentary conductors, cooling, quench...)
  – AC losses in superconducting stator
    • Modeling
    • Experimental validation
  – Higher fidelity LCOE model considering dynamic analysis
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• ARPA-E funded program
• UH-led program with SuperPower, TECO-Westinghouse, Tai-Yang Research and NREL.

Technology Impact

Present-day superconducting wire constitutes more than 60% of the cost of a 10 MW superconducting wind generator. By quadrupling the superconducting wire performance at the generator operation temperature, the amount of wire needed would be reduced by four which will greatly enhance commercial viability and spur a tremendous growth in wind energy production in the U.S.

Engineered nanoscale defects

4x improved wire manufacturing

Quadrupling Superconductor Wire Performance for Commercialization of 10 MW Wind Generators
• Warm iron rotor core
• Individual cryostats for HTS coils
• Copper air-gap stator
• GHe cooling system

• Design of 2MW generator used as starting point for the 10 MW generator
The rotor magnetic configuration is controlled using binary parameters.

*The gray parts are magnetic*
Geometry Parameterization

• Geometry is entirely parameterized

• Poles are represented by non-dimensional parameters
Model Input and Output Parameters

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Number of pair of poles</td>
<td>• $B_{\text{max}}$ in the Inductor’s Winding</td>
</tr>
<tr>
<td>• Magnetic Length</td>
<td>• $B_{\text{max radial}}$ in the Inductor’s Winding</td>
</tr>
<tr>
<td>• Angle</td>
<td>• $B_{\text{max tangential}}$ in the Inductors’ Winding</td>
</tr>
<tr>
<td>• Size of the Pole</td>
<td>• $B_{\text{max}}$ in the airgap</td>
</tr>
<tr>
<td>• Size of the Crown</td>
<td>• Torque</td>
</tr>
<tr>
<td>• Size of the Air hole</td>
<td>• Active Mass</td>
</tr>
<tr>
<td>• Size of the Spacing between the Winding and the Pole</td>
<td>• Mass of the Stator’s Winding</td>
</tr>
<tr>
<td>• Rotor pole height</td>
<td>• Mass of the Rotor’s Winding</td>
</tr>
<tr>
<td>• Rotor Crown side height</td>
<td>• Mass of the Core</td>
</tr>
<tr>
<td>• Rotor Radius</td>
<td>• Volume of Superconductor</td>
</tr>
<tr>
<td>• Iron Pole</td>
<td>• Flux in the phase A</td>
</tr>
<tr>
<td>• Size of Rotor Winding Width</td>
<td>• Flux in the phase B</td>
</tr>
<tr>
<td>• Size Rotor Winding Height</td>
<td>• Flux in the phase C</td>
</tr>
<tr>
<td>• Stator Slot Height</td>
<td></td>
</tr>
<tr>
<td>• Size Slot Width</td>
<td></td>
</tr>
<tr>
<td>• Stator Core Height</td>
<td></td>
</tr>
<tr>
<td>• Air Gap</td>
<td></td>
</tr>
<tr>
<td>• Iron Slots</td>
<td></td>
</tr>
<tr>
<td>• Coil Pitch Size</td>
<td></td>
</tr>
<tr>
<td>• Number Slot per Phase and per pole</td>
<td></td>
</tr>
<tr>
<td>• Current density in the Rotor</td>
<td></td>
</tr>
<tr>
<td>• Current density in the Stator</td>
<td></td>
</tr>
<tr>
<td>• Frequency of the current in the Armature</td>
<td></td>
</tr>
</tbody>
</table>

- Mesh parameters
- Domain limit
- Safety and filling factor

- Fixed Parameter
- Value between 0 and 1
- Binary value

Machine Geometry Data
Main Algorithm is Implemented in Python

Machine geometries and sources are created in Python using classes for each component.

The superconductor operating point is found using a dichotomy in Python.

Python generates the FlexPDE scripts.

FlexPDE is used as a solver and creates output text files imported in the Python environment.
• For this study, only the field in the c-axis direction is considered.

• Engineering current density $J_c(B)$ was estimated for tapes based on:
  – 12mm width
  – 0.15 mm thickness
  – 2760 A @ 2.75 T @ 35 K
Design Requirements

- Minimum length of 4X HTS conductor
  - Ideally less than 10 km
  - 30 K operation
  - 30% margin on $J_c$

- Cost should be more penalized than mass in optimization

- Investigate the impact of
  - Rotor-stator gap
  - Number of pole pairs
  - Aspect ratio
  - on
    - Generator active mass
    - Length of 4X HTS wires
Example of Data Generated

- Monte-Carlo exploration of design space
- Very time consuming
- Need to fix parameters and perform optimization
Examples of Designs Generated

- **model A**
  - Iron poles
  - 15 km of HTS

- **model B**
  - Iron poles
  - Lower rotor field
  - Thicker stator
  - 7 km of HTS

- **model C**
  - No iron poles
  - High excitation field
  - 92 km of HTS
## Comparison Between 3 Selected Designs

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
<td>28</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td>Air gap (m)</td>
<td>0.011</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Radius rotor (m)</td>
<td>2.6875</td>
<td>2.60</td>
<td>1.425</td>
</tr>
<tr>
<td>J Stator (A/mm²)</td>
<td>1.80E+06</td>
<td>1.80E+06</td>
<td>1.80E+06</td>
</tr>
<tr>
<td>J Rotor (A/mm²)</td>
<td>1.16E+08</td>
<td>1.20E+08</td>
<td>1.50E+08</td>
</tr>
<tr>
<td>Torque (N.m)</td>
<td>1.20E+07</td>
<td>1.20E+07</td>
<td>1.20E+07</td>
</tr>
<tr>
<td>Filling factor of the Superconductor</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Angle of maximal Torque (rad)</td>
<td>0.0703</td>
<td>0.0809</td>
<td>0.1528</td>
</tr>
<tr>
<td>Length of the machine (m)</td>
<td>3.299023</td>
<td>2.886807</td>
<td>2.0956</td>
</tr>
<tr>
<td>Active Mass (metric tons)</td>
<td>217</td>
<td>169</td>
<td>135</td>
</tr>
<tr>
<td>Mass Winding Stator (metric tons)</td>
<td>31.61</td>
<td>48.29</td>
<td>38.84</td>
</tr>
<tr>
<td>Mass Winding Rotor (metric tons)</td>
<td>1.03</td>
<td>0.53</td>
<td>2.54</td>
</tr>
<tr>
<td>Mass Core (metric tons)</td>
<td>184.75</td>
<td>120.5</td>
<td>93.52</td>
</tr>
<tr>
<td>HTS 4X wire (km)</td>
<td>15.12</td>
<td>7.74</td>
<td>92.82</td>
</tr>
<tr>
<td>Max Field on the Superconductor (T)</td>
<td>1.597</td>
<td>1.80</td>
<td>4.936</td>
</tr>
<tr>
<td>Max Field in air gap (T)</td>
<td>2.051</td>
<td>1.42</td>
<td>3.635</td>
</tr>
</tbody>
</table>
Impact of the Rotor-Stator Gap

- Mass and HTS length increase with air gap length
- Air gap length should be kept as small as possible
Impact of the Aspect Ratio

- Minimum HTS length for $L_{\text{active}}/R_{\text{rotor}}$ of 0.5
- Mass increases with aspect ratio
• Minimum mass for 36 poles
• HTS length decreases with number of poles
Mass vs. Number of Poles and Aspect Ratio

![Graph showing mass vs. number of pole pairs for different aspect ratios (L/R)].

- Mass on the y-axis (kg)
- Number of pole pairs on the x-axis
- Different lines represent varying aspect ratios (L/R) with markers indicating specific points of interest.
Number of Poles for Minimum Mass

- Optimum number of poles between 32 and 36
- Optimum number of poles fairly independent from L/R
Conductor Length vs. p and L/R

Number of Pole Pairs vs. Length of HTS 4X Tape

- L/R = 0.2
- L/R = 0.3
- L/R = 0.4
- L/R = 0.5
- L/R = 0.6
- L/R = 0.7
- L/R = 0.8
- L/R = 0.9
- L/R = 1.0
- L/R = 1.1
- L/R = 1.2
- L/R = 1.3
- L/R = 1.4
Next steps

- Perform parametric sweep/multi-objective optimization based on **cost** and **mass**
  - **Ongoing** (OpenMDAO)

- Complete detailed mechanical and thermal design

- Test of a full scale HTS coil using 2X conductors
HTS Coil Operating Point

- Coil performance based on estimated 4X wire
- Ic around 1500 A
- Transverse Peak field of about 1.8 T
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Availability of low cost HTS conductor is paramount to the economical viability of HTS wind generators

- Conductor development for wind generators is driven by 2 projects (ARPA-E and DOE) in the US
  - 4X improvement in transport current at 3T, 30K in 2G tapes
  - Fine filament high current density MgB2 conductors

- Preliminary LCOE calculations show very promising results for both YBCO and MgB2

- De-risking and modeling activities will take the technology to the level of full-scale prototype development
Aknowledgements

• Advanced Magnet Lab
  – Dr. Rainer Meinke
  – Mr. Vernon Prince

• University of Houston
  – Prof. Selvamanikam
  – Prof. Denis Netter
  – Dr. Clement Lorin
  – Dr. Yaw Nyanteh
  – Mr. Nicolas Escamez