

# Cost Comparison Studies of Different Superconductors for a Direct Drive Superconducting Wind Generator

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# Presentation Outline

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- Introduction
- Background
  - Projects with TECO participation
  - Experiences Gained for Wind Industry
- Challenges to Commercialization
- Steps forward
- Summary



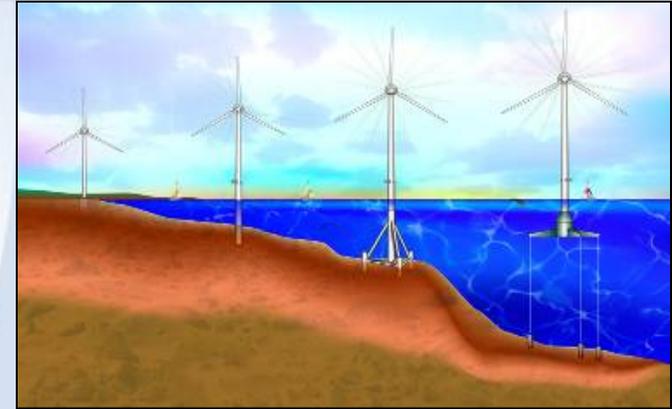
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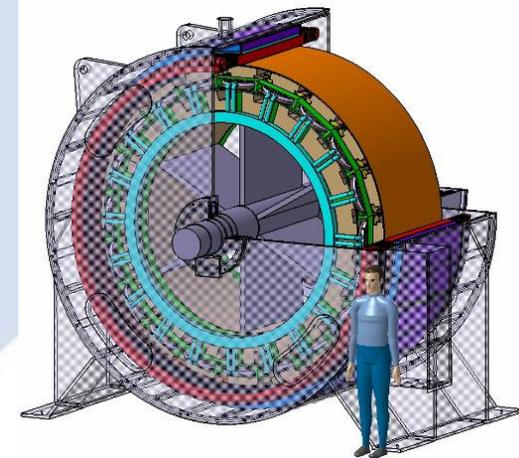


# Direct Drive Wind Generators

- Superconducting (SC) machines offers advantages for
  - Reduced active material usage
  - Increased power density
  - Higher efficiency
- These advantages make SC technology very attractive to large multi-MW direct drive (DD) wind generators used in offshore applications.



Offshore wind turbines



DD Wind Generator Concept



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# Specifications of a 2 MW Generator

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- **Rated Power: 2 MW**
- **Rated Speed: 18 r/min**
- **Rated Voltage: 3000 V**
- **Rated Efficiency: 95% (including cryogenic system)**
- **Rated Power Factor  $\geq 0.99$**
- **Total Weight: 35 ~ 40 t**
- **Armature Temperature: F-class**
- **Armature Insulation: F or H**
- **Noise Level:  $\leq 82$  dB**
- **Design Life: 20 years**



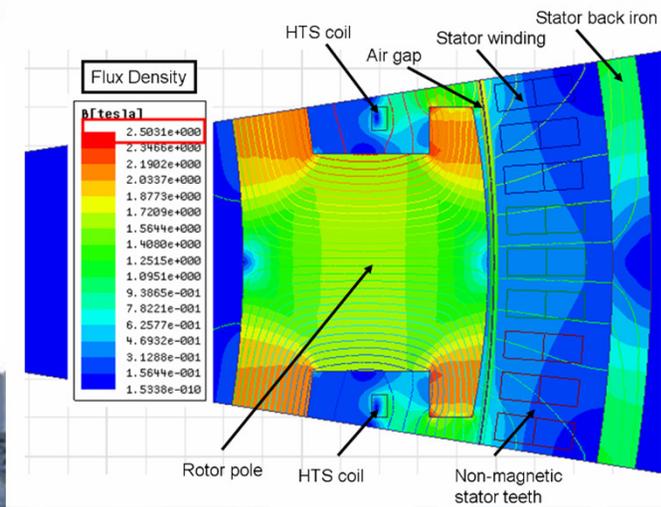
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# Design Topologies Investigated

- 4 Cases
  - Conventional
  - Air-gap winding on stator & pole
  - Air-gap winding on stator
  - Air gap pole
- Topology C was selected based on trade-off between SC requirements and practical implementation



Topology	HTSC wire length (12 mm width)	Comments
	3 km	Poor voltage regulation (-) Minimum HTS wire (+) Saturated iron (-) High air gap flux harmonics (-) Poor cogging torque (-)
	15 km	Good voltage regulation (+) No cogging torque (+) Maximum HTS wire consumption (-) Low air gap flux harmonics (+)
	7.8 km	No cogging torque (+) Good voltage regulation (+) Average HTS wire consumption (+/-)
	5.9 km	Additional losses on shield (-) High cogging torque (-)

# SC Material Usage Comparison Summary

- **YBCO** – High current (+)
  - High cost (-)
  - Lack of supply chain (-)
  - Potential quench problem (-)
- **MgB2** – Low cost (+)
  - No quench issue (+)
  - Available supply chain (+)
  - Low operation temperature (-)
- **Bi2223** – Good supply chain (+)
  - High cost (-)
  - Low current (-)
  - Potential quench problem (-)

Cost of SC Material for 2 MW DD Wind Generator

	Cost/Meter [US\$]	Total length [Km]	Cost [US K\$]
YBCO	118	7.8	920.4
MgB2	9	35.2	316.4
Bi2223	33	38.8	1280.4

Rotor Coils for 2 MW DD Wind Generator

	Field Coil Layout	Length [mm]	Width [mm]	Section Area [mm <sup>2</sup> ]
YBCO		1872.92	372.92	33.66 x 12
MgB2		1881.96	381.96	38.18 x 12
Bi2223		2148.32	648.32	171.36 x 12



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# Specifications of a 10 MW Generator

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- Rated Power: 10 MW
- Rated Speed: 8 r/min
- Rated Voltage: 3300 V
- Rated Efficiency > 96%
- Rated Power Factor 1
- Weight Target: 200 t
- Armature Temperature: F class
- Armature Insulation: F or H
- Noise Level:  $\leq 82$  dB
- Design Life: 20 years



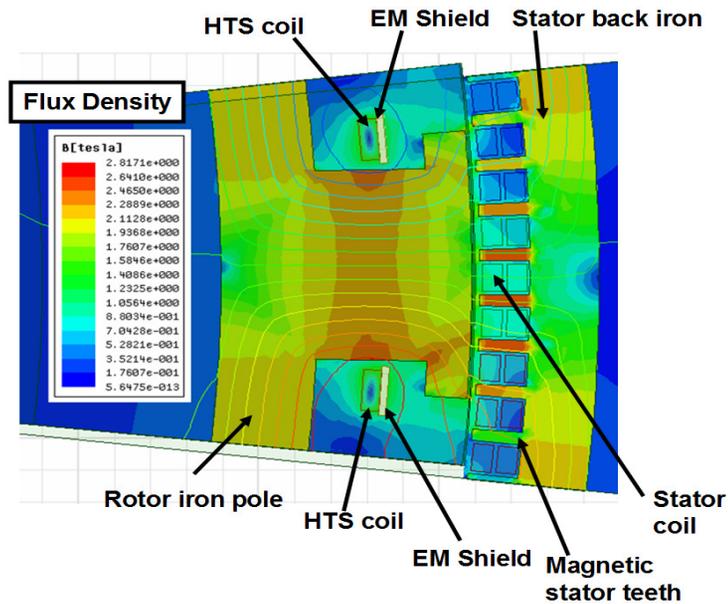
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# Cost Comparisons Using 4X SC

- 10 MW direct drive SC generator design using 4X improved SC developed by University of Houston and SuperPower



Design topology options	Description	Active material weight	Total weight	Improved HTS 2G conductor cost	Total cost
1	Rotor iron yoke and non-magnetic stator teeth	0.33	0.95	0.37	1.21
2	Non-magnetic rotor yoke and non-magnetic stator teeth	0.15	0.82	0.51	1.34
3	Rotor iron yoke and magnetic stator teeth	0.35	0.97	0.31	1.15
4	Non-magnetic rotor yoke and magnetic stator teeth	0.17	0.83	0.45	1.29
5	Salient-pole iron rotor and magnetic stator teeth	0.39	1.00	0.16	1.00

**Lowest Cost Design for 10 MW Direct Drive Wind Generator**



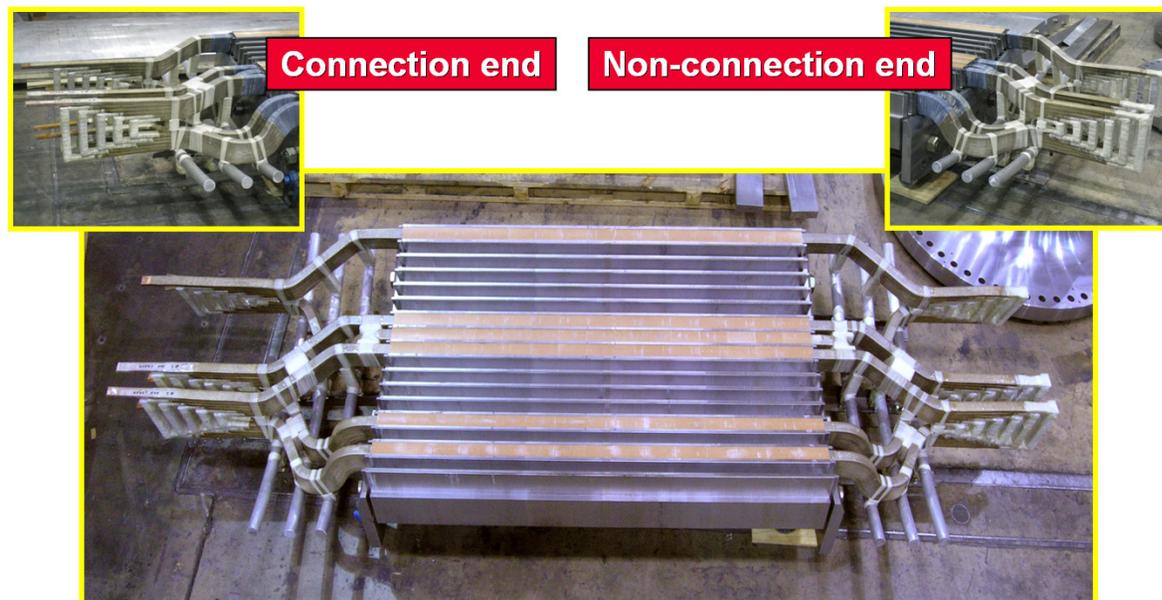
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# TECO Manufacturing Experience

- Large (~5 meters) diameter stator with Roebel transposed half coils manufacturing for wind turbine generator using SC rotor.



Manufactured and tested wound stator section



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# Experiences Related to Wind Industry

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- These projects show the vast challenges for SC technology still to address.
  - Performance, weight and volumetric comparison ([performance issue](#))
  - Machine design topology comparison (iron core vs. air core) ([cost/performance issue](#))
  - Costs of different SC materials (YBCO, Bi2223 and MgB<sub>2</sub>) ([cost issue](#))
  - Feasibility study on different rotor designs ([manufacturing/performance issue](#))
  - Current leads ([reliability issue](#))
  - Quench protection ([reliability issue](#))



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# Challenges for Commercialization

- Engineering Challenges:
  - Electromagnetic Design
    - Operating and fault currents and torque
    - Losses, inductance and time constants
    - Iron saturation
  - Mechanical/Manufacturing Design
    - Manufacturing costs and reliability, especially for field coils and current leads
    - Vacuum system integrity
  - Thermal Design
    - Minimum heat leakage
    - Cryo cooler capacity
- Other Challenges:
  - Subcomponent Suppliers
    - Availability of subcomponents (e.g., rotating union, brushless exciter)
    - Lack of mass production data for components
  - Lack of Field Test / Reliability Data
    - Lack of field test data for generator and subcomponents
    - Lack of life test data for generator and subcomponents
  - Financial Challenges
  - Industry Hesitancy for Risk Mitigation and Acceptance



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# Offshore Wind Industry

- In order to commercialize SC technology in offshore wind industry, one has to not only look at the cost of SC, but also understand the industry's needs.
- Besides the costs of SC and generator, there are also initial construction and commissioning costs, as well as maintenance costs.
- Many costs incurred are due to SC technology for offshore wind industry.
- SC technology allows for larger wind turbines operate in deeper water, which means
  - Transportation challenges (boats with large cranes)
  - Unpredictable weather / high tide from the sea
- Ultimately, the utility companies want to know the time it will take to recoup the investment. They have to first understand these challenges before committing to the technology.



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# Costs Breakdown for Offshore Wind Turbines

Assuming the infrastructures (power transmission) are in place:

- Installation / Tower / Blades
  - Construction cost
  - Transportation cost (ships with crane)
  - Commissioning cost
- Generator Cost
  - SC cost
  - Complicated manufacturing process due to SC and vacuum
  - Generator testing cost
  - Subcomponents validation cost
- Power Electronic Converter Cost
- Maintenance Cost / Time
  - Since most components have no MTBF data, it's difficult to estimate the cost.
  - Renting / owning ships for maintenance
  - Maintenance frequency
  - Training personnel for the SC technology
  - Downtime for component replacement or repair
  - Availability and cost of spare parts



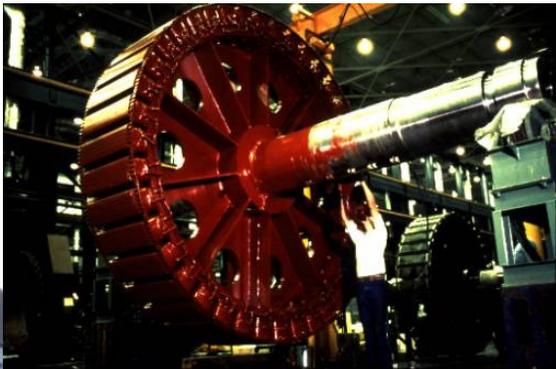
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# Industry Hesitancy

- Industry's general perception of traditional electric machines
  - Rugged-built and robust
  - Optimized for cost and manufacturing
  - Documented history (harsh environment operation)
- Industry's general perception of HTS technology
  - Still in laboratory development
  - Fragile system
  - High costs
  - Unknown reliability
  - Lack of field data



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# Reliability / Life Field Test Data

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- Due to high costs, there are not many reliability / life test data.
- Most companies / facilities hesitate to be guinea pigs.
- Government funding usually encourages high risk innovation development, so funding never applies to reliability testing.
- The funding has to come from either Government support or pool of funds from multiple sources.
- Without the field test data, it is difficult for the SC technology to move forward for industrial applications.
- This becomes a “chicken-egg” conundrum
  - Industry: not interested in the technology because there are no reliability field data
  - SC vendors: not spending funds on reliability test because there is not enough market interest



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# Steps to Commercialization

- Technical:
  - Develop robust manufacturing processes
  - Optimize electromagnetic and thermal performances using multi-physics simulation tools
  - Reduce SC costs through continual development
- Other:
  - Working with Government agencies, secure funding for prototypes for complete generator and for life testing of the machine and subcomponents
  - To increase public awareness of the SC technology, we must understand the industry's needs and educate the industry by attending and sharing information in industry conferences



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# Summary

- TECO has worked on several projects to better understand the needs of the offshore wind turbine industry using SC designs.
- Commercialization of the SC technology requires development of supply chains of SC and subcomponents.
- Many challenges need to be addressed to commercialize the SC technology. Financially and commercially, many practical issues must be addressed for its acceptance by Industry.
- Bringing awareness to Industry and Government agencies about these challenges and demonstration of complete prototypes is the path forward towards the commercialization of the SC technology.



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