Evaluation of Warm and Cold Shaft Designs for Large Multi-megawatt Direct Drive Offshore Superconducting Wind Generators

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Presentation Outline

- Introduction
- HTS rotor topologies from commercial perspectives
- Advantages/challenges
  - Cold shaft design
  - Warm shaft design
- Other commercial challenges
- Conclusions

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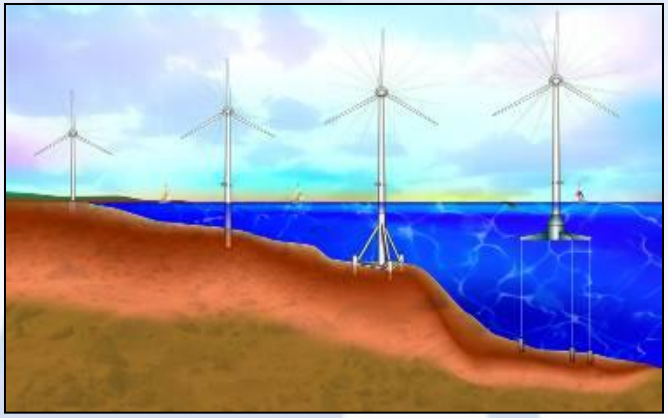
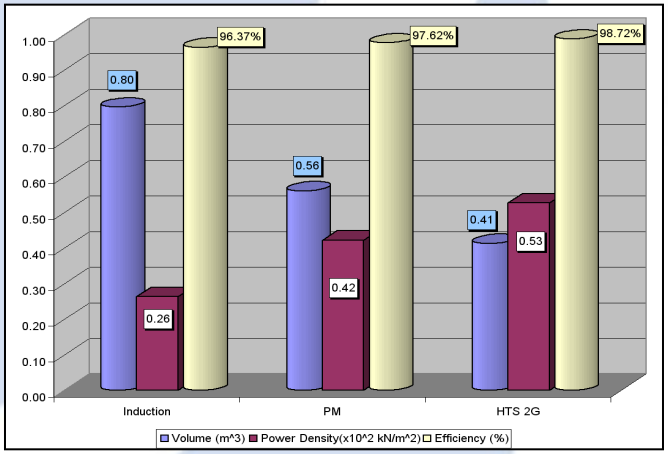
Direct Drive Wind Turbine Generator

- For ratings > 6 MW, HTS is one of the few feasible technologies, considering
  - Active material usage
  - Power density achievement
  - High efficiency





- Challenges
  - Technical
  - Commercial

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Impact of Rotor Topology from Commercial Perspectives

- Two topologies to consider
  - Warm shaft
  - Cold shaft

- Different rotor topologies can affect cost and time for:
  - Manufacturing
  - Testing
  - Maintenance/Service

HTS Rotor Design Topology

- Definition (Cold shaft design)
  - Entire rotor core encased in a vacuum chamber and coupled by 2 torque tubes between the rotor core and external shaft.
  - HTS material resides and is mechanically supported inside the rotor core.

HTS Rotor Design Topology

- Definition (Warm shaft design)
  - Only the HTS material and minimum rotor support structures are vacuum sealed and cooled to cryogenic temperatures; a single shaft to transfer the torque
  - Because there are many possible warm shaft designs, we focus on a design where each individual rotor pole is a cryostat and is a fully vacuum-sealed unit.

Cold Shaft Design

- Advantages
  - ✓ Simplified cryostat design
  - ✓ Simplified piping design
  - ✓ Possible less current lead connections

- Challenges
  - Long cool down times
  - Long evacuation times
  - Possible long test times and costs
  - High downtime costs
  - Possible high factory/ overhead costs for manufacturing facility

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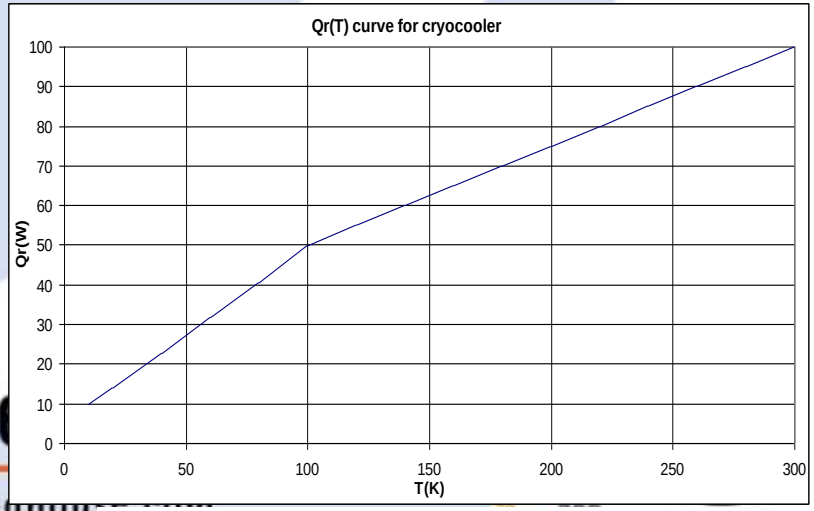
Quick Estimate of Cool Down Time

- For 10MW direct drive wind generator, the total weight varies between 95,000 kg to 200,000 kg, from different published literatures.
- Assume
  - Rotor is 50% of 95,000 kg = 47,500 kg
  - 100% stainless steel for entire rotor core
  - Cooling rate is sufficiently slow to cool down stainless steel in a uniform fashion over the entire volume
  - Operating temperature = 30K
  - 6 cryocoolers



Qr(T) curve for one magnet cryocooler

Iwasa, Yukikazu, "Case Studies in Superconducting Magnets: Design and Operational Issues," 2nd Edition, pp 231-232

Cool Down Time

Ti (K)	Top (K)	M (kg)			
τ (day)		10000	47500	75000	100000
300	77	24	112	177	236
	50	26	123	194	259
	30	27	128	201	268
	10	27	129	204	272
77	50	2	11	18	24
	30	3	16	25	34
	10	4	18	28	38

For 47,500 kg of stainless steel and 6 cryocoolers, it takes
–112 days to cool from 300K to 77K
–16 days to cool from 77K to 30K

Total 128 Days ~ 4+ MONTHS

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Down Time Costs

- Assume the utility company charges USD$0.10/kW-hr
- 4-month down time due to cool down costs ~ USD$3,000,000 (EUR 2,200,000) for a single 10MW turbine (“potential cost”, assuming continuous 100% output for the wind turbine)
- Assume a spare rotor is ready for installation. This does not include cost for
  - Repair / spare rotor
  - Transportation
  - Rerouting power from other sources

Investors need to consider the costs before making the investment.

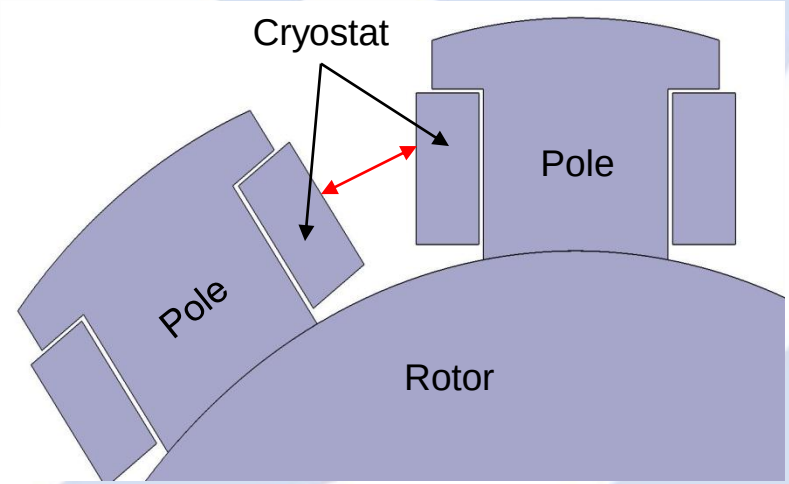
Warm Shaft Design

- Advantages
  - ✓ Shorter cool down / warm up times
  - ✓ Shorter evacuation times
  - ✓ No torque tube
  - ✓ Parallel production
  - ✓ Shorter test times
  - ✓ Lower downtime costs
  - ✓ Cheaper to control facility environment

- Challenges
  - – Complex cryostat design
  - – Complex piping design
  - – Complex current lead design
  - – Possible large heat leak
  - – Possible multiple heat leak sources

Cryostat Design Considerations

- Space constraint
  - Minimum physical space radially between poles
- Mechanical constraint
  - Internal cryostat support structure to withstand force and torque during fault condition



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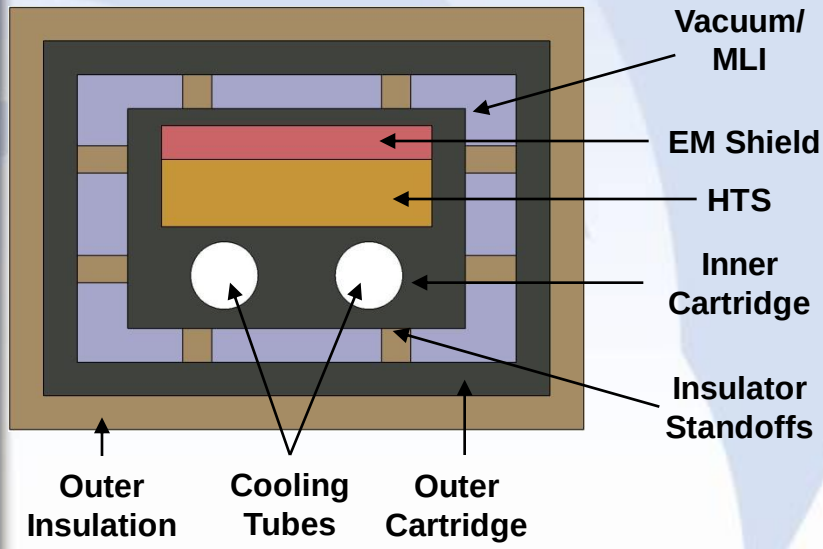
Cryostat Design Considerations

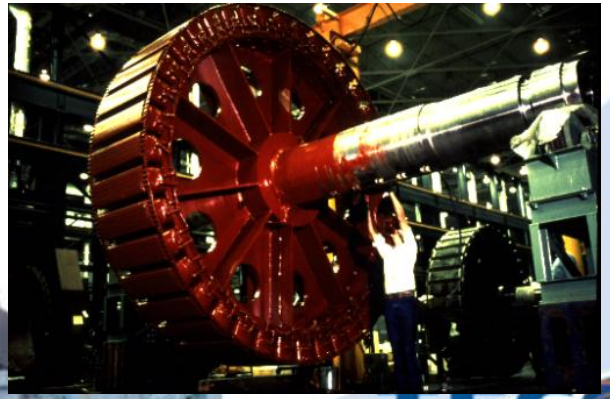


- Heat leaks
  - Conduction
  - Convection
  - Radiation

- For total heat leak of the system, we need to consider
  - Cryogenic pipe connections, current leads and manifold
- CFD and FEA have to be used for detailed analysis

Other Challenges for HTS Commercialization

- Industry's general perception of traditional electric machines
  - Rugged-built and robust
  - Well-optimized for cost and manufacturing
  - Well-documented test history (harsh environment)



- Industry's general perception of HTS technology
  - Still in laboratory development
  - Fragile system
  - High costs
  - Low reliability
  - Lack of field test data

Efforts to Promote HTS Technology

- In order to increase public awareness to HTS technology, TECO-Westinghouse has
  - Participated in several government funded projects (ATP, ARPA-E, ONR…etc.) with many partners (AMSC, SuperPower, NREL, MIT…etc.)
  - Published papers in IEEE PCIC, ICEM…etc.
  - Collaborated HTS projects with foreign research institutes.

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Conclusions

- HTS technology has tremendous potential for large multi-megawatts rated direct drive wind generators.
- Pros and cons for different rotor topologies are considered.
- Cold shaft design presents many challenges which must be considered for commercialization.
- Warm shaft offers tremendous advantages, but, technically, is very challenging to design.
- The general public needs to be continually informed of the HTS technology advancement for its commercialization.
- The HTS technology devices need rigorous testing to validate all components.