High-power generators for offshore wind turbines

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Outline

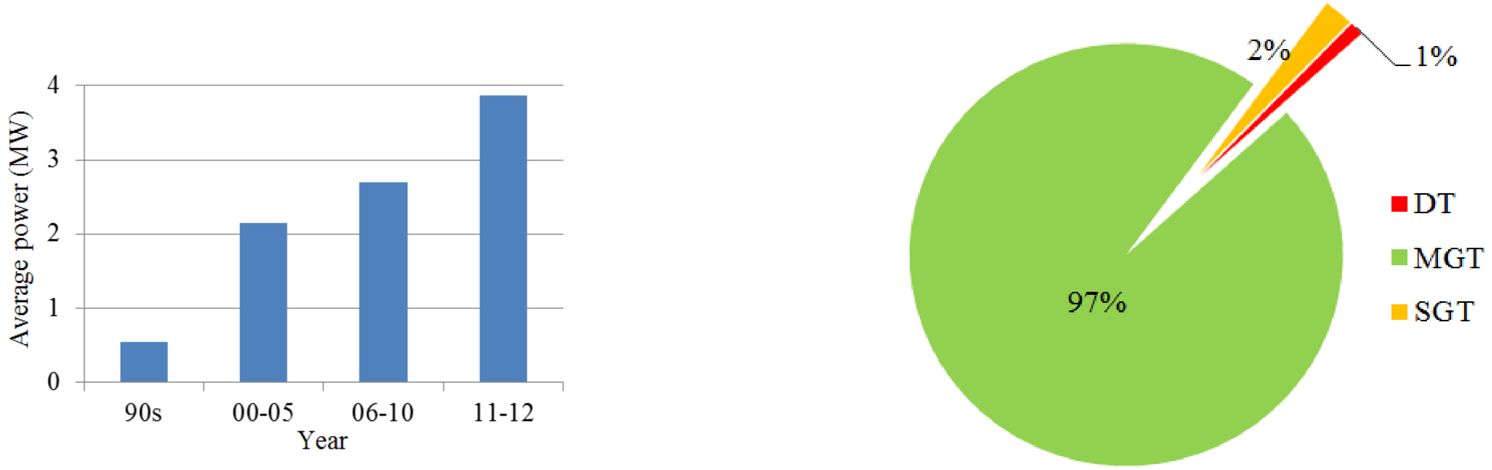
- Introduction of this research
- Review of the generators in operational offshore wind farms
  - Average rating of turbine; Drive trains; Generators
- Generator mass
  - Problems description; Modeling approach; Optimization results
- Review of the solutions for high power generators
  - Direct-driven DFIG; Conventional radial-flux PM generators; Ironless PMSG; Super conducting generator; HVDC generator
- Conclusion

Introduction

- Objective:
  - Investigate the technological challengies related to the high-power generators for offshore wind turbines
  - High-power: >6MW

Generators in operational offshore wind farms (I)

- By the end of 2012, 1886 wind turbines installed in 57 offshore wind farms; total operational capacity of 5.45 GW.



(a)

(b)

Figure 1: (a) Development of average rating per turbine.
(b) Market share of drive trains.
DT: Direct drive Train; MGT: Multi-stage Geared drive Train; SGT: Single-stage Geared drive Train

Generators in operational offshore wind farms (II)

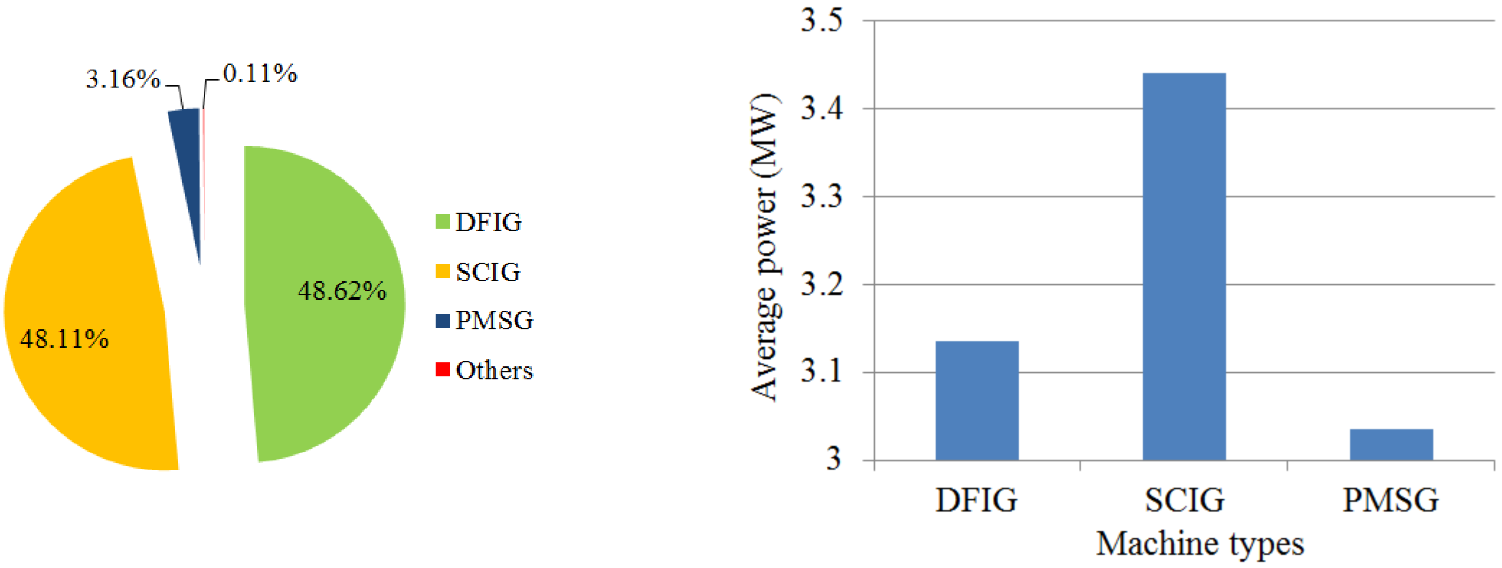
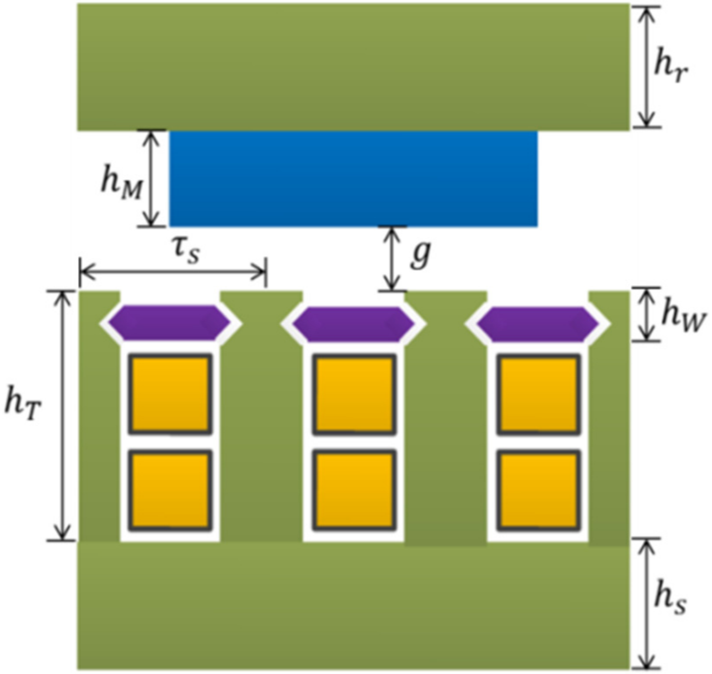


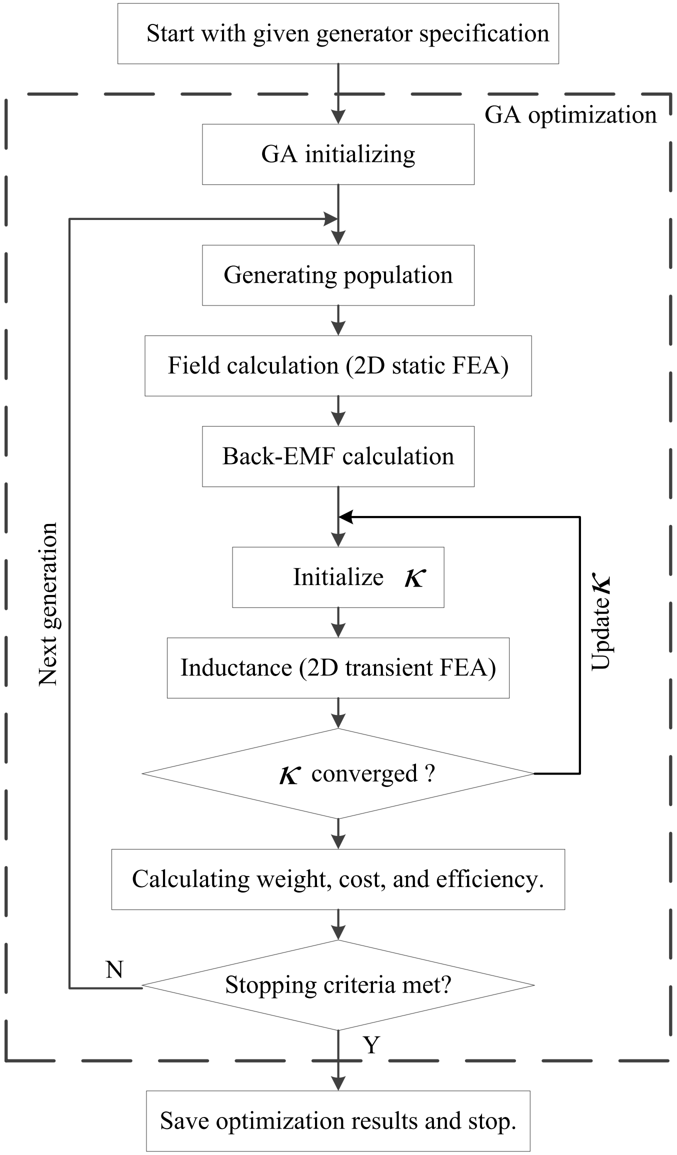
Figure 2: (a) Market share of different machine types
DFIG: Doubly-Fed Induction Generator; SCIG: Squirrel-Cage Induction Generator;
PMSG: Permanent Magnet Synchronous Generator
(b) Average power vs. machine types for 2008-2012.

Generator mass

- It is not clear how the structural mass evolves as the power grows.
- Estimation with scaling law gives much error.
- Structural design demands extensive knowledge on mechanical and structural analysis.
- In this paper
  - The total mass: estimated by statistically investigation of the commercial design and curve fitting;
  - Active mass: finite element analysis and optimization;
  - Supporting mass: Total mass-active mass

Modeling (I)




Start with given generator specification

GA optimization

GA initializing

Generating population

Field calculation (2D static FEA)

Back-EMF calculation

Initialize κ

Inductance (2D transient FEA)

κ converged ?

Update κ

Calculating weight, cost, and efficiency.

Stopping criteria met?

N

Next generation

Y

Save optimization results and stop.

Modeling (II)

Table 1: Generator specification.

Quantity	Value				
Power (MW), P_N	6	7	8	9	10
Speed (rpm), n	14	13	12	11	10
Stator voltage (kV), U_N	3.3				
Phase number, m	3				
Air gap (mm), g	$0.001D_o$				
Fill factor, k_f	0.65				
1st AC resistance ratio, k_{1r}	1				
Staking factor, k_s	0.95				
PM B_r (T) at working temperature	1.2				
PM relative permeability	1.05				
Slot per pole per phase, q	1				
Number of parallel branch, a	1				
Slot wedge thickness (mm)	5				
Min. area of 1 turn coil (mm^2), S_T	5				
PM specific cost (€/kg)	80				
Copper specific cost (€/kg)	27				
Steel specific cost (€/kg)	16				

Table 2: Free variables.

Quantity	Range
Frequency (Hz), f	10-60
Outer diameter (m), D_o	6-10
PM thickness (mm), h_M	5-100
Thickness of rotor back iron (mm), h_r	5-100
Thickness of stator back iron (mm), h_s	5-100
Ratio of tooth height over tooth width, k_{ts}	4-10
Ratio of PM width over pole pitch, k_M	0.5-0.9
Ratio of tooth width over slot pitch, k_T	0.3-0.7
Current density (A/mm^2), J	2-5

Table 3: Constrains.

Quantity	Range
Slot pitch (mm), τ_s	>5
Flux density in yoke of stator and rotor (T)	<3
Electric load (kA/m), E_L	<50

Modeling (III)

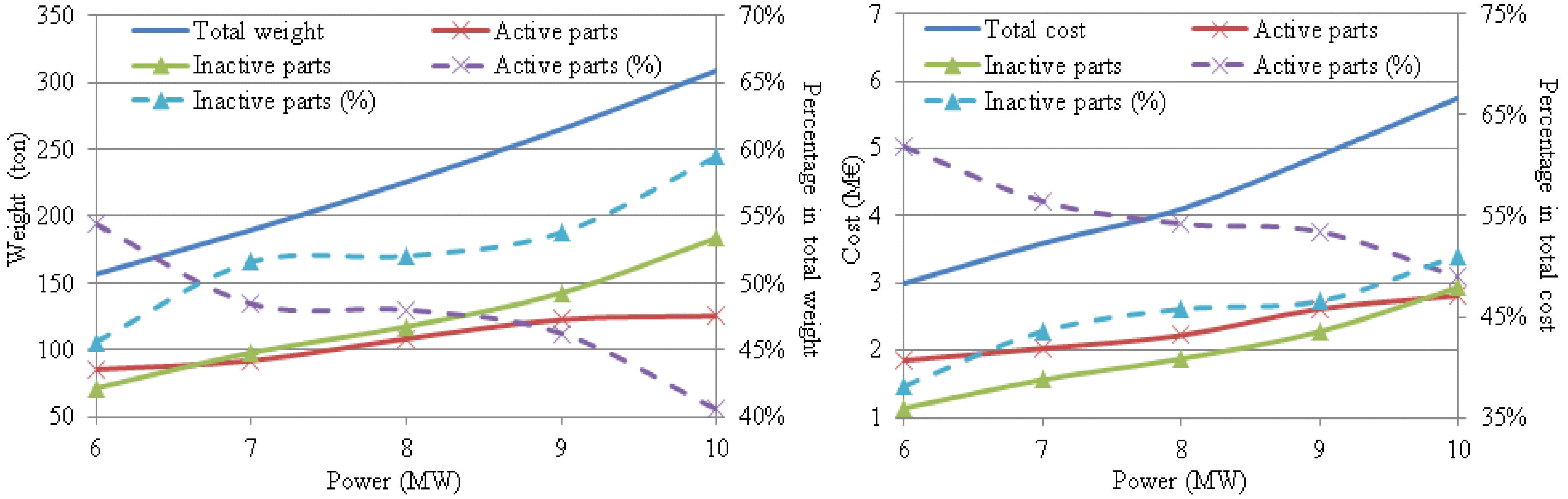
- Total mass

$$\overset{\text{ton}}{M} = 97.7\,\frac{\overset{\text{MW}}{P_N}}{\underset{\text{rpm}}{\sqrt{n}}}$$

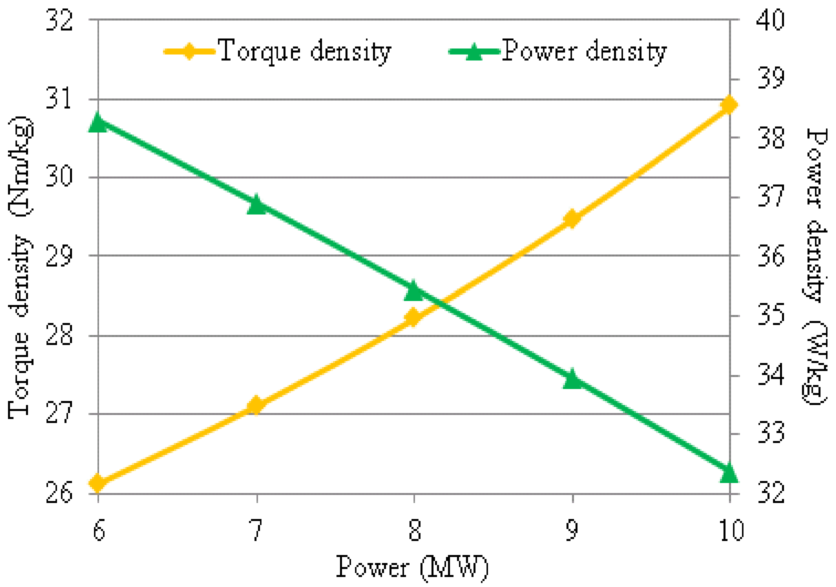
- Optimization objective
  - Cost function: cost of the active material
  - Constrain in efficiency: >95%

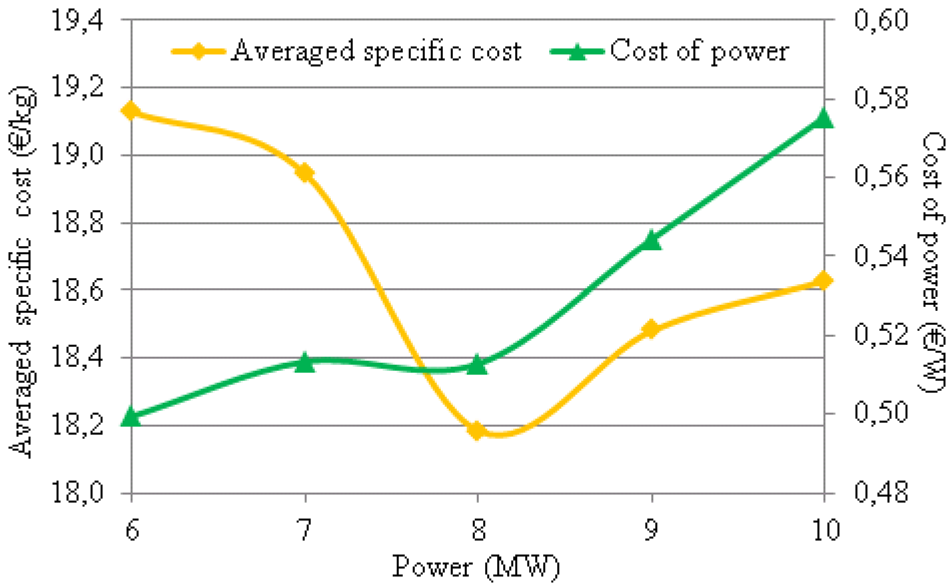
Optimization results (I)

- Mass and Cost



Optimization results (II)

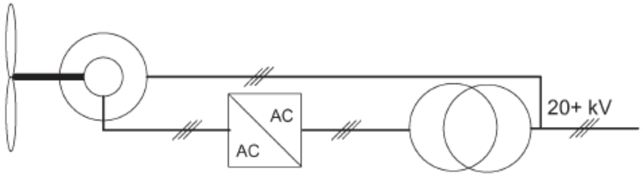


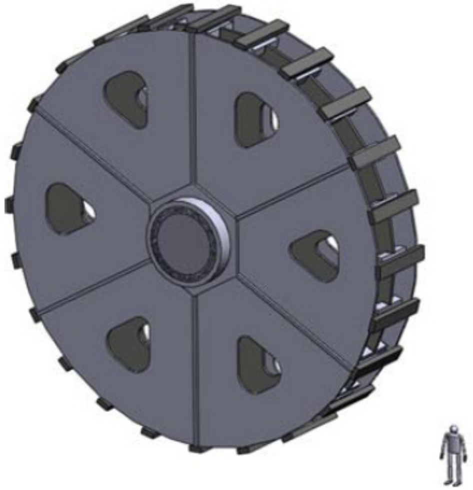


Solutions for high-power generators

- Industry and academic designs
- Less system components, less generator mass and higher efficiency are the concerns of these solutions.
  - Direct-driven DFIG
  - Conventional radial-flux PM generator
  - Ironless PM generator
  - Super conducting generator
  - HVDC generator

Direct-driven DFIG

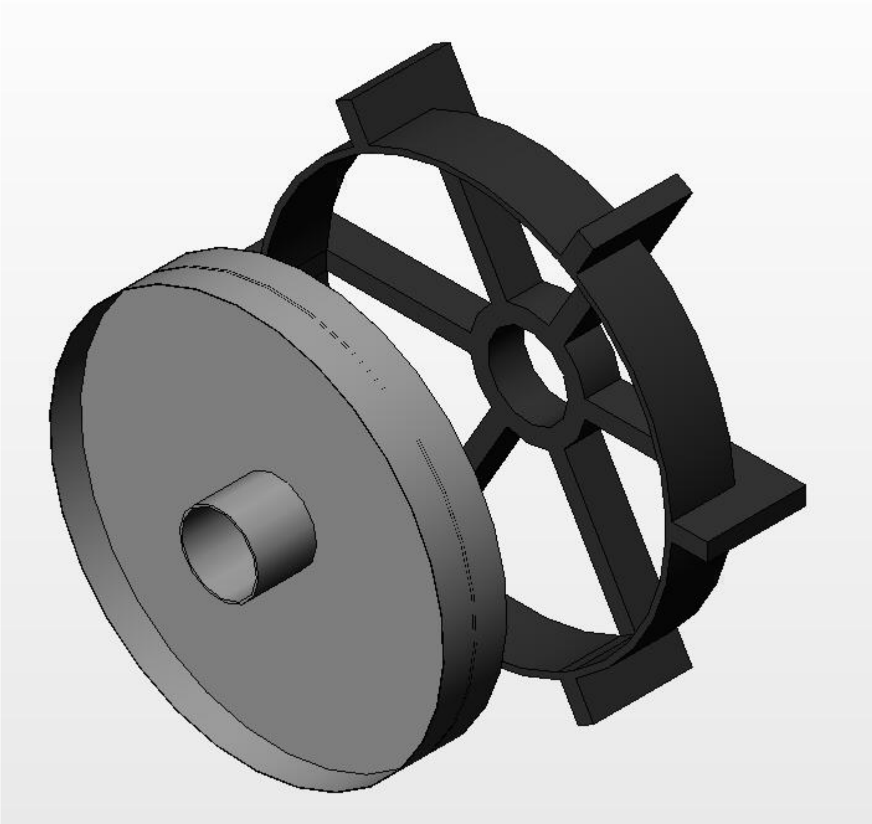




Quantity	Value
Power	10 MW
Speed	10 rpm
Stator voltage	23.5 kV
Rotor voltage	0.7 kV
Slip	0.2
Stator internal diameter	6 m
Pole number	600
Current density	2.5 A/mm^2
Magnetic load	0.6 T
Slot per pole per phase	1.5 (stator) and 2 (rotor)
Air gap	1 mm
Length	1.3 m
Efficiency	94%
Copper weight	30 ton
Laminations weight	36 ton
Construction weight	282 ton

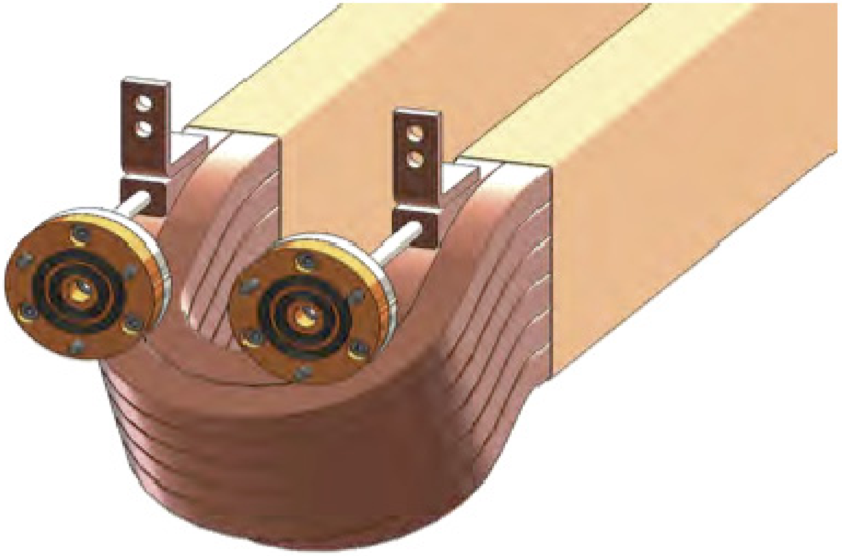
Conventional radial-flux machine (I)

Quantity	Value
Power	10 MW
Speed	10 rpm
Stator diameter	10 m
Pole number	320
Slot per pole per phase	1
Air gap	10 mm
Pole number	600
Copper weight	12 ton
PM	6 ton
Lamination weight	47 ton
Construction weight	260 ton
Total	325 ton

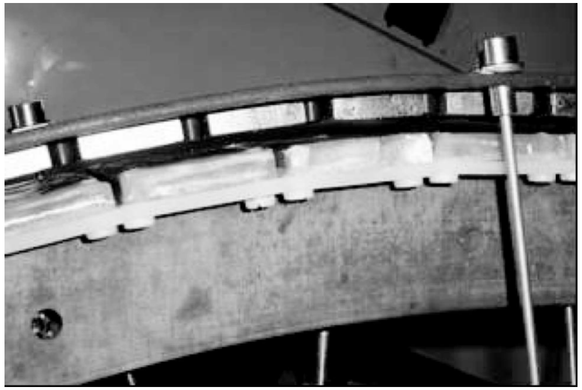


Conventional radial-flux machine (II)

Quantity	Value
Power	8 MW
Speed	11 rpm
Stator voltage	3.3 kV
Stator segments	12
Pole number	120
Slot number	144
Pole number	600
Air gap diameter	6.93 m
Length	1.1 m
Air gap	8.66 mm
Electric load	150 kA/m
Efficiency	92%
Copper weight	9.2 ton
Magnet weight	3.6 ton
Laminations weight	31 ton
Construction weight	NA

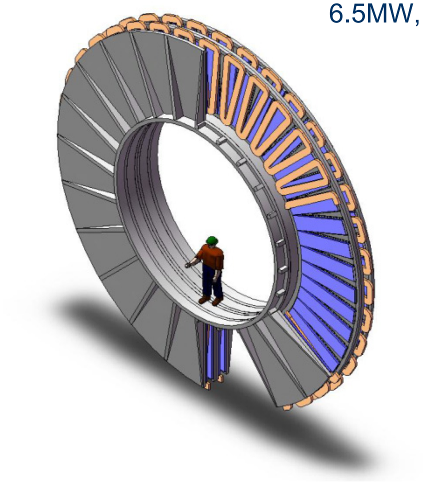


Ironless PM generator

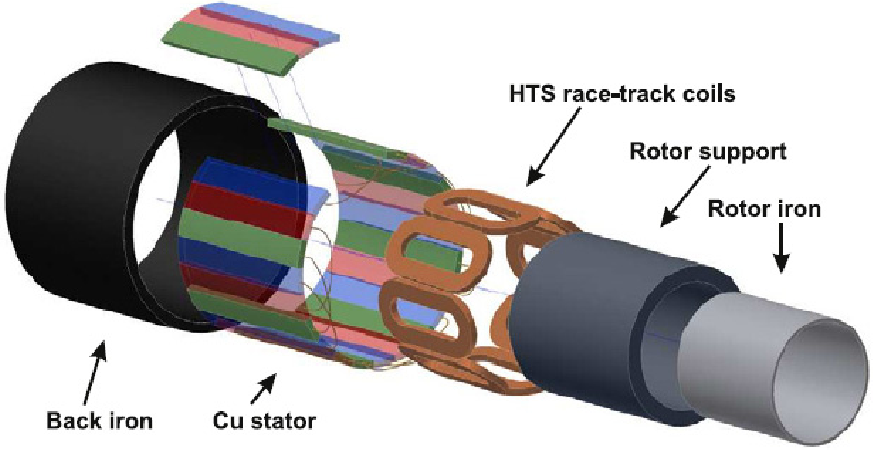


6MW Generator Structure by BWP

6.5MW, 48 poles PM machine

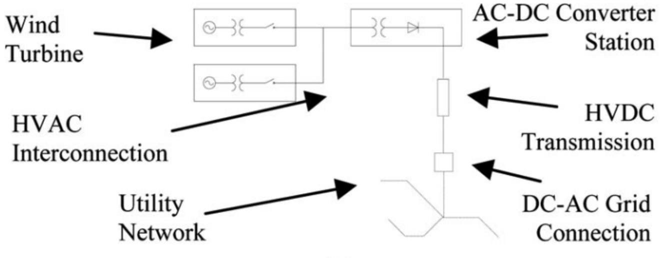


Super conducting generator

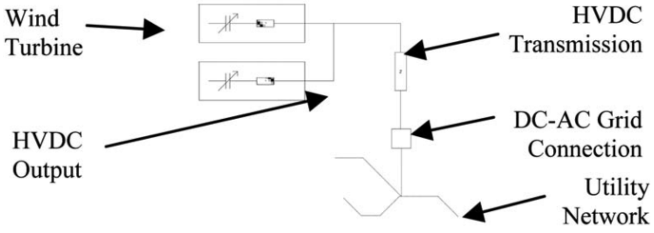


Rated power P_N (MW)	10
Poles	16
Diameter D_{gen} (m)	4.7
Length L_{gen} (m)	1.15
Rotation speed $\omega_{\mathrm{R,rpm}}$ (rpm)	10
Shaft torque τ_T (10^6 N m)	9.7
Mass superconductor m_{sc} (ton)	22
Mass Cu m_{Cu} (ton)	14
Mass Fe m_{Fe} (ton)	32
Mass glass fiber m_{GF} (ton)	20
Mass total (ton)	88
Length of SC (km)	1450
Current density J_e (A m^{-2})	6.3×10^7
Temperature T (K)	20
Maximum field $B_{\max}$ (T)	9.1

HVDC generator



(a)



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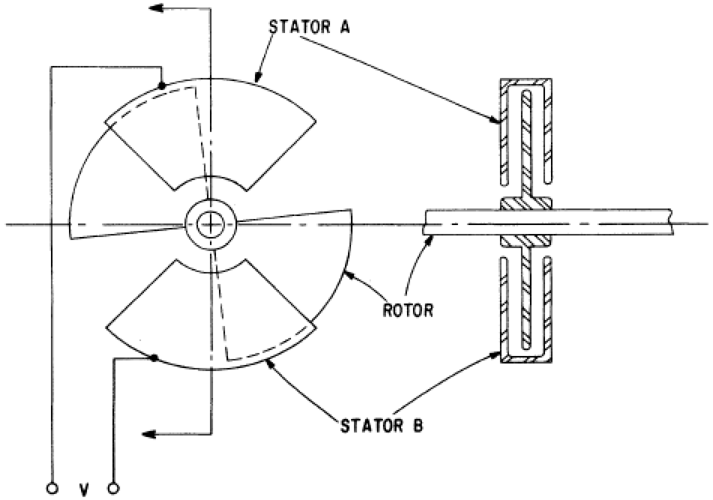

Compare with Vestas V90-3MW

Conventional system	Output voltage	Generator	Transformer	Total
	$34.5kV_{AC}$	8,500kg	8000kg	16,500kg
V-C system	Output voltage	Generator and auxiliaries	Additional gearbox	Total
	$\pm 50kV_{DC}$	15,000kg	690kg	15,690kg

Conclusions (I)

- This presentation presents a thorough investigation of the global operational offshore wind farms from the perspective of generators, and gives the quantitative analysis.
- It is found that the dominant solution for offshore energy conversion system is the multi-stage geared drive train with the induction generators.

Conclusions (II)

- With the help of numrerical method and genetic algorithm, it is found that most of the cost and mass for high-power generators go to the supporting structure.
- It is therefore not economic to simply upscale the conventional technology of iron-cored PM generator.
- Furthermore, developing lightweight technology or other cost-effective solutions becomes necessary.

Conclusions (III)

- It reviews the generator solutions for high-power offshore wind turbines.

References

[1] Zhang Z, et al. State of the art in generator technology for offshore wind energy conversion system. Proc. IEMDC, 15-18 May 2011, p. 1131-1136.

[2] Colli VD, et al. 2-D mechanical and magnetic analysis of a 10 MW doubly fed induction generator for direct-drive wind turbines. Proc. IECON09, p. 3863-3867.

[3] Colli VD, et al. Feasibility of a 10 MW doubly fed induction generator for direct-drive wind turbines. Proc. IEEE PES/IAS, 28-30 Sept. 2009, p. 1-5.

[4] Polinder H, et al. 10MW wind turbine direct-drive generator design with pitch or active speed stall control. Proc. IEMDC, 3-5 May 2007, p. 1390-1395.

[5] Alexandrova Y, et al. Defining proper initial geometry of an 8 MW liquid-cooled direct-drive permanent magnet synchronous generator for wind turbine applications based on minimizing mass. Proc. ICEM2012, p. 1250-1255.

[6] Polikarpova M, et al. Thermal design and analysis of a direct-water Cooled direct drive permanent magnet synchronous generator for high-power wind turbine application. Proc. ICEM2012, p. 1488-1495.

[7] Report on next generation drivetrain development program. Boulder Wind Power.

[8] Spooner E, et al. Lightweight ironless-stator PM generators for direct-drive wind turbines. Proc. IEE. Elec. Power Appl., 2005, vol.152, no.1, p. 17-26.

[9] Kobayashi H, et al. Design of axial-flux permanent magnet coreless generator for the multi-megawatts wind turbines. EWEC2009.

[10] O'Donnell, et al. Design concepts for high-voltage variable-capacitance DC generators. IEEE Trans. Ind. Appl., Sep.-Oct. 2009, vol.45, no. 5, p. 1778-1784.

[11] Philp SF. The vacuum-insulated, varying-capacitance machine. IEEE Trans. Electri. Insul., April 1977, vol. EI-12, no. 2, p.130-136.

[12] Abrahamsen A. et al. 2010 Supercond. Sci. Technol. 23 034019 doi:10.1088/0953-2048/23/3/034019