Realization of a large-scale superconducting generator for a wind power generation system

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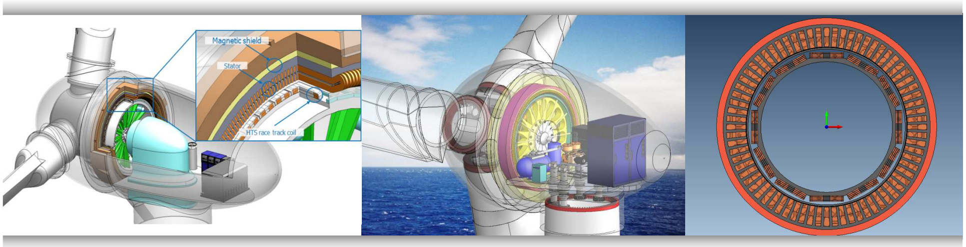
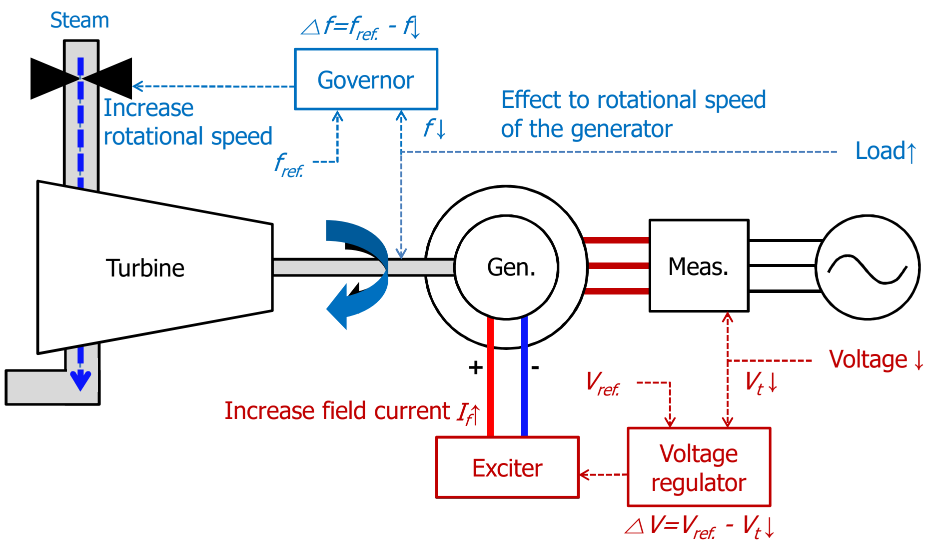
Contents

Basic theory of generator & wind turbine



Basic theory of generator

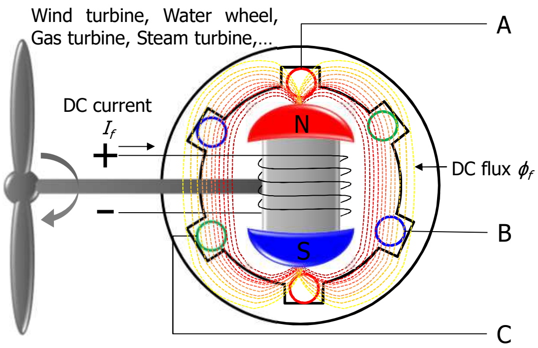
- Speed control and voltage control



More detail

➢Principle of operation

1. From an external source, the field winding is supplied with a DC current excitation.
2. Rotor (field) winding is mechanically turned (rotated) at synchronous speed.
3. The rotating magnetic field produced by the field current induces voltages in the outer stator (armature) winding. The frequency of these voltages is in synchronism with the rotor speed.



➢ Operation concept

HTS application

- The rotor is supplied by DC current I_f that generates a DC flux ϕ_f.
- The rotor is driven by a turbine with a constant speed of N.
- The rotating field flux induces a voltage in the stator winding.
- The frequency of the induced voltage depends upon the speed.
- The frequency f & speed relation is P is the number of poles.

- Rotating speed & Rated frequency & Num. of poles

$$N = \frac{120f}{P}$$

- The rms. value of the induced voltage

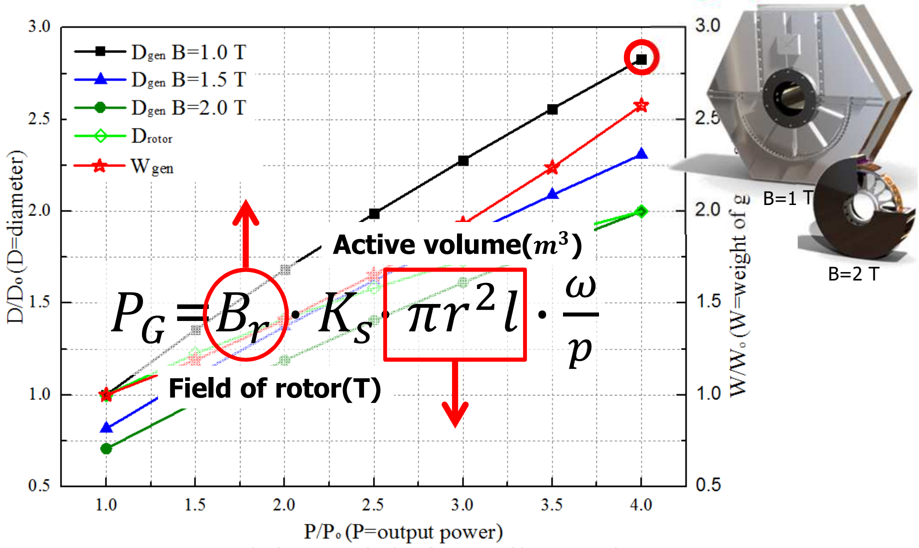
$$E_{rms} = \frac{k_w \omega N \emptyset_f}{\sqrt{2}} = 4.44 f N \emptyset_f k_w$$

*k_w=0.85~0.95 is the winding factor.

Reason that should use HTS technology

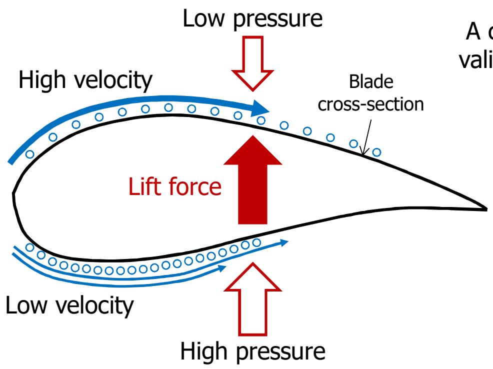
➢Best way to reduce the weight is to increase the field

The high field of rotor makes small active volume and light generator.



Very basic of blade aerodynamics

➢Bernoulli's equation



A common form of the Bernoulli's equation, valid at any arbitrary point along a stream

$$\frac{p}{\rho} + \frac{v^2}{2} + gh = \boxed{constant}$$

$$p + \frac{\rho v^2}{2} + \rho g h = p + q + \rho g h = constant$$

$$\because q \equiv \frac{\rho v^2}{2}$$

The change in the *ρgh* term along the streamline is so small compared with the other terms that it can be ignored. This allows the above equation to be presented in the following simplified equation.

$$p + q = p_0$$

v : the fluid flow speed at a point on a streamline [m/s]
g : the value of acceleration due to gravity [m/s²]
h : the elevation of the point above a reference plan [m]
ρ : the density of the fluid at all point in the fluid [kg/m³]
p : the pressure at the chosen point [Pa]
q : the dynamic pressure [Pa]
p_0 : the total pressure [kg/m³]

Power Coefficient Cp

➢Wind energy

$$\frac{dE}{dt} = \frac{d\frac{1}{2}mv^2}{dt} = \frac{1}{2}v^2\frac{dm}{dt}, \quad \frac{dm}{dt} = \rho A v$$

$$P = \frac{dE}{dt} = \frac{1}{2}v^2\frac{dm}{dt} = \frac{1}{2}v^2\rho A v$$

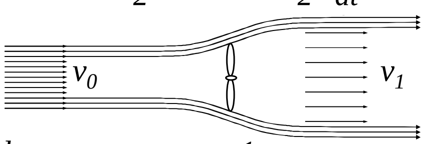
$$P = \frac{1}{2}v^2\rho A v = \frac{1}{2}\rho A v^3$$

$$P = \frac{1}{2}\rho A_0 v_0^3 - \frac{1}{2}\rho A_1 v_1^3 = \frac{1}{2}\frac{dm}{dt}(v_0^2 - v_1^2)$$

To fully transfer wind energy (100%) from wind energy to kinetic energy, V_1 should be zero.
It is ideal condition, therefore, V_1 is commonly lower than V_o.

$4\alpha(1-\alpha)^2$ is Power Coefficient "C_p" which is the ratio of power extracted by the turbine to the total contained in the wind resource. (real less than 50%)

E: Kinetic energy (J)
ρ: Air density (1.225 kg/m³)
m: Air mass (kg)
A: Swept area (m²)
V: Wind speed (m/s)
α: Axial induction factor



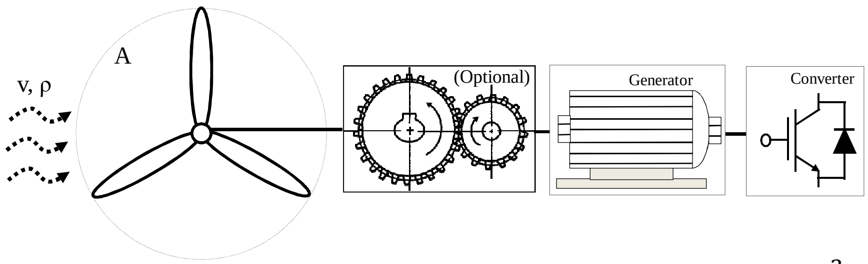
$$v = v_0(1-\alpha)$$
$$v_1 = v_0(1-2\alpha)$$

$$P = \frac{1}{2}\frac{dm}{dt}(v_0^2 - v_1^2) = \frac{1}{2}\rho A v(v_0^2 - v_1^2) = \frac{1}{2}\rho A v_0^3 \boxed{(4\alpha(1-\alpha)^2)}$$

Turbine output power, longer blade, better wind quality

➢Structure of wind power generation system

Kinetic energy | Mechanical power | Electrical power



Kinetic energy of wind

$$E_k = \frac{1}{2} m v^2$$

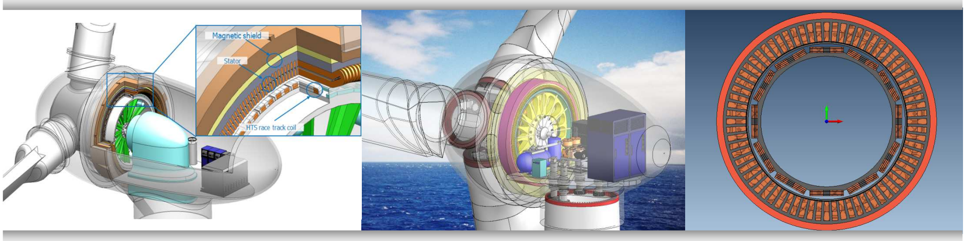
$$\frac{dE_k}{dt} = P_{wind} = \frac{1}{2}\rho A v^3$$

$$T_{turbine} = \frac{P_{turbine}}{\omega} = \frac{1}{2} A \rho C_p \frac{V^3}{\omega} = \frac{1}{2} A \rho \frac{C_p}{\lambda} R_{blade} v^2$$

$$P_{turbine} = C_p \frac{1}{2}\rho A v^3$$

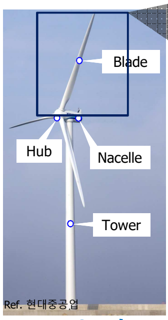
$$\lambda = \frac{\omega_{blade} R_{blade}}{V_{wind}}$$

Components of the wind turbine

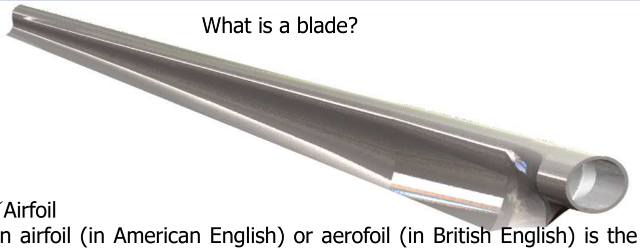


Components of the wind turbine (blade)

➢ Blade

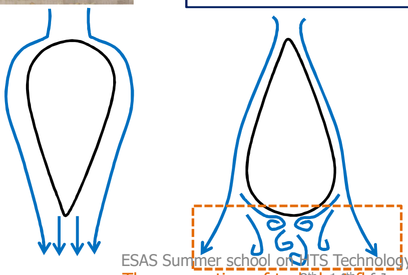


What is a blade?



✓Airfoil

An airfoil (in American English) or aerofoil (in British English) is the shape of the blade in cross-section. The shape of an airfoil is such that wind can pass both above and below it.



The generation of turbulent flow

✓Title of airfoil

- NACA XXXX

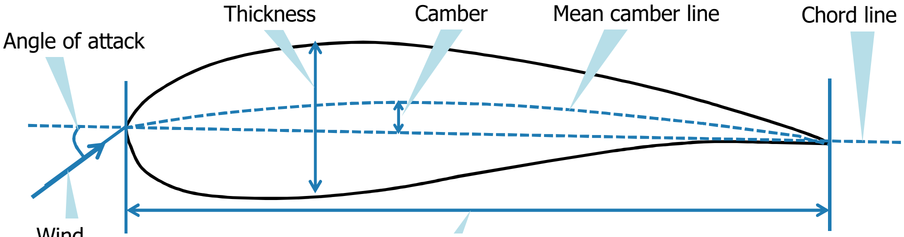
→First number:
Maximum mean camber line is X% of the chord line.
→Second and third number:
Maximum mean camber line is XX% from leading edge.
→Fourth number:
Maximum thickness is X% of the chord line.

- NACA 00XX

→Symmetric airfoil:
The symmetry of top and bottom
→Maximum thickness is XX% of the chord line.

Components of the wind turbine (blade)

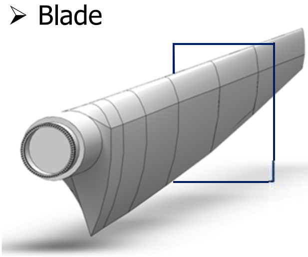
➢ Blade



Mean camber line	A line joining the leading and trailing edges of an airfoil equidistant from the upper and lower surfaces.
Chord line	A line drawn from the leading edge of the wing to the trailing edge contrail
Chord	The chord refers to the imaginary straight line joining the trailing edge and the center of curvature of the leading edge of the cross-section of the airfoil.
Camber	Camber is the asymmetry between the top and the bottom surfaces of an aerofoil.
Thickness	A height difference of top and bottom.
Angle of attack	The angle of attack is the angle at which relative wind meets an airfoil.

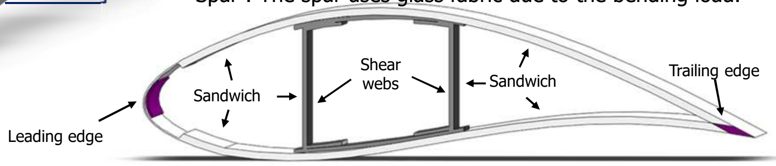
Components of the wind turbine (blade)

➢ Blade



The cross sectional of the rotor blade is comprised of skin, spar, web.

- Skin and web : Skin and web are sandwich structure composed of glass fabric and core material.
- Spar : The spar uses glass fabric due to the bending load.



✓Why do wind turbine blades spin?

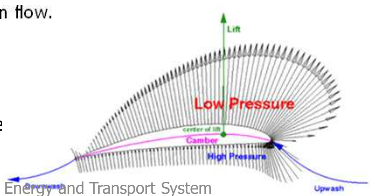
- Lift force : Lift is the component of aerodynamic force perpendicular to the relative wind. It is due to a difference in pressure between the top and bottom of an object in flow.
- Bernoulli's equation

$$\frac{Speed^2}{2} + \frac{Pressure}{Density} = Constant$$

→Increase in speed due to decrease in pressure → Generation of life

- What is the reason that the pressure decrease?

The pressure is occurred outward because airflow is curved.
= Centrifugal force → Decrease in pressure



Ref. www. emaze. com

Components of the wind turbine (blade)

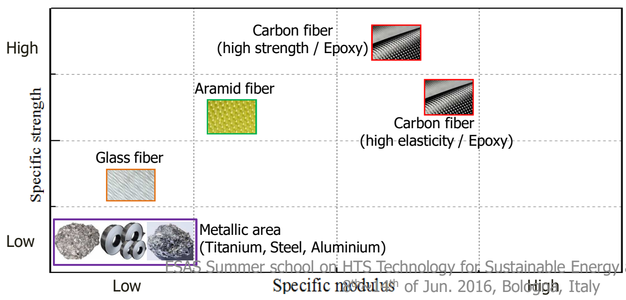
➢ Blade

✓Material of blade

■ *: blade material*

Material type	Tensile strength (GPa)	Tensile modulus (GPa)	Typical density (g/cm^3)	Specific strength	Specific modulus
Carbon Fiber	4.9	230	1.82	27.5	13.5
Aramid Fiber	3.6	131	1.45	25.5	9.2
Glass Fiber	3.4	74	2.55	13.7	2.9
Aluminium Ally	0.4	69	2.7	1.6	26
Titanium	0.95	110	4.5	3	24
Mild steel	0.45	205	7.8	0.65	26
Stainless steel	0.5	196	8.03	0.7	25

✓ Mechanical property of each materials



•Weigh of carbon is 25% of steel or 70% of aluminum. And strength of carbon is tenfold of steel.
→Stronger and lighter material

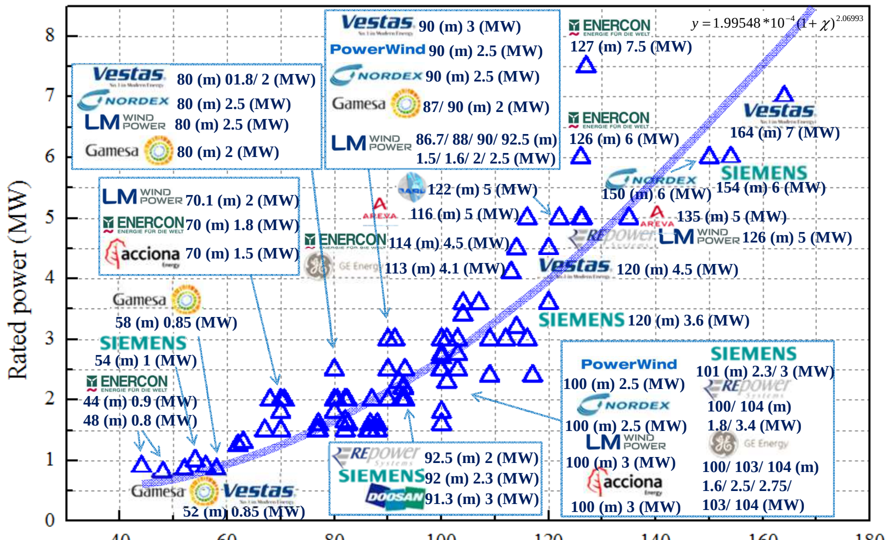
•Specific stiffness of the glass fiber is similar to the aluminum. But specific strength of the glass fiber is 8.5 times higher than the aluminum.

Components of the wind turbine (blade diameter)

➢ Blade

Ref. CAPTA

<Rotor diameter and Rated power>

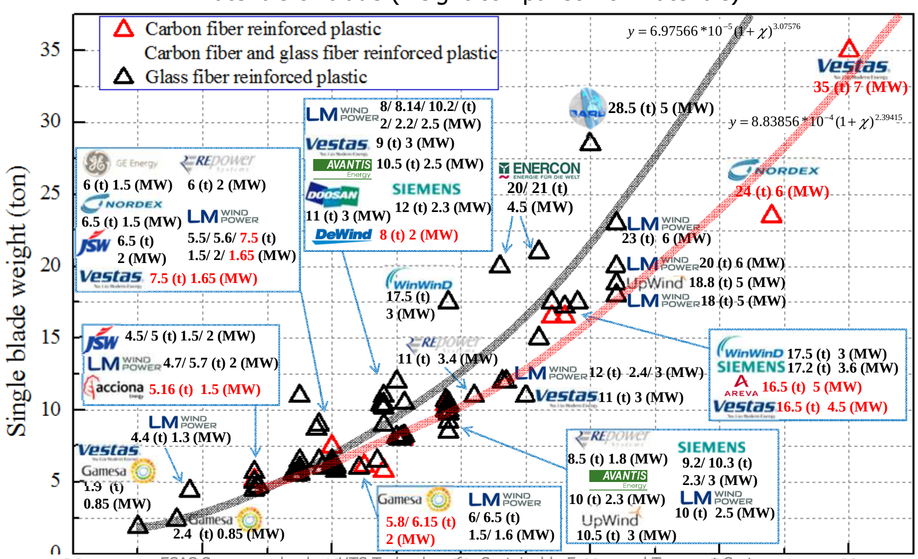


Components of the wind turbine(CFRP, GFRP)

➢ Blade

Ref. CAPTA

<Materials of blade (weight comparison of materials)>



Components of the wind turbine (Hub)

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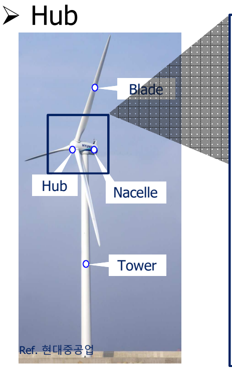
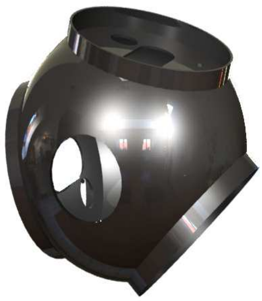
➢ Hub



What is a hub?



- A hub is directly bolted to the blades.
- It is component of the wind turbine what receives dynamically high stress.
- Therefore, it is important that selects material to prevent ultimate load and fatigue load.
- It requires a lifetime of more than 20 years.

- Material of the hub
  EN-GJS-400-18U-LT (Ductile Cast Iron or Spheroidal Graphite Cast Iron)
  → Excellent mechanical properties, heat, abrasion and mach-inability

- Mechanical properties of ductile cast iron

Part	Tensile stress [Rp N/mm^2]	Yield stress [Rp0.2 N/mm^2]	Elongation ratio [A%]	Impact strength		Hardness [HB]	The modulus of elasticity [N/mm^2]
				Average (J)	Minimum		
Value	370	220	12	10	7	130~175	165,000

Standard : DIN EN 1563

Components of the wind turbine (Hub inside)

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➢ Hub

✓ Component of the rotor hub

- **Pitch controller**
  The pitch controller delivers pitch angle and velocity from the encoder to the motor drive.
- **Encoder**
  The encoder that is installed at each box delivers signs of blade pitch and velocity to the pitch controller.
- **Motor drive**
  The motor drive that receives signal runs the pitch motor.
- **Battery box**
  The battery box is installed to run the motor when power outages and emergency stop is occurred.
- **Rubber mount and cross beam**
  The rubber mount and the cross beam protect electric apparatus of inner.

Components of the wind turbine (Hub)

➢ Hub

✓ Pitch bearing

The outer race of the blade bearing is fixed to the hub. And blades are rotated by the inner race that is engaged at the pinion.

❖What is bearing?

A bearing is a device to allow constrained relative motion between two or more parts, typically rotation or linear movement. Bearings may be classified broadly according to the motions they allow and according to their principle of operation as well as by the directions of applied loads they can handle.

The main role of the bearing is to reduce friction of machine.

•Mechanical advantage according to the decrease of friction

1. Improvement in operational efficiency of machine
2. Position fixing of moving machine parts
3. Transformation prevention due to the frictional heat

•Material : Steel or Ceramic

Ref. Google image

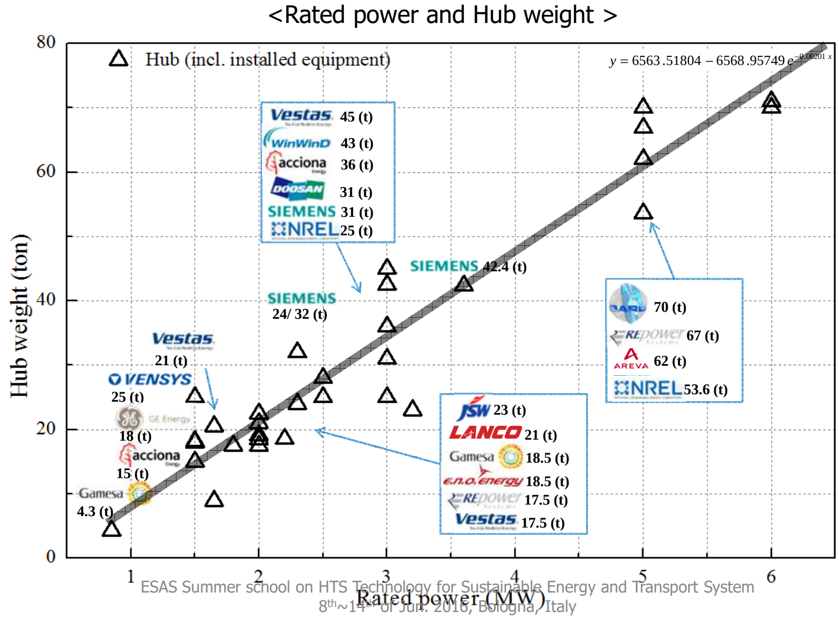
Bearing type	Corresponding components
Floating bearing	Main shaft (front)
Thrust bearing	Main shaft (rear)
Slewing bearing	Pitch, Yaw

Components of the wind turbine (Hub weight)

➢ Hub

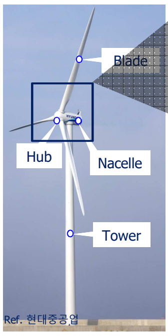
Ref. CAPTA

<Rated power and Hub weight >

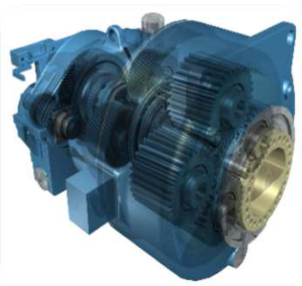


Components of the wind turbine (Gearbox)

➢ Gearbox



What is a gearbox?



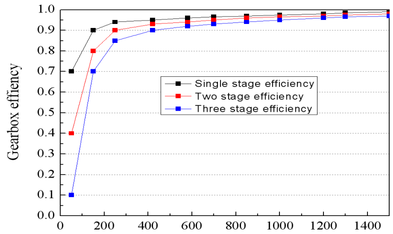
- Mechanical method of transferring energy from one device to another
- To increase rotating speed while reducing torque
- Located between main shaft and generator

✓ How to calculate the gearbox losses?

$$\eta = \frac{Power_{Outofgearbox}}{Power_{Intogearbox}}$$

$$= \frac{Power_{Intogearbox} - q \times 0.01 \times Power_{rated}}{Power_{Intogearbox}}$$

*q : stage of gear



Ref . A Preliminary Evaluation of a Multiple-Generator Drivetrain Configuration for wind Turbines

<Theoretical gearbox efficiency estimate for a 1.5MW wind turbine>

Components of the wind turbine (Gearbox loss)

➢ Gearbox

✓ How to calculate the gearbox losses?
Main losses in a gearbox are proportional to the shaft speed

$$P_{Gear} = P_{Gearn} P_N \frac{n}{n_{rated}}$$

P_{Gearm} = Loss in the gearbox at rated power
P_N = Rated power of wind turbine
n = Rated wind speed of wind turbine
n_{Rated} = Rated rotor speed

- Losses percentage at the rated power for 1-stage : 1.5%
- Losses percentage at the rated power for 3-stage : 3.0%

✓ Analysis of gearbox losses on manufacturers

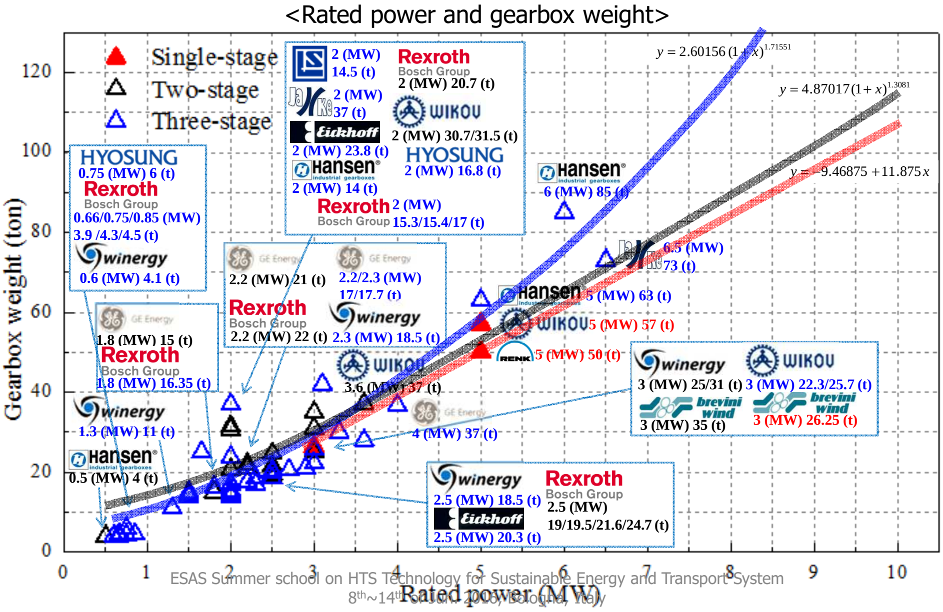
Company	Rated power (MW)	Rated wind speed (m/s)	Rotor speed (m/s)	Gearbox type	Stage	Loss (kW)	Weight (ton)
SIEMENS	3.6	12-13	5-13	spur / planetary gear	3	108	
	2.3	12-13	6-16	spur / planetary gear	3	69	
	1	15	15	spur / planetary gear	3	30	
Acciona	3	10.6	12.3	spur / planetary gear	3	90	25, 31
	1.5	10.5	16.7	spur / planetary gear	3	45	
Dewind	2	12.5	13.9-25.9	spur / planetary gear	3	60	
	1.25	12	15.7	planetary gear	3	37.5	

Components of the wind turbine (Gearbox weight)

➢ Gearbox

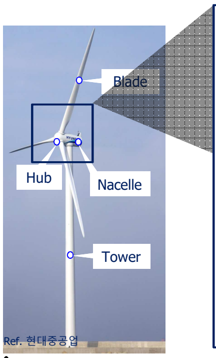
Ref. CAPTA

<Rated power and gearbox weight>

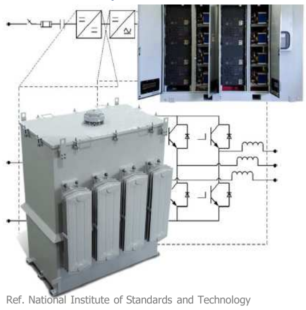


Components of the wind turbine (PCS)

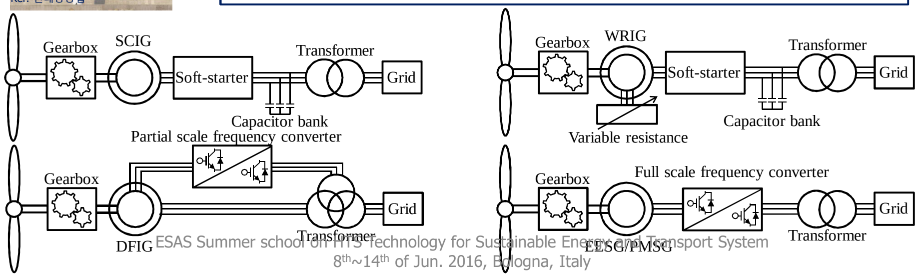
➢ Power converter



What is a power converter?



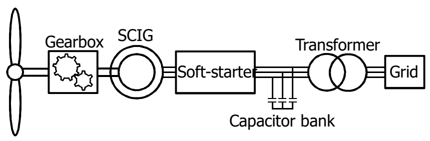
- A power electronic converter enables efficient conversion of the variable frequency output of an induction generator.
- Generator speed is fully controllable over a wide rage even to very low speeds.
- It can effectively help the connection between the generator and grid.



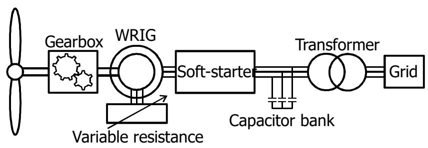
ESAS Summer school on HTS Technology for Sustainable Energy and Transport System
8th~14th of Jun. 2016, Bologna, Italy

Components of the wind turbine (PCS)

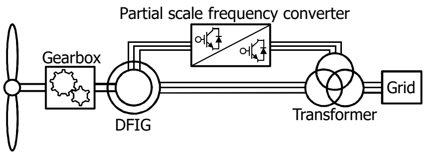
- Power converter



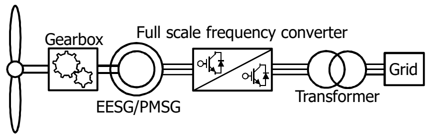
- **Fixed speed wind turbine concept**
- **Asynchronous squirrel cage induction generator (SCIG)**



- **Limited speed wind turbine concept**
- **Wound rotor induction generator (WRIG)**



- **Variable speed concept with a partial-scale power converter**
- **Doubly fed induction generator (DFIG)**



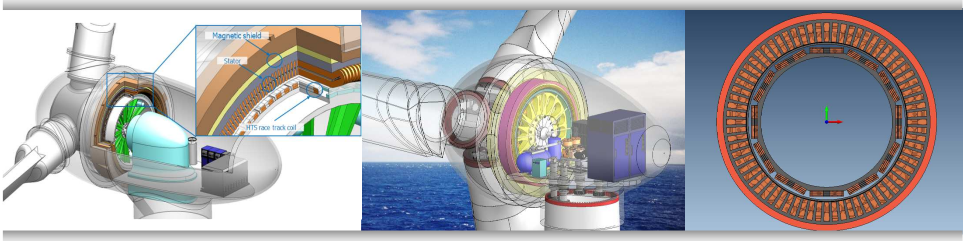
- **Variable speed concept with a full-scale power converter**
- **Electrically excited synchronous generator (EESG)**
- **Permanent magnet synchronous generator (PMSG)**

Components of the wind turbine (PCS)

- Power converter

Concept	Generator	Feature
Fixed speed wind turbine concept	SCIG	▪ Installation of a capacitor bank for reactive power compensation ▪ Installation of soft-starter to protect the system from inrush current ▪ Use of the stall control method for power control
Limited speed wind turbine concept	WRIG	▪ Installation of variable rotor resistance for the dynamic speed control (typically 0%~10% above synchronous speed) ▪ Installation of a capacitor bank for reactive power compensation ▪ Installation of soft-starter to protect the system from inrush current
Variable speed concept with a partial-scale power converter	DFIG	▪ A wider range of dynamic speed control compared with the limited speed wind turbine concept (the variable speed range is ±30% around the synchronous speed) ▪ The power converter performs reactive power compensation and smooth grid connection.
Variable speed concept with a full-scale power converter	EESG	▪ The amplitude and frequency of the voltage can be fully controlled by the power converter at the generator side. → the generator speed is fully controllable over a wide rage even to very low speeds. ▪ Connection with generator rotor and exciter (DC current)
	PMSG	▪ The amplitude and frequency of the voltage can be fully controlled by the power converter at the generator side. → the generator speed is fully controllable over a wide rage even to very low speeds. ▪ No additional power supply for the magnet field excitation

The large-scale wind turbine using **HTS**



One of examples, the large-scale wind turbine

➢ Specifications of the wind turbine

Items	Value
Rated output power P_N (MW)	12
Shaft power P_T (MW)	12.96
Rated ideal wind velocity V_{RI} (m/s)	11.4
Tip speed ratio λ (V_R)	8.9
Blade length (m)	97.4
Tip speed V_{TIP} (m/s)	85.6
Rotation speed ω_R (rad/s)	0.838
Maximum power coefficient C_{Pmax}	0.48
Mass density of the air ρ (kg/m³)	1.225

$$R_{blade} = \sqrt{\frac{2P_T}{\rho C_p \pi V^3}} = \sqrt{\frac{2(1+\varepsilon)P_N}{\rho C_p \pi V^3}}$$

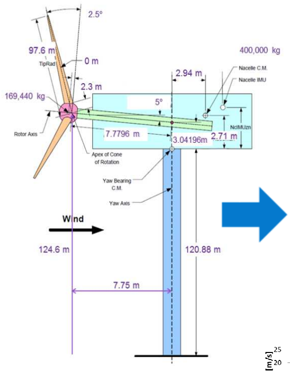
- ρ : Air density, 1.225 kgm^{-3}
- C_p : Max. power coefficient of rotor
- V : Rated ideal wind velocity
- P_T: Mechanical power of the rotor shaft
- P_N : Rated power of wind turbine
- $P_T = (1+\varepsilon)P_N$ includes a loss factor of the drive train (ε~8%)

The large-scale wind turbine (Blade)

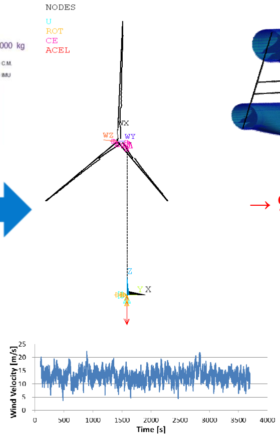
Ref. KIMS, Development of 12MW FOWT core technology for commercialization

➢ Blade & Flexible shaft from KIMS

- Design of the shaft/ blade



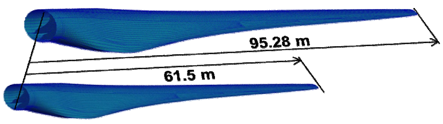
Based on NREL 5MW wind turbine



12MW wind turbine model (Scale up)

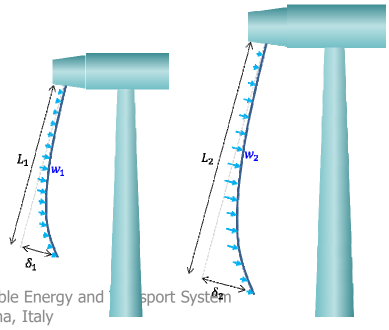
Simulation (FAST-Fatigue, Aerodynamics, Structures & Turbulence)

- **Scale up to 12 MW**



61.5 m 5 MW glass blade

→ 95.28 m 12 MW carbon (sparcap) blade



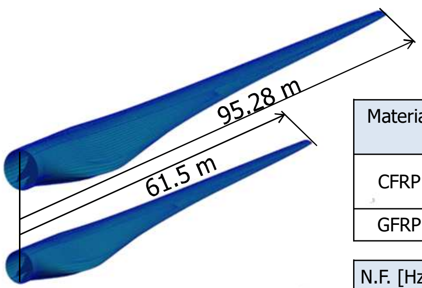
The large-scale wind turbine (Blade)

Ref. KIMS, Development of 12MW FOWT core technology for commercialization

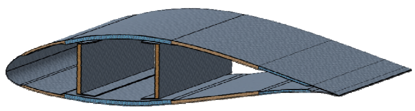
➢ 12 MW class blade

❖ Blade

61.5 m 5 MW glass/epoxy blade scale up
→ **95.28 m** 12 MW carbon (sparcap) & glass/epoxy blade



Sparcap
(43% of the total weight – 5MW class)



Material	0° stiffness [GPa]	Density [kg/m^3]	Blade weight [ton]	Center of gravity [m]
CFRP	130	1572	42.7 (carbon sparcap)	31.8
GFRP	41.5	1920	62.6	31.8

N.F. [Hz]	1st flapwise	2nd flapwise	1st edgewise	2nd edgewise
12MW blade	0.58	1.63	0.89	3.27

The large-scale wind turbine (Shaft)

Ref. KIMS, Development of 12MW FOWT core technology for commercialization

- ➢ Composite flexible shaft
  - ❖ Direct drivetrain with a composite flexible shaft

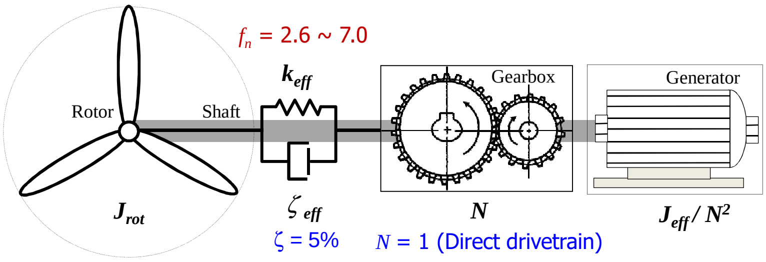
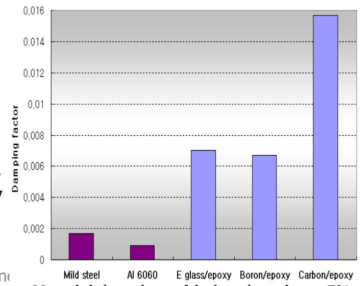


Figure shows the configuration of the two-mass model commonly used to model the dynamics of drivetrains in **FAST**.
Input parameters: J_{rot}, k_{eff}, ζ_{eff}, N, and J_{eff}/N^2

❖ Nonzero eigenfrequency

$$f_n = \frac{1}{2\pi}\sqrt{k_{eff}\left(\frac{1}{J_{rot}}+\frac{1}{J_{eff}}\right)}$$

J_{rot} : Inertia of the rotor
k_{eff} : Effective drivetrain torsional stiffness
ζ_{eff} : Effective drivetrain torsional damping
N : Drivetrain gear ratio
J_{eff} :Effective inertia of the generator and gearbox



Material damping + friction damping > 5%

The large-scale wind turbine (FAST)

Ref. KIMS, Development of 12MW FOWT core technology for commercialization

➢FAST-What is it?

❖Structural-dynamic model for horizontal-axis wind turbines:
- Used to stand for Fatigue, Aerodynamics, Structures & Turbulence
- Coupled to AeroDyn, HydroDyn & controller for aero-hydro-servo-elastic simulation

❖FAST Simulation
- Nonlinear time-domain s
- Design situations & conc
  - Turbulent & determini
  - Regular & irregular wa
  - Earthquake excitation
  - Power production wit
  - Start-up & shut-down
  - Control system faults
  - So on..

The large-scale wind turbine (NTM)

Ref. KIMS, Development of 12MW FOWT core technology for commercialization

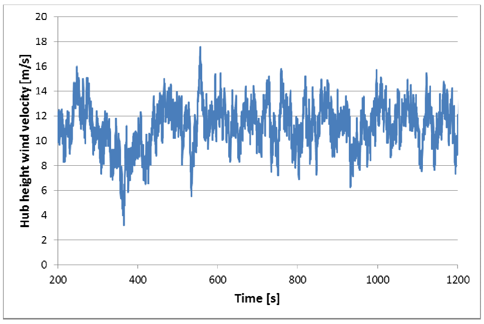
*I : 50 m/s (in tropical storms such as hurricanes, cyclones and typhoons)

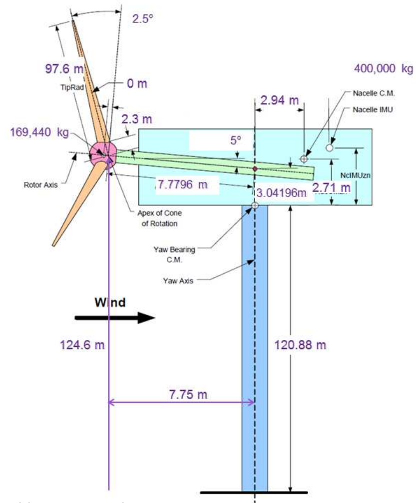
*A : The category for higher turbulence characteristics

- Normal turbulence model
  - Wind condition : NTM Class IA (from 3 m/s to 25 m/s)

Assumed "no slope of the wind inflow" for preliminary design

Wind velocity (NTM Class IA 11.2m/s)

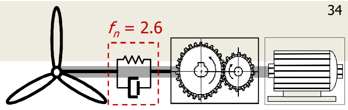




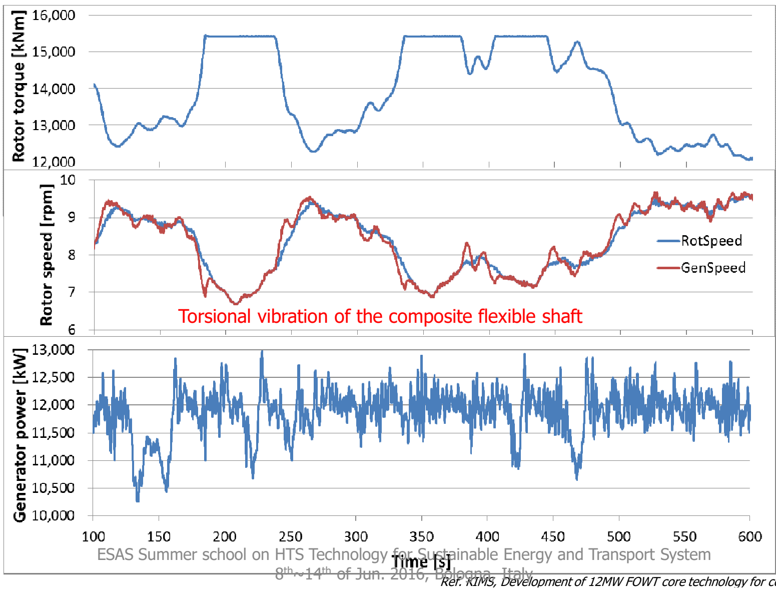
Analysis results

- Rotor/generator torque
- In-plane and out-of-plane tip deflection
- Shaft bending moment M_y and M_z

The large-scale wind turbine

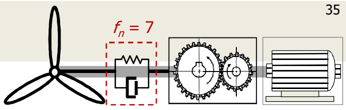


- Normal turbulence model
  - **When f_n = 2.6**

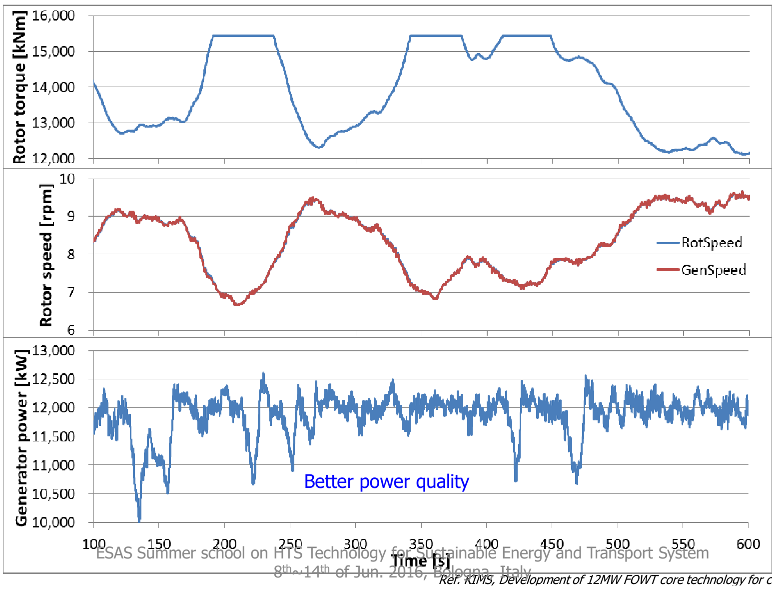


Ref. KIMS, Development of 12MW FOWT core technology for commercialization

The large-scale wind turbine



- Normal turbulence model
  - **When f_n = 7**

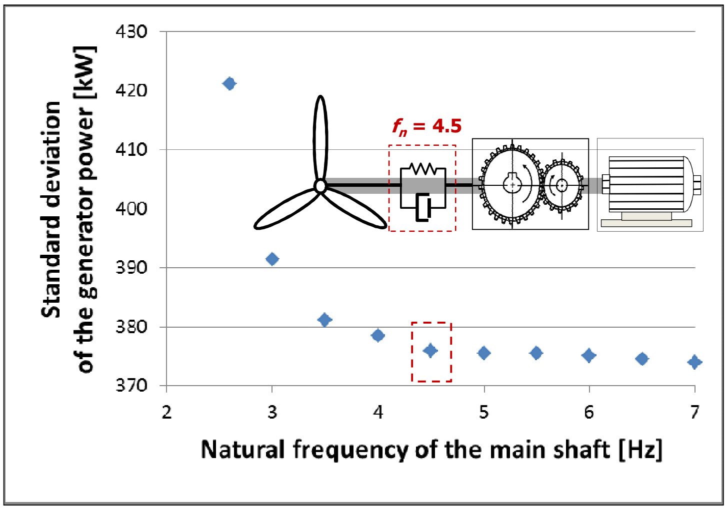


Ref. KIMS, Development of 12MW FOWT core technology for commercialization

The large-scale wind turbine (Min. weight of shaft)

Ref. KIMS, Development of 12MW FOWT core technology for commercialization

- Normal turbulence model
  - **Optimal stiffness of a composite flexible shaft having minimum weight**



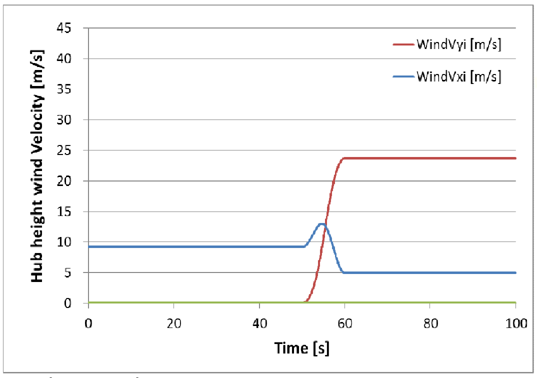
The large-scale wind turbine (ECD)

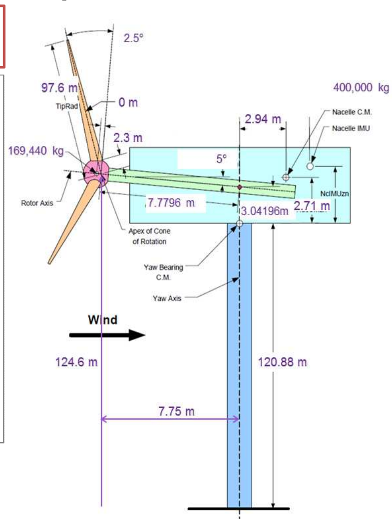
Ref. KIMS, Development of 12MW FOWT core technology for commercialization

➢ Extreme coherent gust with direction change

❖ **Wind condition : ECD (from 9.2 m/s to 13.2 m/s)**

Wind velocity
(ECD 9.2m/s rotating along the negative direction)





Analysis results
- Rotor/generator torque
- In-plane and out-of-plane tip deflection
- Shaft bending moment M_y and M_z

The large-scale wind turbine (ECD)

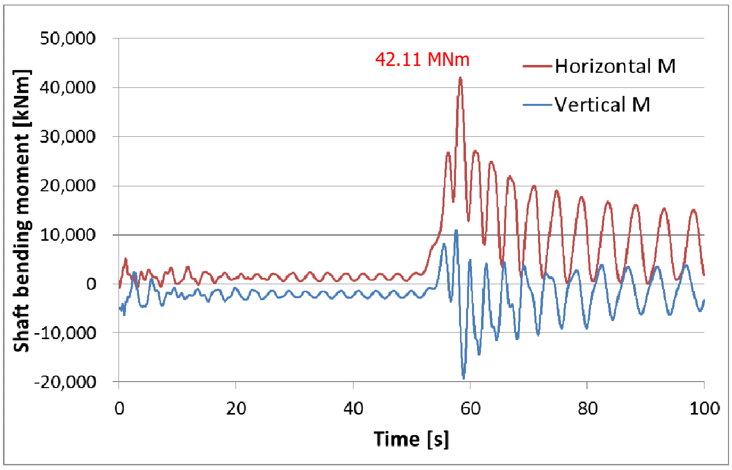
Ref. KIMS, Development of 12MW FOWT core technology for commercialization

➢ Extreme coherent gust with direction change

❖ **Horizontal bending moment**

At the gust velocity of 15.0 m/s + hub height velocity of 9.2 m/s:

M_z = 42.11 MNm (→ with safety factor : 56.84 MNm)



The large-scale wind turbine (EWS)

39

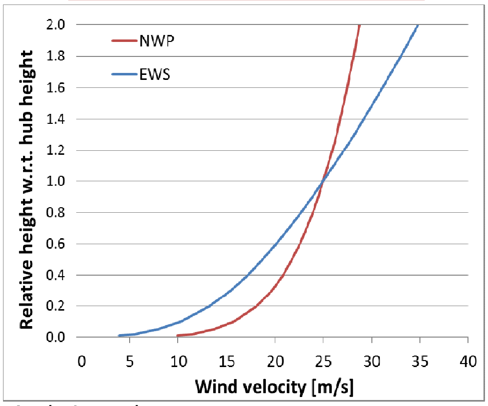
Ref. KIMS, Development of 12MW FOWT core technology for commercialization

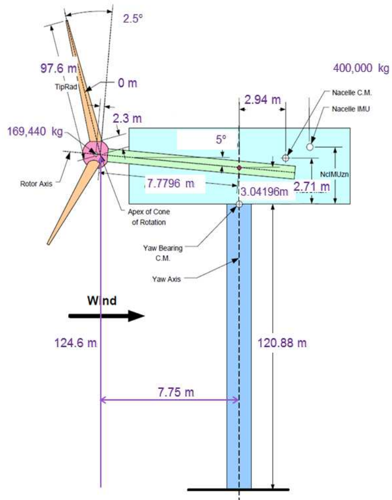
- Extreme wind shear

*I : 50 m/s (in tropical storms such as hurricanes, cyclones and typhoons)
*A : The category for higher turbulence characteristics
*NWP : Normal Wind Profile model

- ❖ **Wind condition : EWS Class IA (from 3 m/s to 25 m/s)**

Wind velocity (EWS Class IA 25.0 m/s)





Analysis results
- Rotor/generator torque
- In-plane and out-of-plane tip deflection
- Shaft bending moment M_y and M_z

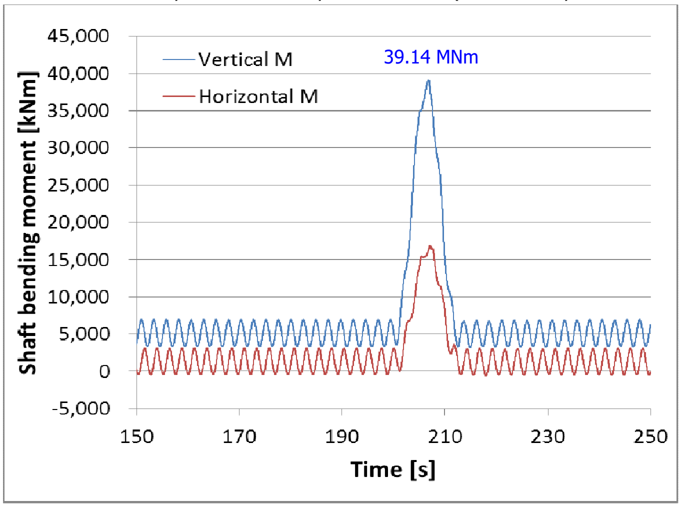
The large-scale wind turbine (EWS)

40

Ref. KIMS, Development of 12MW FOWT core technology for commercialization

- Extreme wind shear
  - ❖ **Vertical bending moment**

At the wind velocity of 25.0 m/s : My = 39.14 MNm (→ with safety factor : 52.85 MNm)

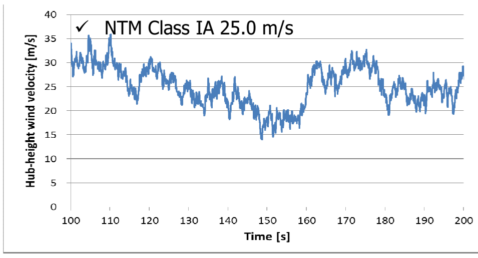


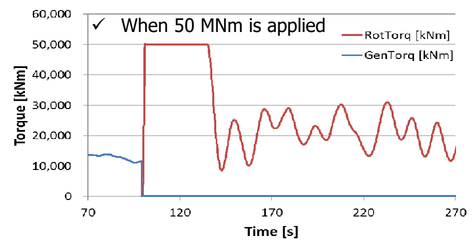
The large-scale wind turbine (Mechanical braking)

Ref. KIMS, Development of 12MW FOWT core technology for commercialization

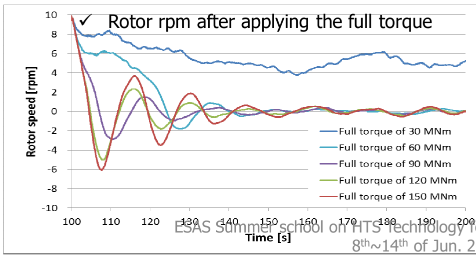
- Emergency shut down (mechanical braking)
  - ❖ **Full torque of a mechanical braking system (from 30 MNm to 150 MNm)**

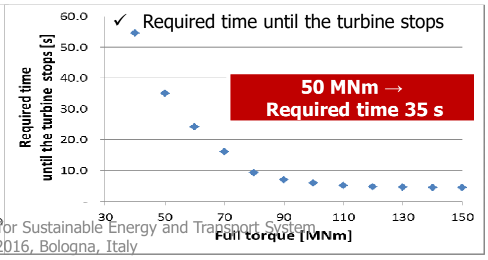
At the wind velocity of 25.0 m/s : My = 39.14 MNm (→ with safety factor : 52.85 MNm)





To stop the wind turbine, a full torque larger than 30 MNm is needed.



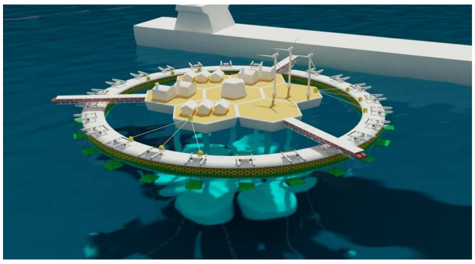


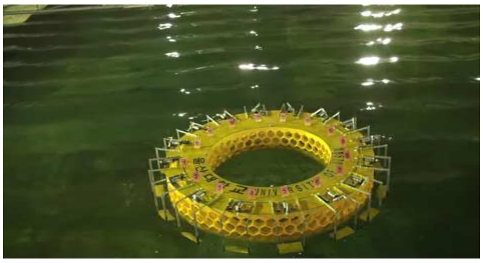
The large-scale wind turbine (Offshore floater)

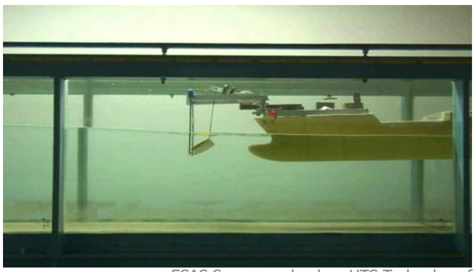
Ref. UOU, Development of 12MW FOWT core technology for commercialization

- Novel offshore floater

\- Anti-motion device / Station-keeping device





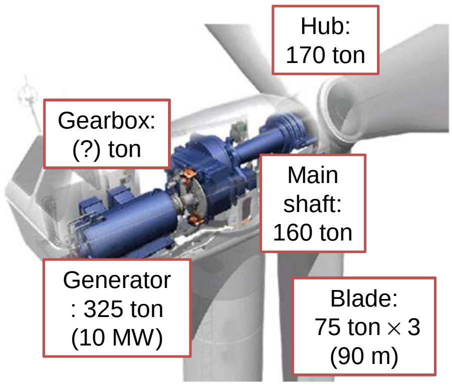


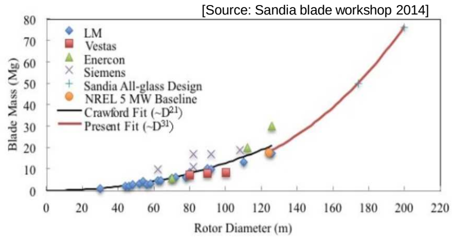
The large-scale wind turbine using the conventional

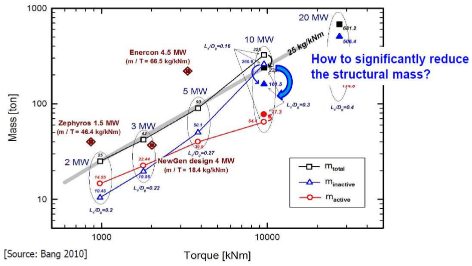
43

Ref. UOU, Development of 12MW FOWT core technology for commercialization

➢ Tower top mass of a 12 MW wind turbine







880 + α ton in conventional WT?

The large-scale wind turbine (tower **height**)

44

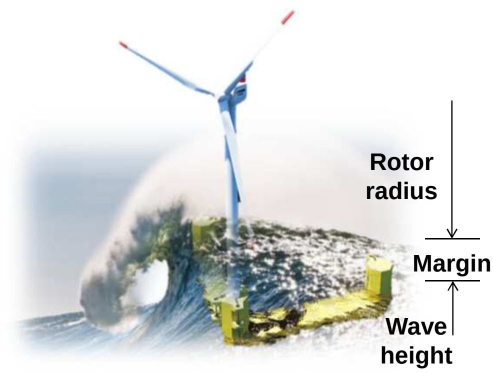
Ref. UOU, Development of 12MW FOWT core technology for commercialization

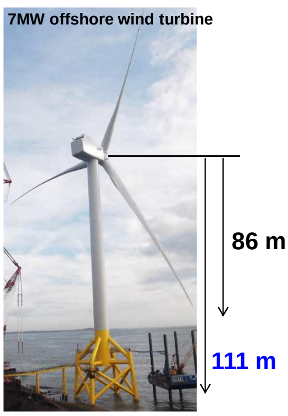
➢ Hub height

- ❖ **Nacelle target mass: 400 ton, Hub target mass: 169.4 ton**
- ❖ **Hub height**

  Rotor radius + Extreme wave height (half) with 50-year occurrence × S.F. of 1.8

  › ***97.6 + 30.0 / 2 × 1.8 = 124.6 m***





(cf. 86.0 + 30.0 / 2 × 1.8 = 113 m)

The large-scale wind turbine using **HTS**

Ref. SANDIA REPORT, June 2011

- Scale-up tower properties

A scale factor, α, is defined as the ratio of the scaled blade length (L_1) to the nominal blade length (L_2):

$$\alpha = \frac{Scaled\ length}{Nominal\ length} = \frac{L_1}{L_2}$$

The total blade mass follows this relationship:

$$m_{up} = \alpha^3 m_{blade}$$

The rotor power:

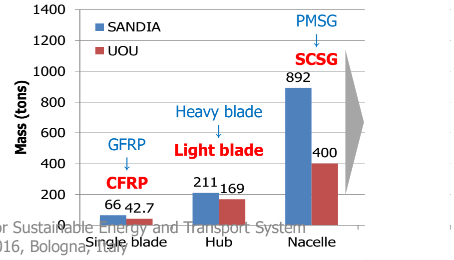
$$P_{up} = \alpha^2 P$$

<Conventional WT> (Criterion: 5MW)

Capacity	Scale ratio (α)	Rotor diameter (m)	Blade length (m)	Blade mass (tons)
5 MW	1	126	61.5	18
10 MW	1.414	178.2	87.0	50
12 MW	**1.549**	**195.2**	**95.3**	**66**
13.2 MW	1.625	204.7	99.9	76
15 MW	1.732	218.2	106.5	92

Capacity	Scale ratio (α)	Top tower mass (tons)	Nacelle mass (tons)	Hub mass (tons)
5 MW	1	350	240	56.8
10 MW	1.414	990	679	161
12 MW	1.549	**1,301**	892	211
13.2 MW	1.625	1,501	1030	244
15 MW	1.732	1,819	1250	295

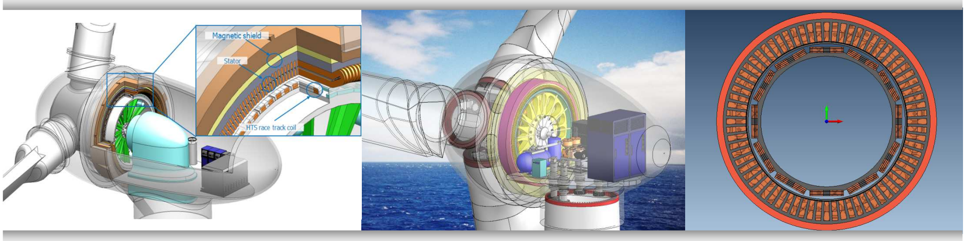
Cap.	Conventional scaling	**HTS generator scaling**			
	Top tower (tons)	Nacelle (tons)	Hub (tons)	Blade-CFRP (tons)	**Top tower (tons)**
12 MW	1,301	400	169	42.7	**697**



Ref. UOU, Development of 12MW FOWT core technology for commercialization

HTS technology can dramatically reduce the weight of generator, but is it possible?

Design process of a large-scale superconducting **generator**



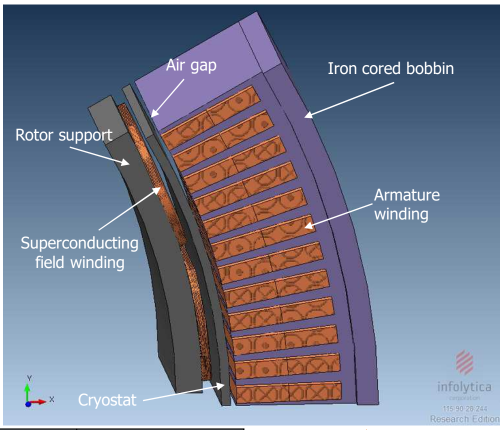
Design process of the superconducting generator

Digit 1	Digit 2	Digit 3
Check the Design Objective	Target of the generator	Cost / Weight / Diameter / Efficiency
2D Generator Design (Modeling in FEM program)	Rating of generator	Output power / Output voltage
	Set of generator parameters	Rotating speed / Number of poles / HTS field coil / Stator coil / etc.
	Electromagnetic analysis	Magnetic distribution / Output power
	Force / Mechanical analysis	Lorentz force
		Torque
		HTS field coil loads
Generator Layout Drawing for 3D Optimization Design	Drawing generator (3D CAD program)	Rotor part (Rotor body, HTS field coil, Cryostat)
		Stator part (Stator body, Coil, Magnetic shield)
3D Generator Optimal Design	Confirm the 2D Optimization Model	Electromagnetic analysis
		Mechanical analysis
Detailed Analysis	**Electromagnetic Analysis**	**Magnetic flux density / Lorentz force**
	Mechanical Analysis	**Torque / Load / Max. stress**
	Thermal Analysis	**Cooling method / Cooling path / Temp.**
Redesign of the Structure	Change the Structure Based on the Detailed Analysis	Verify the analysis results
		Drawing the modified model
		Analysis of the modified model
Confirm the designed generator	Confirm the design objective	Cost / Weight / Diameter / Efficiency
Detailed Drawing	Drawing based on designed generator	Check the assembly process
		Detail drawing of the generator

Designs of the large-scale HTS generator

➤Specifications of the HTS generator

Item	Value
Rated L-L voltage	6.6 kV
Rated rotating speed	8 RPM
Rated torque	12.6 MNm
The num. of rotor poles	30
The num. of DPC layers	4
The length of air gap	20 mm
Thickness of vacuum vessel	50 mm
Number of stator coil /phase/pole	2
Current density of copper wire	3 A/mm^2
Safety margin of operating current	40%



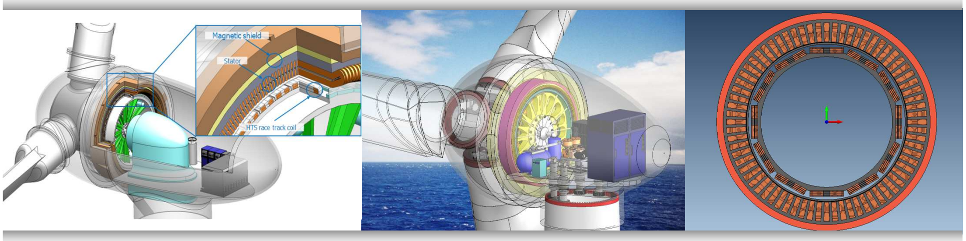
FEM model of the HTS generator

Parts	Material	Density (kg/m^3)
Rotor wire	(RE)BCO	11,000
Rotor body	304 stainless steel	8,190
Vacuum vessel	304 stainless steel	8,190
Stator wire	Copper	8,940
Stator body	304 stainless steel	8,190

Materials of each part

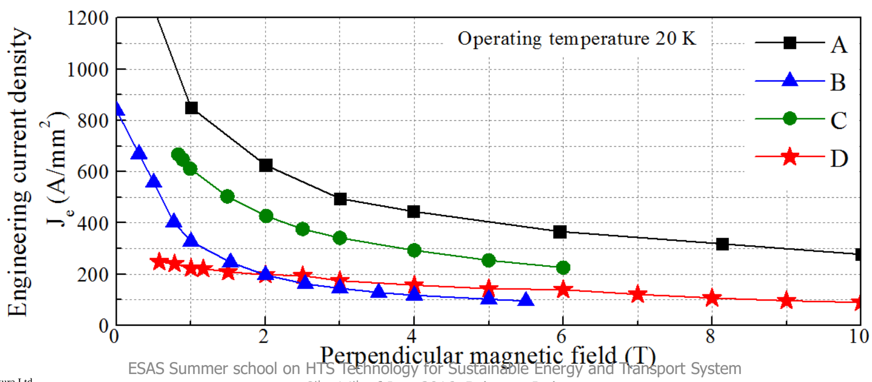
ESAS Summer school on HTS Technology for Sustainable Energy and Transport System
8th~14th of Jun. 2016, Bologna, Italy

Detail design of rotor part
(considering different superconducting wire types)



Properties comparison of superconducting wires

Symbol	A [1]	B [2]	C [3]	D [4]
Type	(Gd/Y)BCO	YBCO	(Gd)BCO	Bi-2223
Thickness (mm)	0.1	0.2	0.3	0.36
Width (mm)	4	4.8	5	4.5
Min. RT bend diameter (mm)	11	30	-	60
Max. RT rated tensile stress (MPa)	550	150	-	250
Critical current (self field, 77 K)	100 A	100 A	230 A	200 A



[1] Supe
[2] Ame
[3] Fujikura Ltd.
[4] Sumitomo Electric Industries

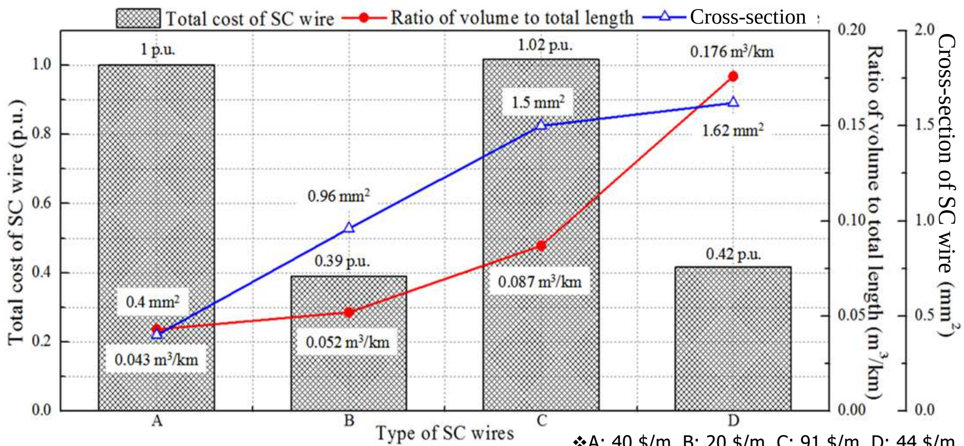
Comparison of the design parameters

➢Specifications of large-scale HTS generators

Specifications	A	B	C	D
Rated power (MW)	10	10	10	10
Rated output voltage (kV)	6.6	6.6	6.6	6.6
Rated output current (A)	874.77	874.77	874.77	874.77
Rotating speed (rpm)	10	10	10	10
Axial length (m)	0.5	0.6	0.2	0.2
The number of poles	24	24	24	24
Turns of SC coil	1,300	1,100	900	740
Total length of SC wire (km)	**586**	**458**	**265**	**222**
Operating current (A)	100	98	217	187
Maximum magnetic field (T)	8.23	4.59	10.9	5.46
Perpendicular magnetic field (T)	6.96	3.6	9.2	4.8
The number of stator slots	144	144	144	144
Turns of copper coil	25	25	25	30
Current density of stator coil (A/mm^2)	7	7	7	7
Air-gap length (m)	20	20	20	20
Diameter of SCSG (m)	5.3	6	5.6	6.8
Volume of SCSG (m^3)	**25**	**41**	**23**	**39**
Active weight of SCSG (ton)	**71**	**98**	**69**	**94**

Comparison results

➢Total cost of the HTS wire and ratio of the volume to the total length of the HTS wire



❖A: 40 $/m, B: 20 $/m, C: 91 $/m, D: 44 $/m

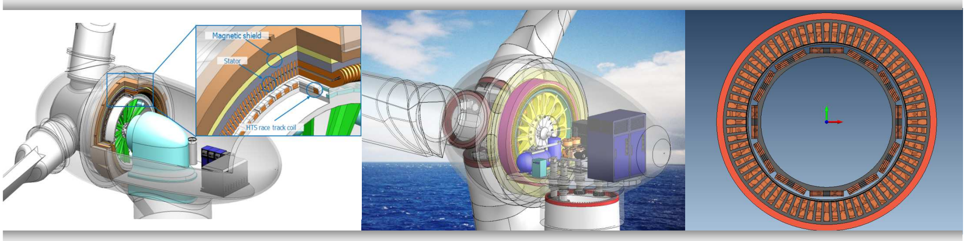
✓The total cost of B is the lowest.

✓The ratio of the volume to the total length of A is the smallest.

✓Therefore, the specifications and performance of the HTS wire influence physical properties of the generator.

Detail design of stator part

(considering different core materials and winding methods)



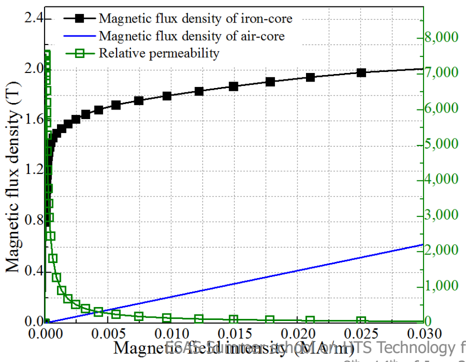
Stator design of the HTS generator

➢Magnetic properties of iron-core (Lamination silicon steel)

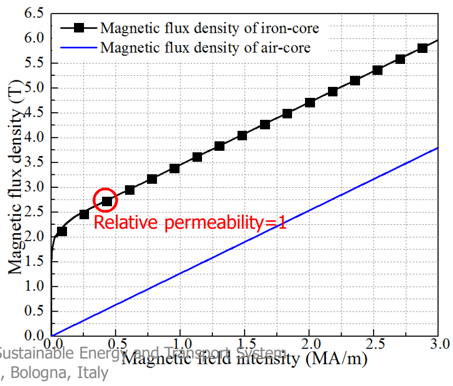
Ref. K. Yoshizawa, S. Noguchi, H. Igarashi, IEEE Trans. on applied supercond., vol. 21, (2011) p. 2088-2091.

- ❖ The iron cores of the SCSGs are exposed to the high magnetic field.
- ❖ Iron manufacturers generally provide the magnetic properties under 2T.
- ❖ In the range of the significantly high magnetic field over the saturation magnetic field of iron-core, the magnetic properties of iron-core should be defined.

➢B-H curves with **low magnetic field**



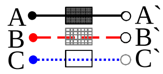
➢B-H curves with **high magnetic field**

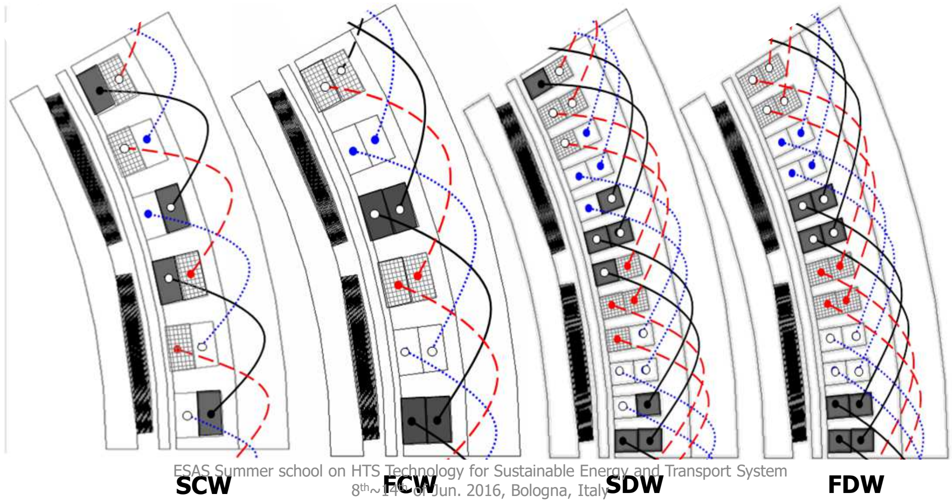


Stator design of the HTS generator

➢Stator winding diagrams

- ❖ SCW: Short pitch Concentrated Winding
- ❖ SDW: Short pitch Distributed Winding
- ❖ FCW: Full pitch Concentrated Winding
- ❖ FDW: Full pitch Distributed Winding

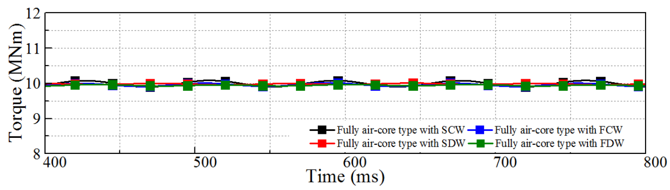




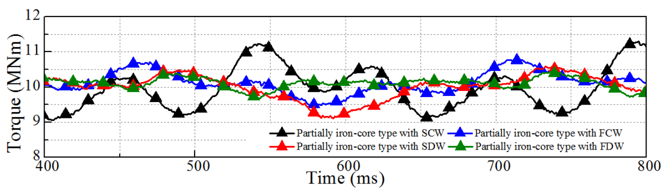
Stator design of the HTS generator

➢Electromagnetic torque waveforms

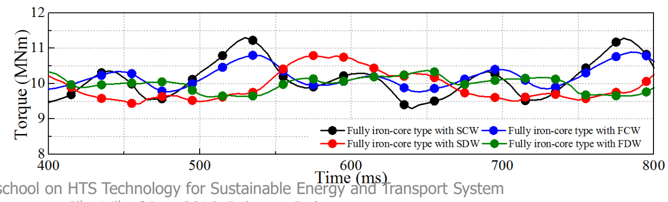
- ❖ Torque ripples of the fully air-core type generators:
  - SCW: 1.8%
  - FCW: 1.0%
  - SDW: 0.4%
  - FDW: 0.3%



- ❖ Torque ripples of the partially iron-core type generators :
  - SCW: 19.7%
  - FCW: 12.3%
  - SDW: 7.0%
  - FDW: 13.4%

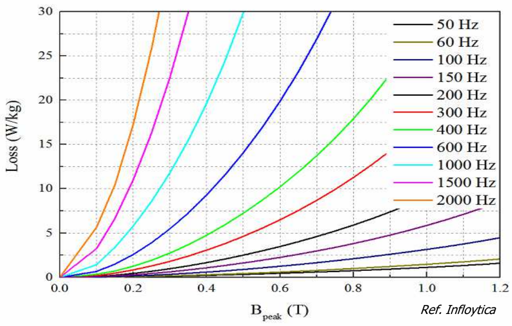


- ❖ Torque ripples of the fully iron-core type generators :
  - SCW: 19.5%
  - FCW: 10.1%
  - SDW: 13.7%
  - FDW: 7.3%



Efficiency of the HTS generator

➢Iron loss curves of silicon lamination steel



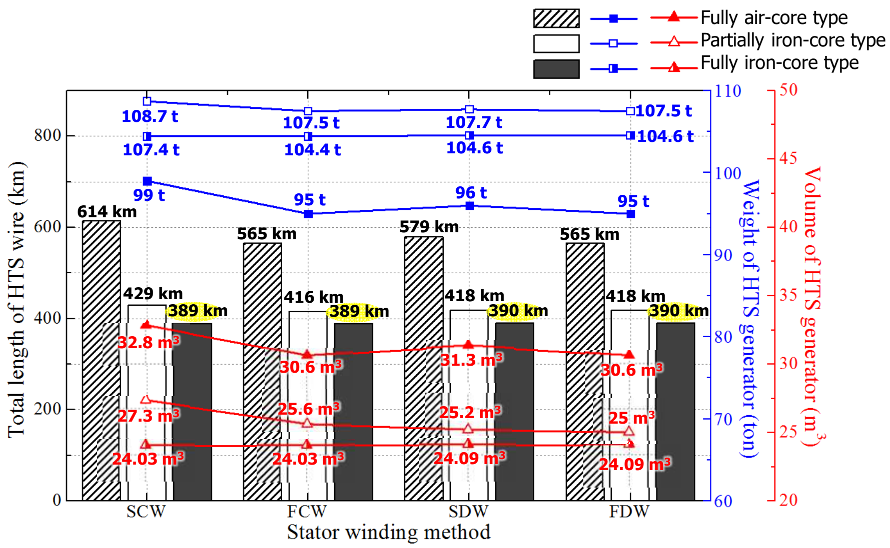
- K_h: 6.13287e-3
- K_e: 8.12391e-5
- α: 1.30958
- β: 1.91075

$$P = K_h f^{\alpha} B^{\beta} + K_e f^2 B^2$$

❖ The efficiencies of the three types of generators are similar about 98%.

Type	Fully air-core type				Partially iron-core type				Fully iron-core type			
Stator windings	SCW	FCW	SDW	FDW	SCW	FCW	SDW	FDW	SCW	FCW	SDW	FDW
Stator coil (kW)	154	154	154	154	154	154	154	154	154	154	154	154
Stator body (kW)	-	-	-	-	9.1	6.75	7.80	7.13	8.21	6.71	7.74	7.19
Vacuum vessel (kW)	2.88	2.21	1.02	0.92	72	38.4	21	20	42	30	12	12
Rotor body (kW)	-	-	-	-	-	-	-	-	0.42	0.42	0.42	0.42
Windage loss (kW)	0.17	0.17	0.17	0.17	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Total loss (kW)	157.1	156.4	155.2	155.1	235	199	183	181	204.8	191.3	174.3	173.8
Efficiency (%)	98.50	98.50	98.50	98.50	97.76	98.10	98.26	98.28	98.05	98.05	98.05	98.05

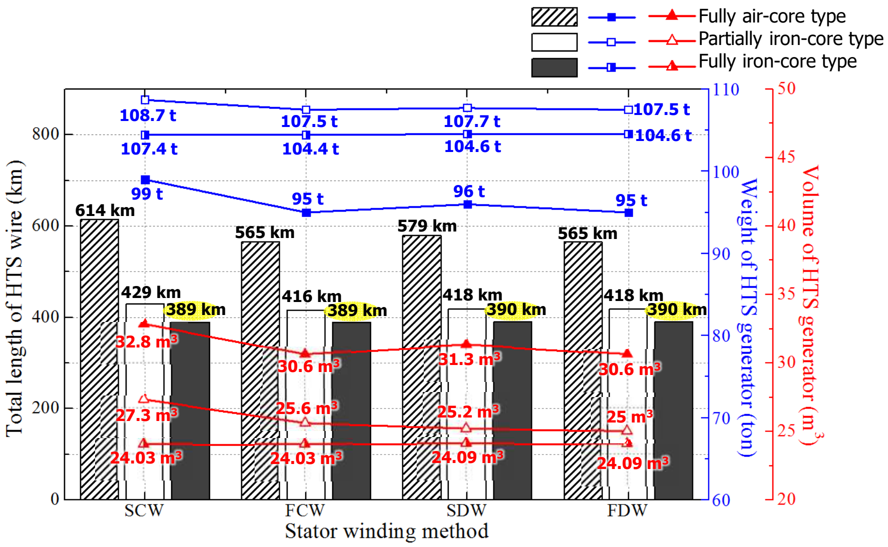
Length of HTS wire & Weight & Volume



❖ The volume and total length of the HTS wire in the fully iron-core type generators with SCW and FCW are the smallest and shortest.

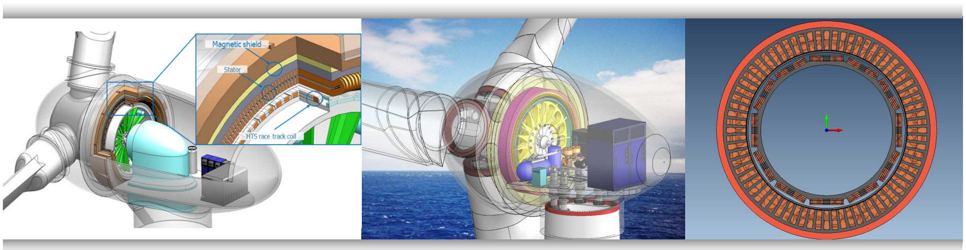
❖ The weight of the fully air-core type generators with FCW and FDW are the lightest because the mass density of the nonmagnetic material is lower than the magnetic material (M-27).

Length of HTS wire & Weight & Volume



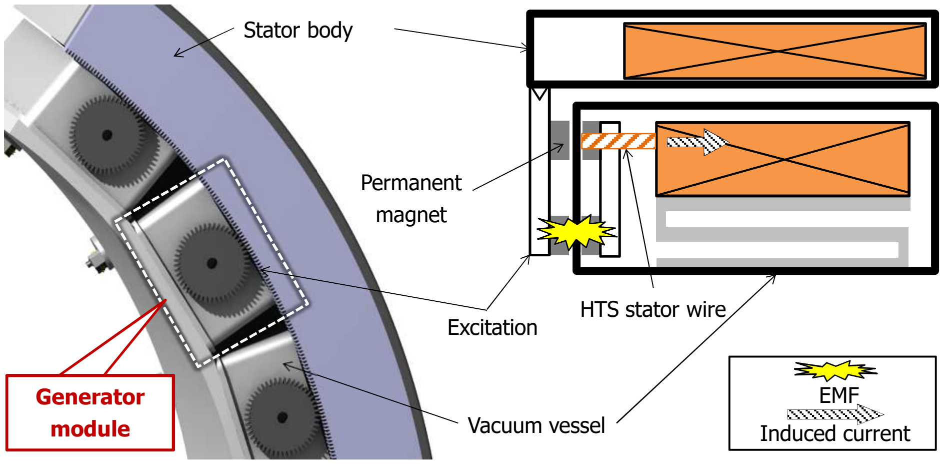
All items considered (torque ripple, efficiency, length of HTS wire, weight, volume), the fully iron-core SCSG with FDW is the good design for large scale wind power systems.

Modularized 12MW HTS generator



The proposed idea of modularization.

➢Configuration of the module for the 12 MW HTS wind power generator

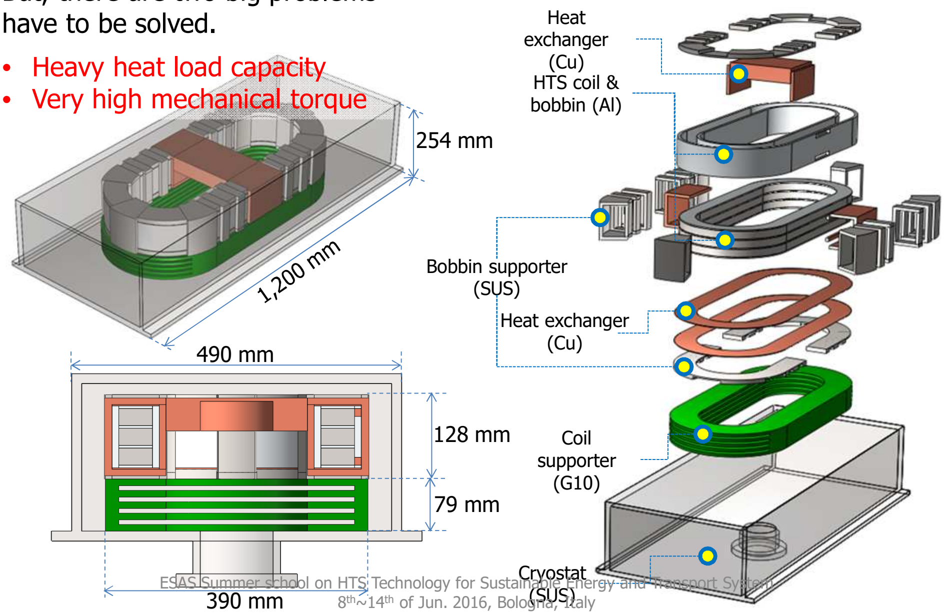


The modularization of the generator enables a smaller cryogenic volume, an easier repair, assembly, and maintenance of the HTS field coil. Modularization will be suitable for commercial mass production and will increase the operational availability of HTS generators in the wind turbine.

Conceptual dimensions of the module(tentative)

But, there are two big problems have to be solved.

- Heavy heat load capacity
- Very high mechanical torque

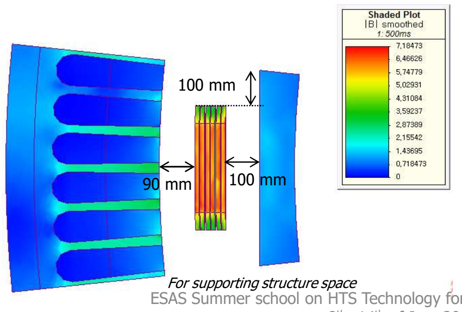


Design of the modularized 12MW class HTS generator

➢ Specification and FEM analysis results

Parts	Property	Value
Rotor	The number of poles	30
	Effective length	450mm
	Rotation speed	8 rpm
	Turns of SC coil/layer/pole	400
	Field current of SC coil	352 A
	Length of SC wire per pole	4.35 km
	Total length of SC wire	130 km(12mm)

Parts	Property	Value
Stator	The number of slot	180
	Copper coil winding type (Distributed Winding)	Short pitch
	Cooling system	Water cool
	Current density of copper coil	3 A/mm^2
	Turns of copper coil	15
	Diameter	6.7 m
Perpendicular magnetic field		5.42 T
Maximum magnetic filed		7 T
Active volume		25 m^3
Active weight		107 ton
Total weight (incl. structure)		**180 ton**
Inductance per pole		4.84 H

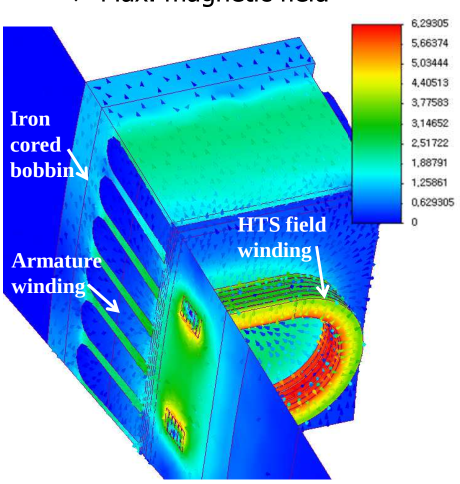


For supporting structure space

Design of the modularized 12MW class HTS generator

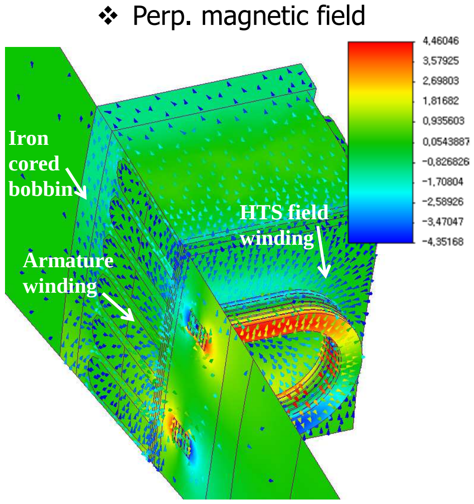
➢FEM simulation results-magnetic distributions

❖ Max. magnetic field



Maximum magnetic field: 6.3 T

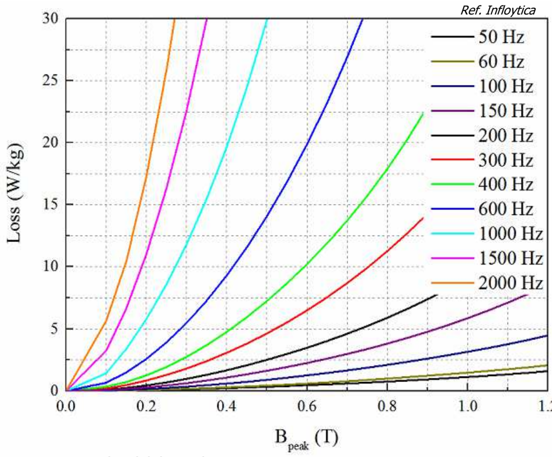
❖ Perp. magnetic field



Perpendicular magnetic field: 4.4 T

Efficiency of the 12 MW HTS generator

➢Iron loss curves of silicon lamination steel



- K_h: 6.13287e-3
- K_e: 8.12391e-5
- α: 1.30958
- β: 1.91075

$$P = K_h f^{\alpha} B^{\beta} + K_e f^2 B^2$$

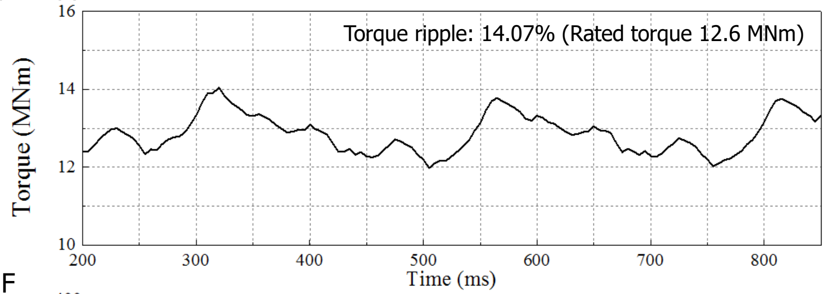
➢Loss of the generator

Ohmic loss		
Cryostat	0.5 kW	
Stator coil	130 kW	
Iron loss		
Stator body	Hysteresis loss	9.81 kW
	Eddy current loss	0.55 kW
Windage loss	0.21 kW	
Total loss	141.07 kW	
Efficiency	**98.8%**	

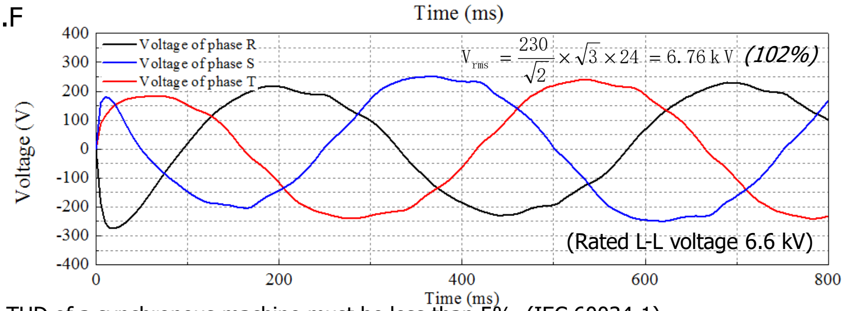
❖ Efficiency of the 12 MW HTS generator with iron stator body is about 99%.

12 MW HTS generator output characteristics

➢Torque ripple

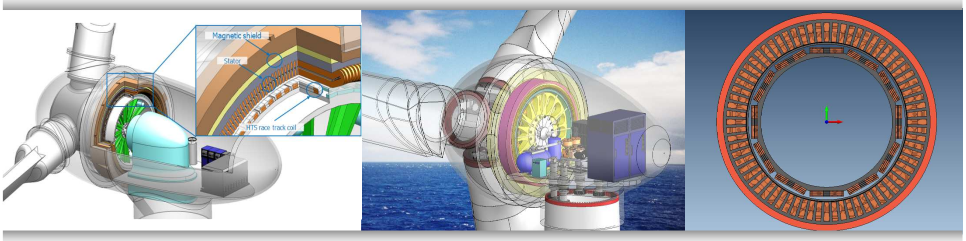


➢E.M.F



❖ The THD of a synchronous machine must be less than 5%. (IEC 60034-1)
❖ This design is suited to standard. (L-L voltage THD is 1.2%)

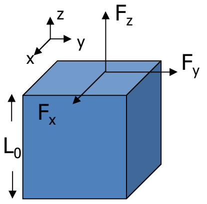
Structural analysis considering high torque



Force and structural analysis and design technique

➢ Stress and Strain of the generator according to the force

❖ Stress/Strain



Normal Strain [Null]

$$\varepsilon \equiv \frac{\Delta L}{L_0}$$

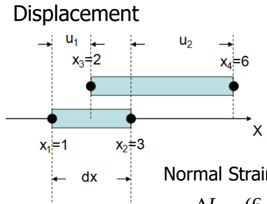
Normal Stress [Pa]: volume variation

$$\sigma_z \equiv \lim_{\Delta A \to 0} \frac{F_z}{\Delta A}$$

Shear Stress [Pa]: shape change

$$\tau_{zy} \equiv \lim_{\Delta A \to 0} \frac{F_y}{\Delta A} \qquad \tau_{zx} \equiv \lim_{\Delta A \to 0} \frac{F_x}{\Delta A}$$

❖ Displacement



Displacement: u(x)

$$u(x_1) = x_3 - x_1 = 2 - 1$$

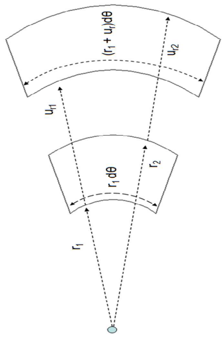
$$u(x_2) = x_4 - x_2 = 6 - 3$$

Normal Strain defined by Displacement

$$\varepsilon_x = \frac{\Delta L}{L} = \frac{(6-2)-(3-1)}{(3-1)} = \frac{(x_4 - x_3)-(x_2 - x_1)}{(x_2 - x_1)}$$

$$= \frac{(x_4 - x_2)-(x_3 - x_1)}{(x_2 - x_1)} = \frac{u(x_2) - u(x_1)}{(x_2 - x_1)} = \frac{\partial u(x)}{\partial x}$$

❖ Hoop strain/Radial strain



Hoop Strain

$$\varepsilon_h = \frac{\Delta L}{L} = \frac{(r_1 + u_r(r_1))d\theta - r_1 d\theta}{r_1 d\theta}$$

$$= \frac{u_r(r_1)}{r_1} = \frac{u_r(r)}{r}$$

Radial Strain

$$\varepsilon_r = \frac{\Delta L}{L} = \frac{u_r(r_2) - u(r_1)}{r_2 - r_1} = \frac{\partial u_r(r)}{\partial r}$$

Force and structural analysis and design technique

➢ Torque characteristics of the superconducting rotating machine

❖ 36.5 MW superconducting motor (AMSC)

❖ Basic specifications

Item	Value
Rated power	**36.5 MW**
Rated terminal voltage	6 kV
Rated armature current	1.27 kA
Rated rotating speed	120 RPM
The num. of rotor poles	**16**

▪ Capacity *vs* Torque

$$P = T \cdot \omega$$

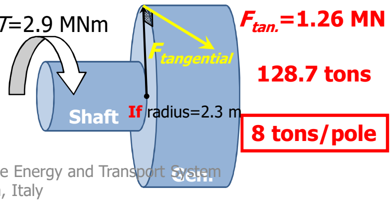
P: Rated power

T: Torque

ω: Angular velocity

$$36.5MW = T \cdot 2\pi(120/60)$$

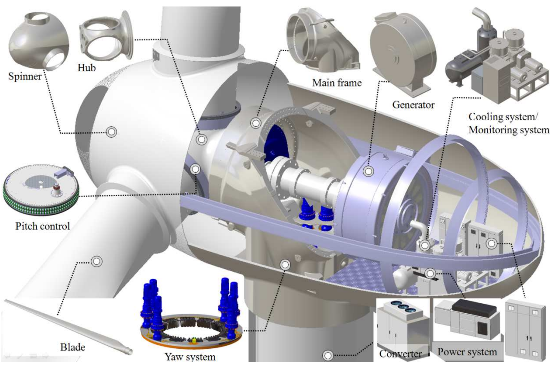
$$T = \frac{36.5MW}{2\pi(120/60)} = 2.9\,MNm$$



Force and structural analysis and design technique

➢ Torque characteristics of the superconducting rotating machine

❖ 12.5 MW HTS wind turbine (CNU)



❖ Basic specifications

Item	Value
Rated power	**12.3 MW**
Rated L-L voltage	6.6 kV
Rated armature current	1.07 kA
Rated rotating speed	**8 RPM**
The num. of rotor poles	30
The num. of DPC layers	6
The length of air gap	90 mm
Thickness of vacuum vessel	20 mm
Number of stator coil /phase/pole	2

▪ Capacity *vs* Torque

$$P = T \cdot \omega$$

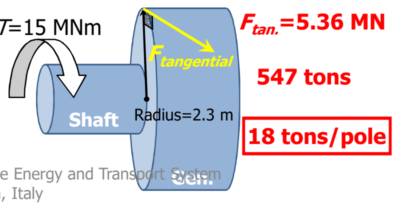
P: Rated power

T: Torque

ω: Angular velocity

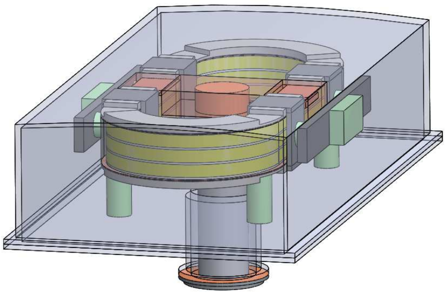
$$12.3MW = T \cdot 2\pi(8/60)$$

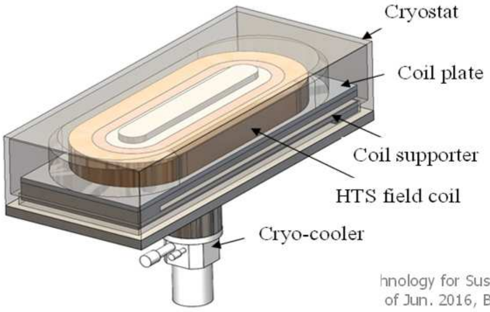
$$T = \frac{12.6\,MW}{2\pi(8/60)} = 15.04\,MNm$$

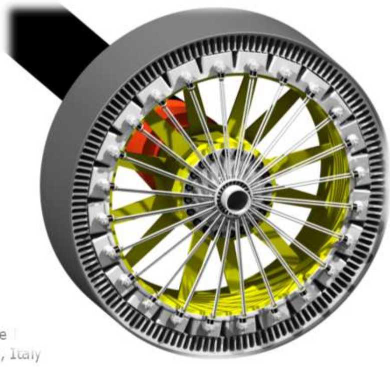


Force and structural analysis and design technique

- Design of the structure of the HTS generator





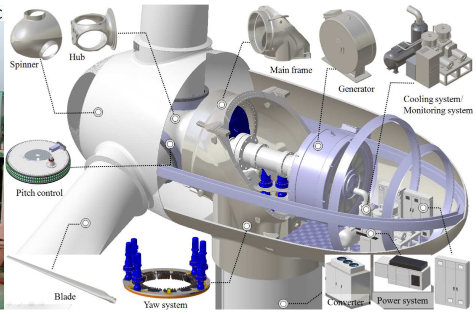


Force and structural analysis and design technique

- Comparison with AMSC's motor

❖ 36.5 MW superconducting motor (AMSC)

❖ 12.5 MW HTS wind turbine (CNU)



$$T = \frac{36.5MW}{2\pi(120rpm/60)} = 2.9\,MNm$$

$F_{tangential}$**=1.26 MN**

8 tons/pole

2 times

$$T = \frac{12.6\,MW}{2\pi(8rpm/60)} = 15.04\,MNm$$

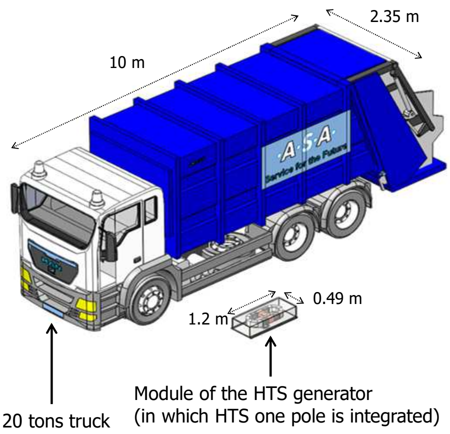
$F_{tangential}$**=5.36 MN**

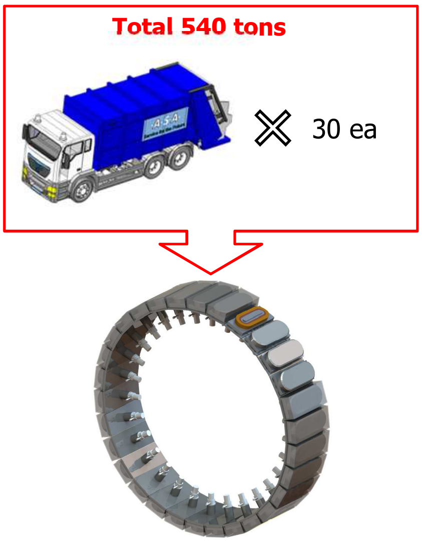
18 tons/pole

Force and structural analysis and design technique

➢ Design of the structure of the HTS generator

▪ The force of 1 pole
→ 0.18 MN= 18 tons

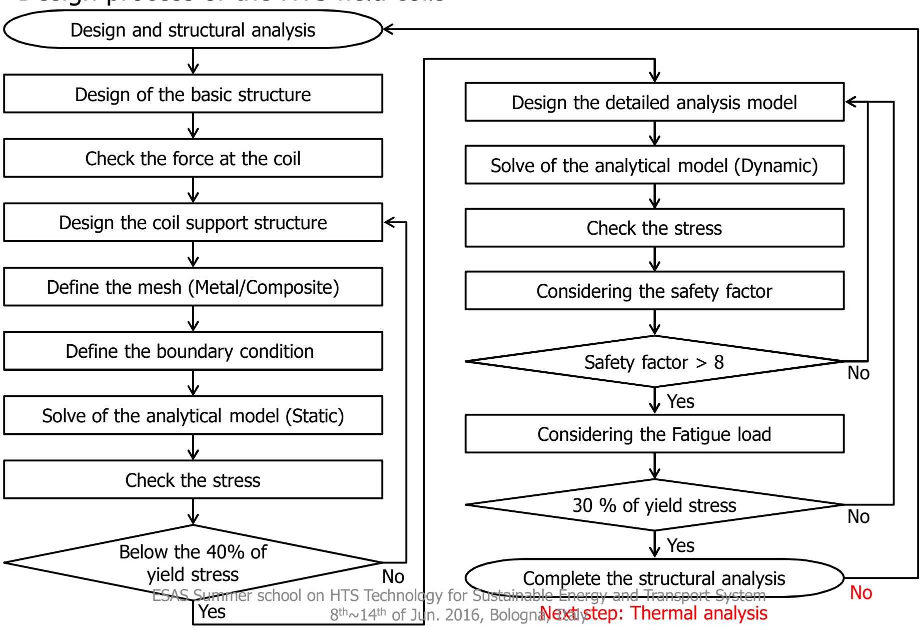




<Rotor part of the 12 MW HTS generator>

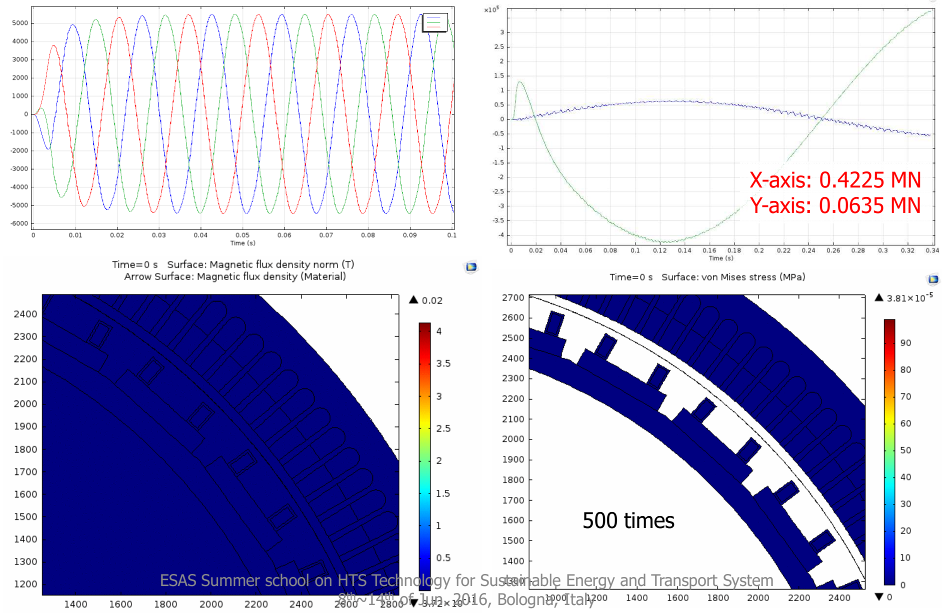
Force and structural analysis and design technique

➢ Design process of the HTS field coils



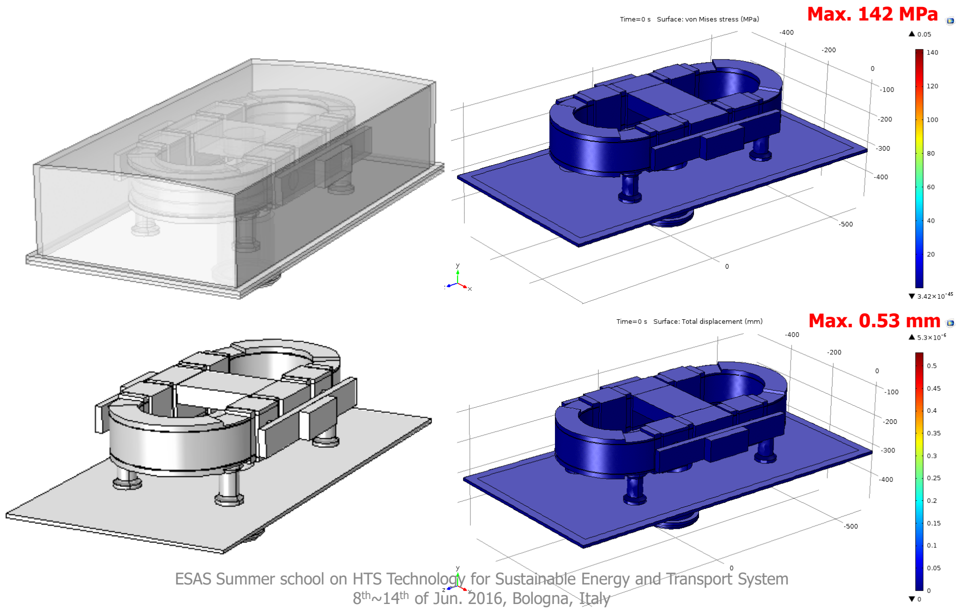
Force and structural analysis and design technique

➢ Force analysis results of the HTS field coils



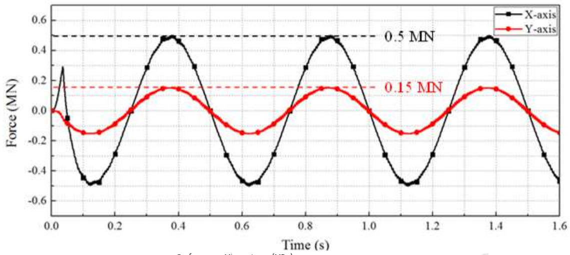
Force and structural analysis and design technique

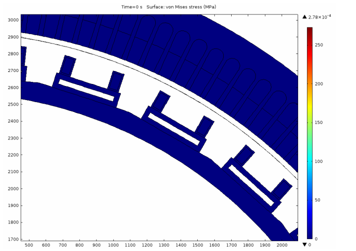
➢ Structural analysis results

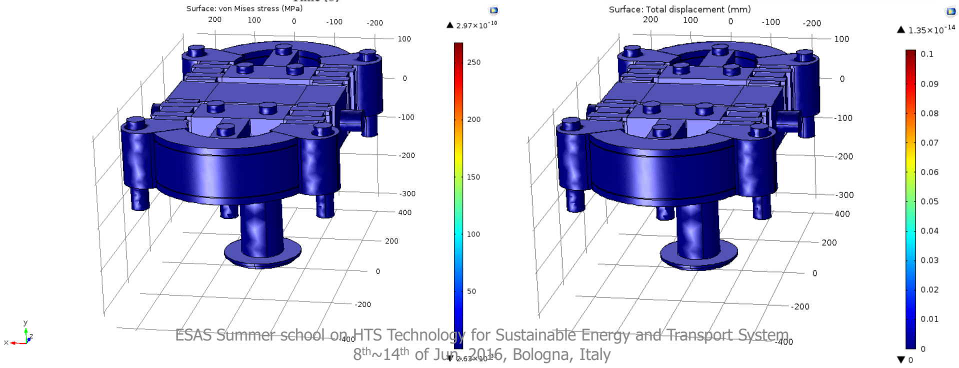


Force and structural analysis and design technique

➢ Structural analysis results (24 poles)





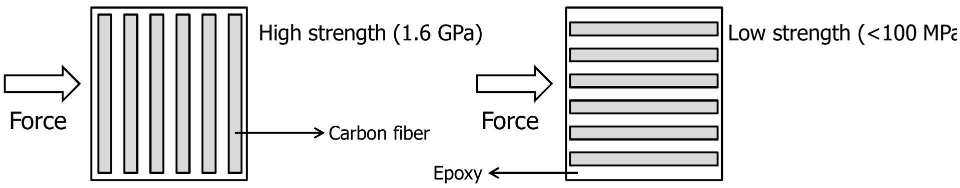


Force and structural analysis and design technique

➢ Mechanical properties of the materials

❖ Properties of CFRP

- Tensile strength of the carbon fiber in a laminate: 1.6 GPa

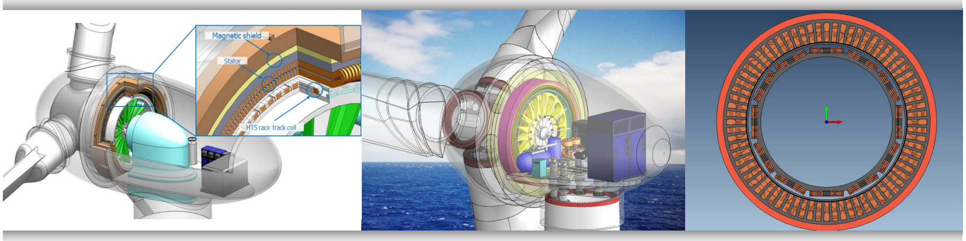


❖ Properties of GFRP

Mechanical Properties	Metric	English
Hardness, Rockwell M	110	110
Tensile Strength at Break	262 MPa	38000 psi
	310 MPa	45000 psi
Flexural Strength	448 MPa	65000 psi
	517 MPa	75000 psi
Flexural Modulus	16.5 GPa	2400 ksi
	18.6 GPa	2700 ksi
Compressive Strength	448 MPa	65000 psi
Izod Impact, Notched	6.41 J/cm	12.0 ft-lb/in
	7.47 J/cm	14.0 ft-lb/in

Tensile Strength (yield) = 262 MPa Allowable stress = 87.33 MPa

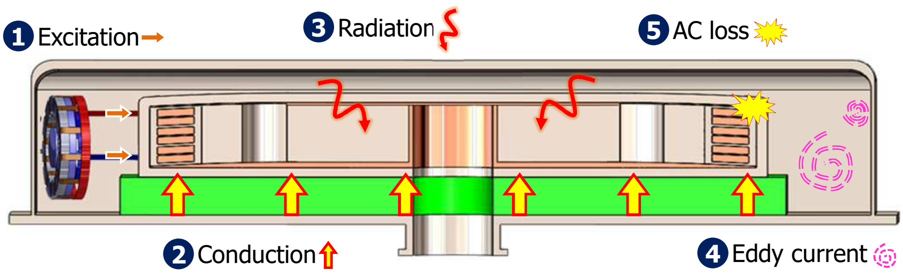
Thermal analysis considering supporter shapes

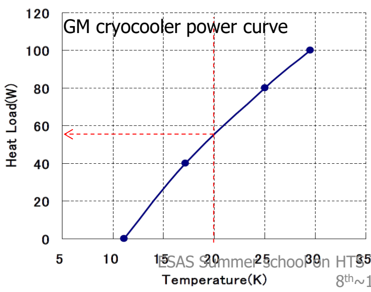


Heat load characteristics of the module

➢Five principal heat sources

$$Q_{Heat\_loss} = Q_{Excitation} + Q_{Conduction} + Q_{Radiation} + Q_{Eddy\ current} + Q_{AC\ loss}\ [W]$$

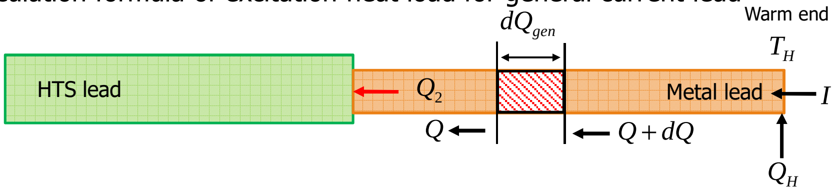




- Gifford-McMahon (1-stage) SRDK-500B
- Operating temperature of the HTS coils: 20 K
- Therefore, the total heat loss in the module should be lower than 50 W.

Heat load characteristics of the module (Excitation heat load)

➢Calculation formula of excitation heat load for general current lead



- Heat generation rate

= Fourier's heat conduction ($q = -kA\frac{dT}{dx}$) + Ohm's heat generation (I^2R)

$$Q = I^2R = I^2\cdot\left(\rho\frac{L}{A}\right)\ [W] \quad (\because R = \rho\frac{L}{A})$$

$$= -\frac{I^2\rho}{Q}\cdot\int_{T_1}^{T_2}k\cdot dT \quad (\because \frac{L}{A} = -\frac{1}{Q}\int_{T_1}^{T_2}k\cdot dT) \qquad \therefore dQ = -\frac{\rho k I^2}{Q}dT$$

- Optimal dimensions of the metal current lead

$$Q_{opt}(T) = I\sqrt{2\int_T^{T_H}\rho_2(\tau)k_2(\tau)\cdot d\tau}$$

+

$$\frac{A_2}{L_2} = \int_{T_J}^{T_H}\frac{k_2}{Q_{opt}}\cdot dT$$

$$\left(\frac{L_2}{A_2}\right)_{opt} = \frac{1}{\sqrt{2}\cdot I}\int_{T_J}^{T_H}\frac{k_2}{\sqrt{\int_T^{T_H}\rho_2(\tau)k_2(\tau)\cdot d\tau}}\cdot dT$$

Heat load characteristics of the module (Excitation heat load)

➢Calculation formula of excitation heat load for general current lead

$$Q_{opt}(T) = I\sqrt{2\int_T^{T_H}\rho(\tau)k(\tau)\cdot d\tau} \quad , \quad \left(\frac{L}{A}\right)_{opt} = \frac{1}{\sqrt{2}\cdot I}\int_{T_J}^{T_H}\frac{k}{\sqrt{\int_{T_J}^{T_H}\rho(\tau)k(\tau)\cdot d\tau}}\cdot dT$$

$\rho(T)k(T) = L_0T\ (L_0 = 2.45\times10^{-8}W\Omega K^{-2})$

Wiedemann-Franz-Lorentz Law

$$Q_{opt}(T) = I\sqrt{L_0(T_H^2 - T^2)}\ [W] \ , \quad \left(\frac{L}{A}\right)_{opt} = \frac{1}{I}\int_{T_J}^{T_H}\frac{k}{\sqrt{L_0(T_H^2 - T^2)}}\cdot dT$$

Optimal heat current — Optimal dimension of the current lead

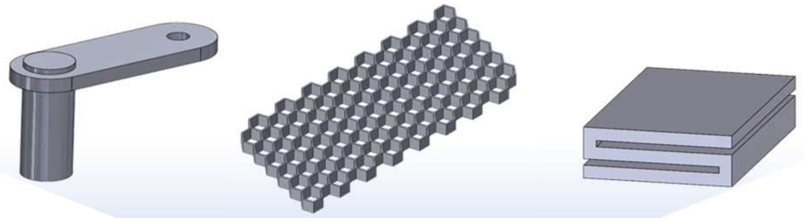
✓ Therefore, the excitation heat load of the 12 MW module is 30 W (352 A).

Heat load characteristics of the module

(Conduction and radiation heat loads)

➢Supporter shapes

1. Pole type
2. Honeycomb type
3. Zigzag type



- Simple structure
- Normal strength
- Easy connection

- High strength
- Complex structure

- Low heat transfer
- Lower strength

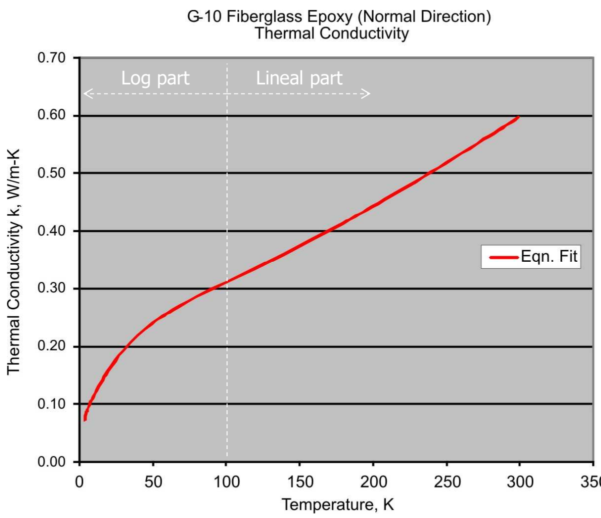
?

What is the best?

Heat load characteristics of the module

(Conduction and radiation heat loads)

➢G10 thermal conductivity



-Log part

y=a-b*ln(x+c)		
0≤K<100	a	-0.24994
	b	-0.11905
	c	12.15699

-Lineal part

y=A+B*x		
K≥100	A	0.16329
	B	0.00145

$$Q_{conduction} = \frac{A}{L}\int_{T_L}^{T_H} k(T)dT \ [W]$$

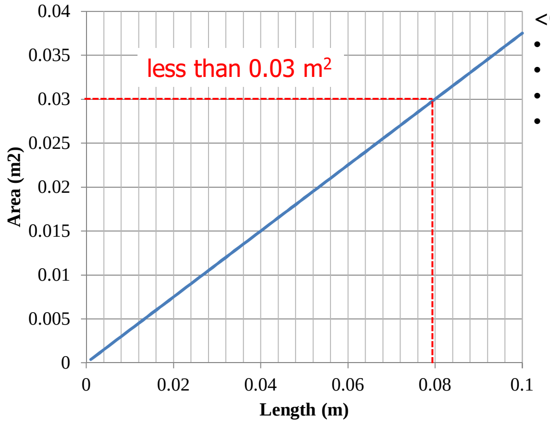
A: Conduction area
L: Conduction length
k(T): Thermal conductivity

Ref. crtogenics.nist.gov

Heat load characteristics of the module

(Conduction and radiation heat loads)

➢Conduction heat load calculation



<Constraint conditions>

- Conduction length: 0.079 m
- Conduction area: <0.03 m^2
- Material: G10
- Radiation heat load: <5 W (2.54W/m^2, module structures: 0.6 m^2)

$$Q_{conduction} = \frac{A}{L}\int_{T_L}^{T_H} k(T)dT \ [W]$$

A: Conduction area
L: Conduction length
k(T): Thermal conductivity

➢Radiation heat load calculation

$$Q_{Radiation} = \frac{\varepsilon\sigma}{N_i+1}(T_r^4 - T_c^4)\ [\mathrm{W}]$$

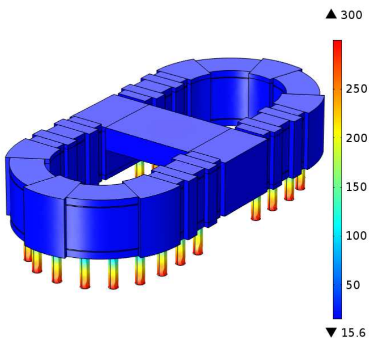
ε: Effective total thermal emissivity of the material (Al; 0.03)
σ: Stefan-Boltzmann constant (5.67×10^{-8}W/m^2/K^4)
N_i: Layer number of multilayer insulations
T_r & T_c: Enclosure temp. & Thermal shield temp.

Heat load characteristics of the module

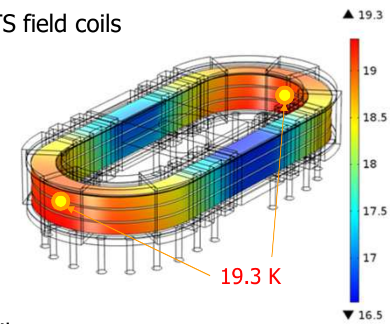
(Conduction and radiation heat loads)

➢Case1- pole type

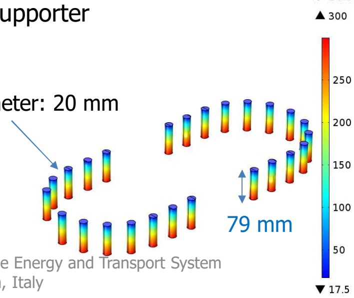
-Full model without cryostat



-HTS field coils



-Coil supporter



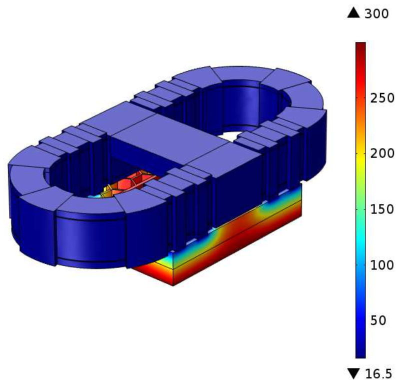
Parts	Heat loss
Max. temperature at the HTS coils	19.3 K
Conduction heat load	11.4 W
Radiation heat load	2.2 W

Heat load characteristics of the module

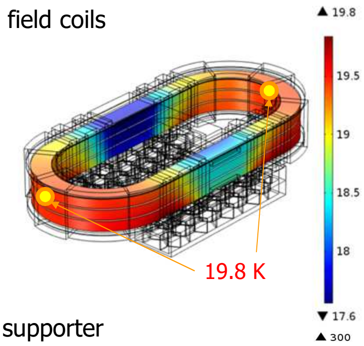
(Conduction and radiation heat loads)

➢Case 2-Honeycomb type

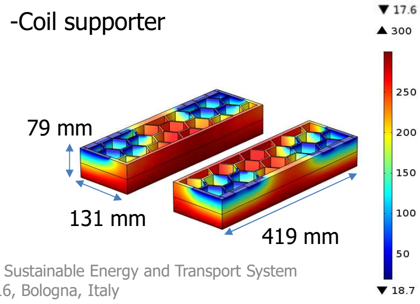
-Full model without cryostat



-HTS field coils



-Coil supporter



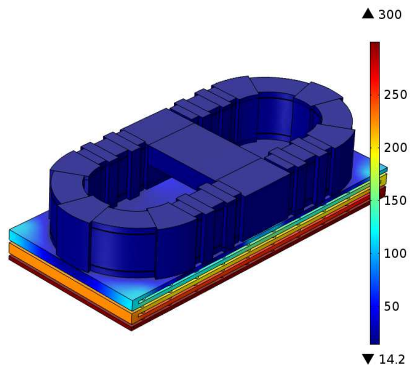
Parts	Heat loss
Max. temperature at the HTS coils	19.8 K
Conduction heat load	14.5 W
Radiation heat load	2 W

Heat load characteristics of the module

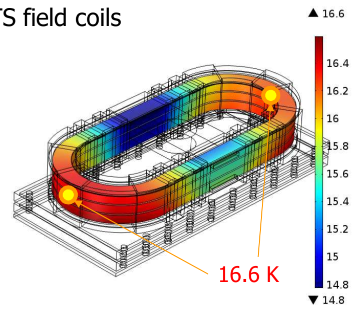
(Conduction and radiation heat loads)

➢Case 3-Zigzag type

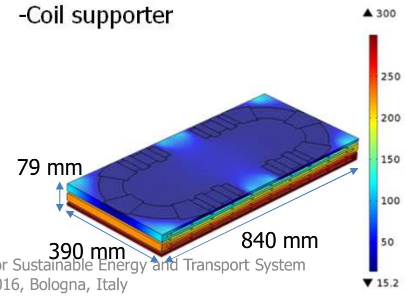
-Full model without cryostat



-HTS field coils



-Coil supporter

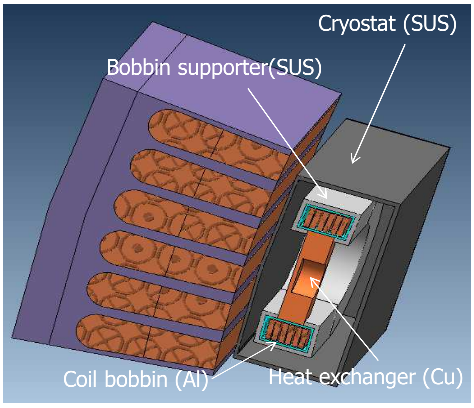


Parts	Heat loss
Max. temperature at the HTS coils	16.6 K
Conduction heat load	11 W
Radiation heat load	2.5 W

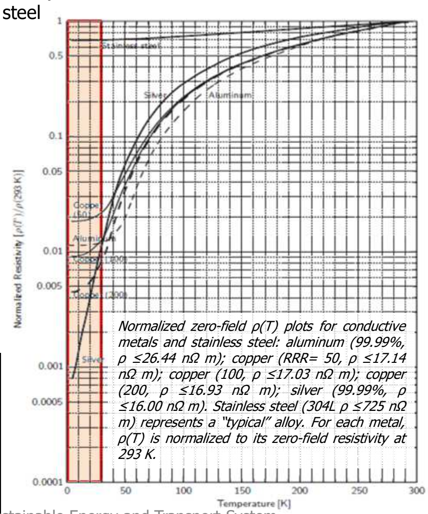
Heat load characteristics of the module

(Eddy current heat load)

➢Simulation model of the module



-Normalized electrical resistivity vs. Temperature: Conductive metals and stainless steel

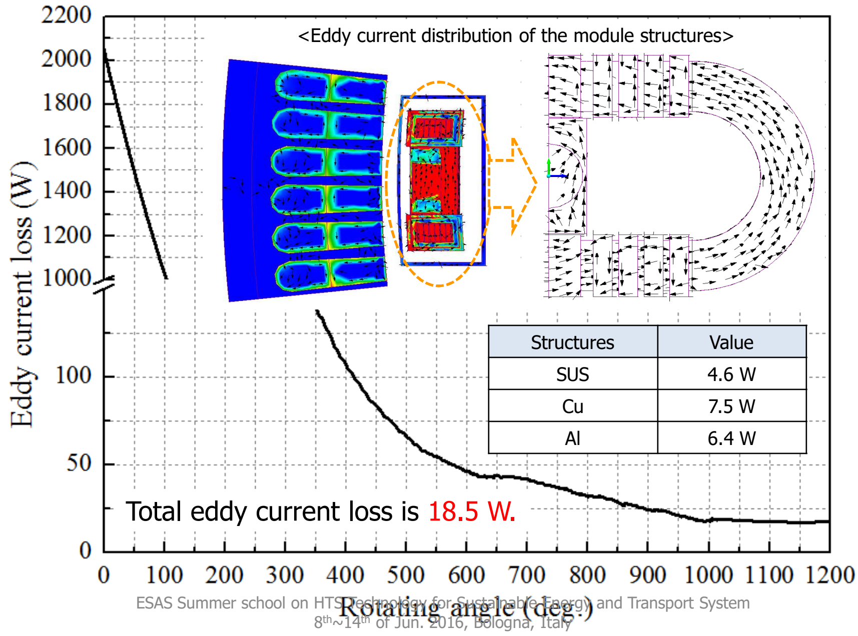


Component	Material	Electrical resistivity
Cryostat	Stainless steel	725 nΩm (at 293 K)
Bobbin supporter	Stainless steel	508 nΩm (at 20K~30 K)
Coil bobbin	Aluminum	0.34 nΩm (at 20K~30 K)
Heat exchanger	Copper	0.16 nΩm (at 15K~20 K)

Ref. Yukikazu Iwasa, "Case Studies in Superconducting Magnets-second edition," page 640

Heat load characteristics of the module

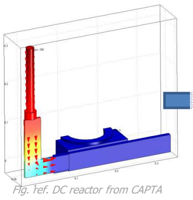
(Eddy current heat load)

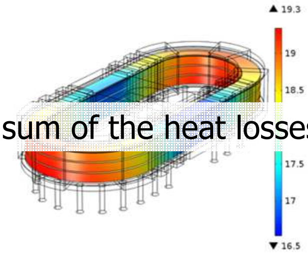


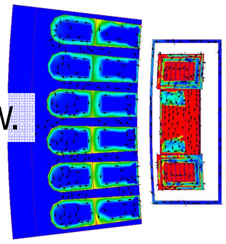
Structures	Value
SUS	4.6 W
Cu	7.5 W
Al	6.4 W

Heat load characteristics of the module

(Total current heat load)

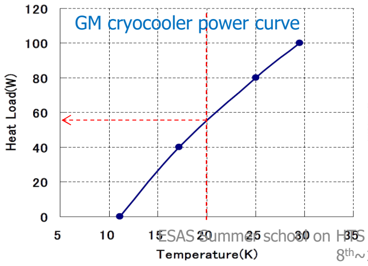


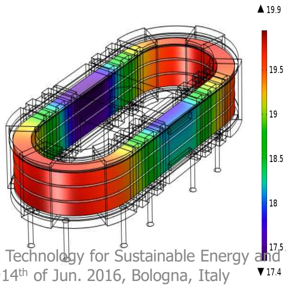




The sum of the heat losses is 63 W.

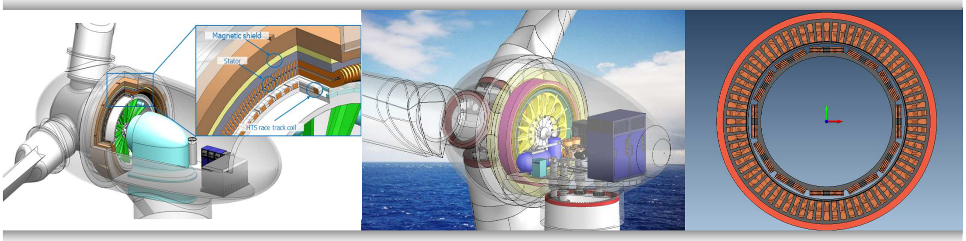
Excitation heat loss	Conduction & Radiation heat losses	Eddy current heat loss
30 W	<14 W	18.5 W





- **The cooling capacity of the GM cryocooler is 53 W at 20 K.**
- However, the total heat loss of the designed module is 63 W.
- To achieve the tem. less than 20 K, we should be reduce the conduction area of the supporter and excitation heat loss.

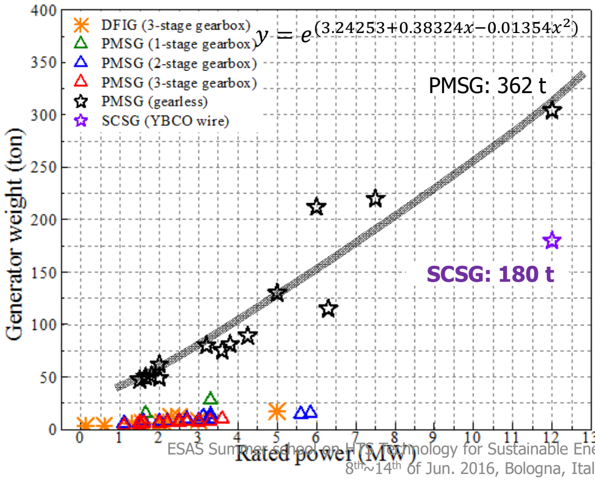
Superconducting generator cost



Weight of the superconducting generator

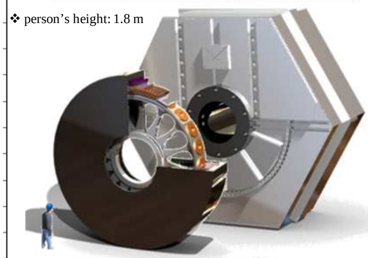
➢Comparison with conventional generators

Generator	Total weight
12 MW PMSG (incl. structure)	362 ton
12 MW SCSG (incl. structure)	180 ton



Generator	Diameter	Axial length
10 MW PMSG	9 m	2.6 m
12 MW SCSG	5.2 m	1.7 m

❖ person's height: 1.8 m

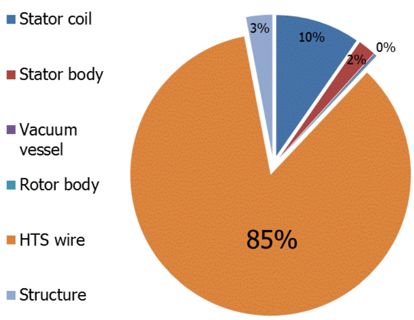


Cost of the generator (Current price of HTS wire; 230 $/kA-m)

Material	Cost
Copper	20.5 $/kg
Stainless steel	1.5 $/kg
Silicon steel plate	4.1 $/kg
HTS wire	23 $/m (100 A @ 77 K)

Active parts	Weight	Material
Stator coil	48 ton	Copper
Stator body	50 ton	Silicon steel plate
Vacuum vessel	12 ton	Stainless steel
Rotor body	11 ton	Stainless steel
Total length of HTS wire		
HTS wire	375 km	

Parts	Cost
Stator coil	985 k$
Stator body	206 k$
Vacuum vessel	18 k$
Rotor body	16 k$
HTS wire	18,616 k$
Structure	306 k$

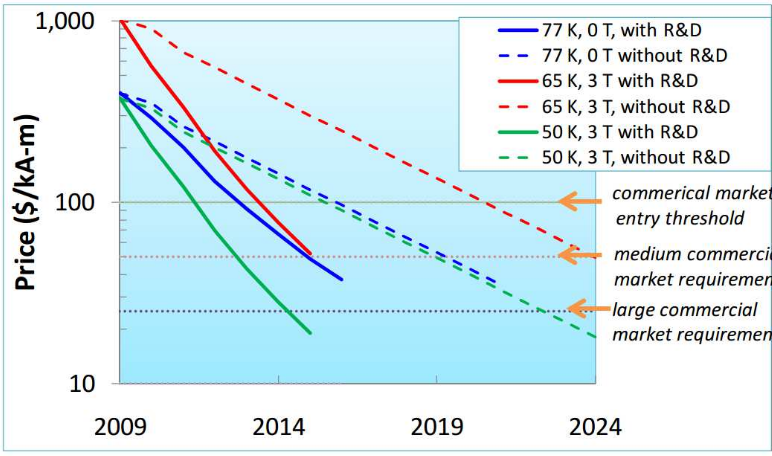


Total cost of the 12 MW SCSG
=10,146,509 $
=11,161,160,184 KRW (1$=1,100 KRW)

Ref. Design of direct-driven permanent-magnet generator for wind turbines, Anders Grauers
Ref. SuperPower (4mm HTS wire)

HTS wire price-performance for commercialization

Ref. SuperPower



✓ Today's HTS wire price: $225/kA-m
(100 A performance at 77 K, zero applied magnetic field)

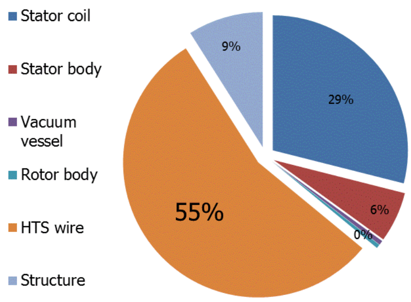
✓ **Improving wire price-performance is key factor for commercialization**

Cost of the generator (Future price of HTS wire; 50 $/kA-m)

Material	Cost
Copper	20.5 $/kg
Stainless steel	1.5 $/kg
Silicon steel plate	4.1 $/kg
HTS wire	5 $/m (100 A @ 77 K)

Active parts	Weight	Material
Stator coil	48 ton	Copper
Stator body	50 ton	Silicon steel plate
Vacuum vessel	12 ton	Stainless steel
Rotor body	11 ton	Stainless steel
Total length of HTS wire		
HTS wire	375 km	

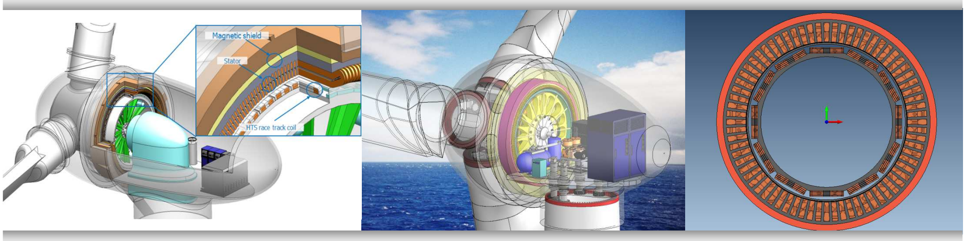
Parts	Cost
Stator coil	985 k$
Stator body	206 k$
Vacuum vessel	18 k$
Rotor body	16 k$
HTS wire	1,873 k$
Structure	306 k$



Total cost of the 12 MW SCSG
=3,403,709 $
=3,744,080,184 KRW (1$=1,100 KRW)

Ref. Design of direct-driven permanent-magnet generator for wind turbines, Anders Grauers
Ref. SuperPower (4mm HTS wire)

Characteristic evaluation for superconducting coil

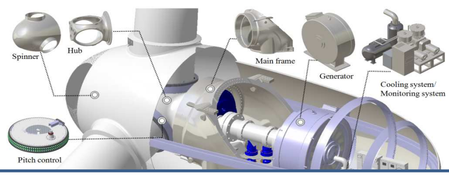


Characteristic evaluation device for HTS field coil

➢ Torque characteristics of the superconducting rotating machine

- 36.5 MW superconducting motor (AMSC)

- 12.5 MW HTS wind power generator (CNU)



In case of MW class superconducting generator, tons of load affect the superconducting coils by high torque of the high-capacity and low rotating speed generator. Characteristics evaluation device for superconducting coils are needed to check the effect of the high torque of the generator.

Rated power	36.5 MW
Rated terminal voltage	6 kV
Rated armature current	1.27 kA
Rated rotating speed	120 RPM
The num. of rotor poles	16
Rated torque	**2.9 MNm**

- Tangential force per 1 pole

→ 0.08 MN (about 8 ton)

Rated power	12.5 MW
Rated L-L voltage	6.6 kV
Rated armature current	1.07 kA
Rated rotating speed	8 RPM
The num. of rotor poles	30
Rated torque	**15.04 MN·m**

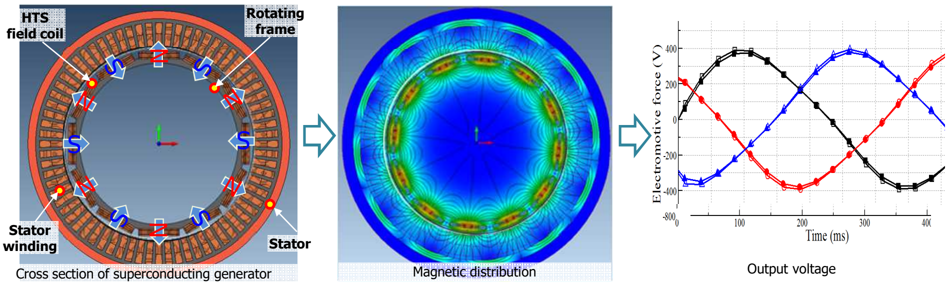
- Tangential force per 1 pole

→ 0.18 MN·m (about 18 ton)

Characteristic evaluation device for HTS field coil

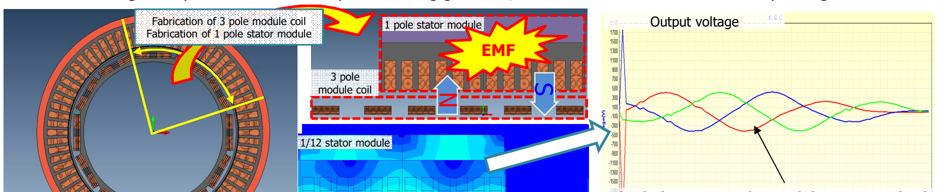
➢ Operation principle of the superconducting generator

✓ Output voltage is generated by time-varying magnetic field of the superconducting field coils (Fleming's right hand rule)



➢ Operation principle of the evaluation device for superconducting coils

✓ After fabricating the 1 pole module of the superconducting generator, the module is tested on the same operating conditions

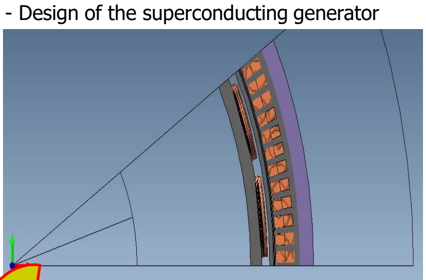


-Check the output voltage of the superconducting generator (1 pole coil)
-Check the damage and availability of the superconducting module coil by the high torque

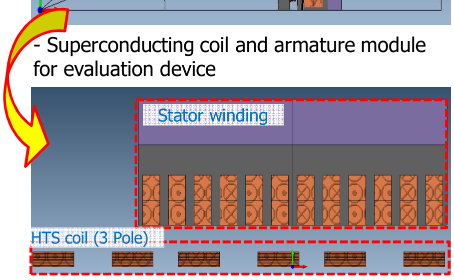
Characteristic evaluation device for HTS field coil

➢ Design of the superconducting coil and armature module for evaluation device

- Design of the superconducting generator



- Superconducting coil and armature module for evaluation device



➢Specifications of the superconducting generator

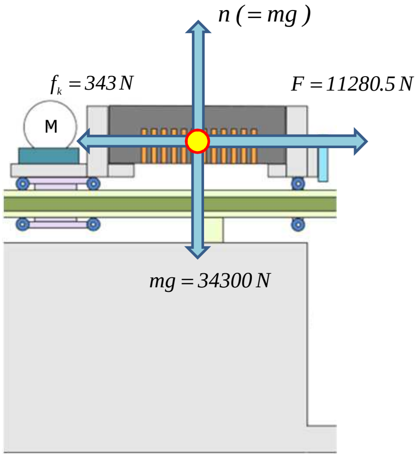
Item	Value
Rated armature current	875 A
Rated speed	2.5 m/s
Turn number of the stator	25
Number of slot	12
Thickness of magnetic shield	150 mm

➢Specifications of module coil for evaluation device

Item	Value
Number of DPC	5
Turn number of coil	1300
Operating current	100 A
Operating temperature	20 K

Characteristic evaluation device for HTS field coil

➢ Accelerated distance and external force for moving the stator part



• Energy of the stator part

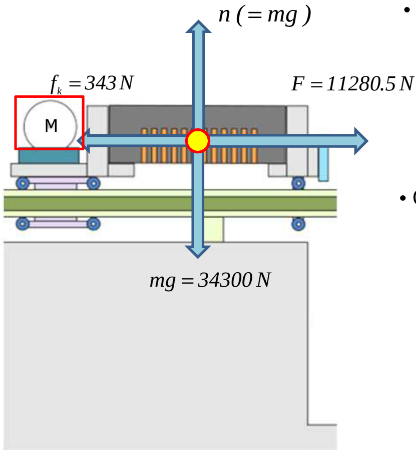
$$f_k = \mu_k mg$$
$$f_k = 0.001(3500\,kg)(9.8\,m/s^2) = 343\,N$$

$$W_{other} = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 + f_x d$$
$$\frac{1}{2}mv_f^2 = \frac{1}{2}mv_i^2 - f_x d + W_{other}$$
$$\frac{1}{2}(3500\,kg)(2.5\,m/s)^2 = 0 - (343\,N)(1\,m) + W$$
$$W = \frac{(3500\,kg)(2.5\,m/s)^2}{2} + (343\,J) = 11280.5\,J$$
$$F = (11280.5\,J)/(1\,m) = 11280.5\,N$$

f_k : frictional force [N]
t : time [s]
m : mass of stator part [kg]
d : moving distance [m]
g : gravity (9.8 m/s²)
W : energy of stator part [J]
μ_k : friction coefficient of roller bearing

Characteristic evaluation device for HTS field coil

➢ Accelerated distance and external force for moving the stator part



• Output power (1 pole)

$$W_{1pole} = \frac{(12\,MW)}{(30pole)} = 0.4\,MW = 400\,kW$$

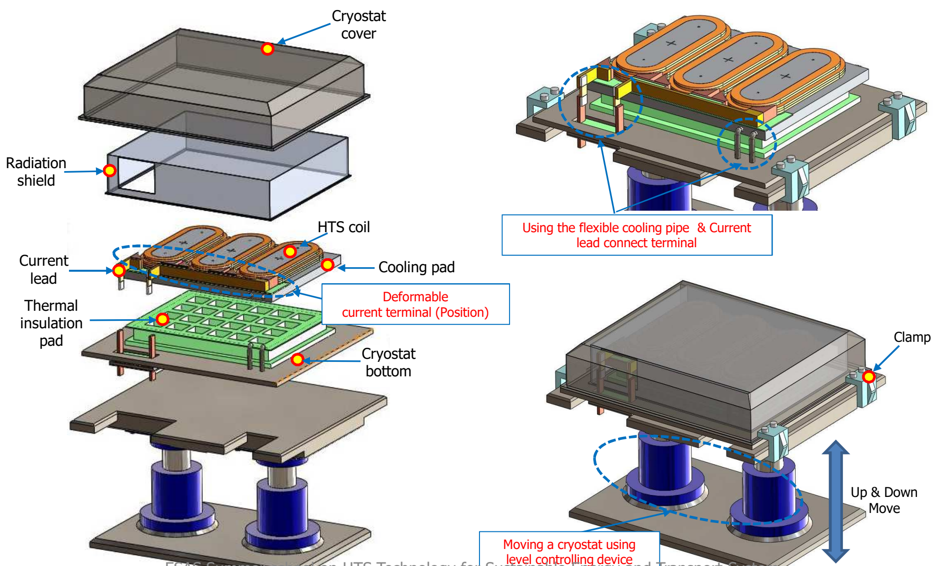
• Output power of the motor to maintain the 2.5 m/s velocity

$$P = Fv_f$$
$$P = (11280.5\,N)(2.5\,m/s) = 28.2\,kW$$

$$Motor_{ontput} = (400\,kW) - (28.2\,kW)$$
$$= 371.8\,kW$$

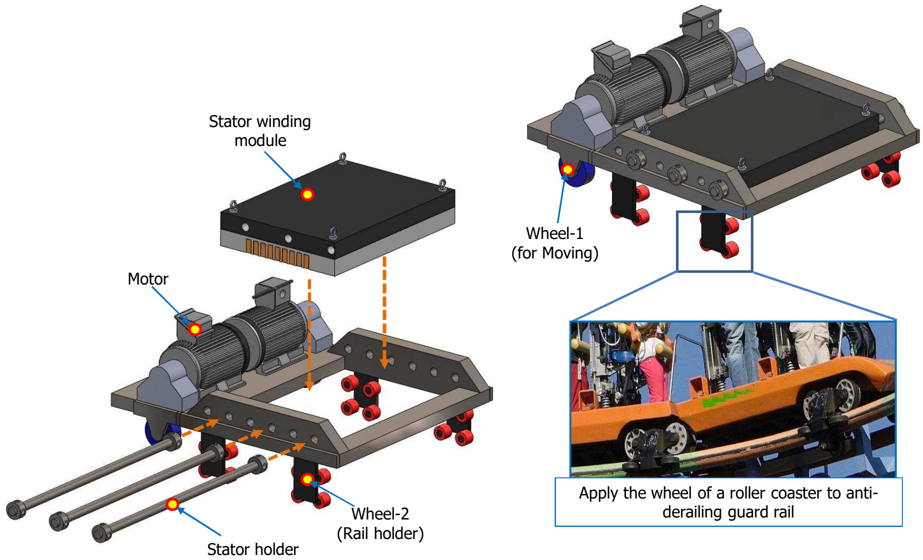
Characteristic evaluation device for HTS field coil

➢ HTS field coil part



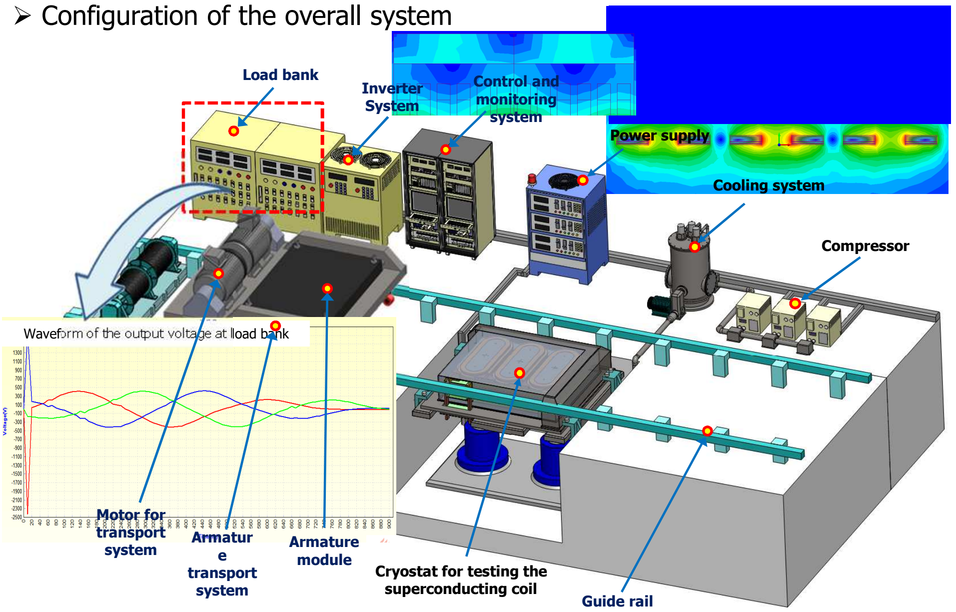
Characteristic evaluation device for HTS field coil

➢ Stator part (with removal equipment)

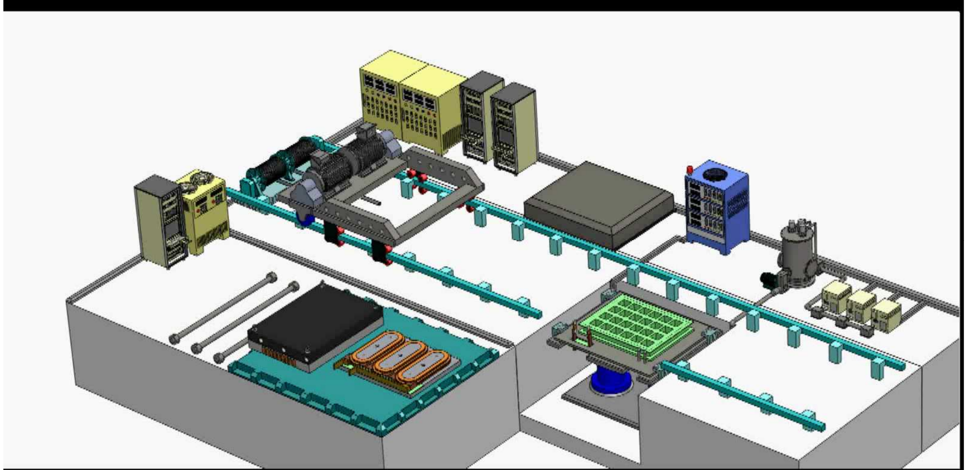


Characteristic evaluation device for HTS field coil

➢ Configuration of the overall system

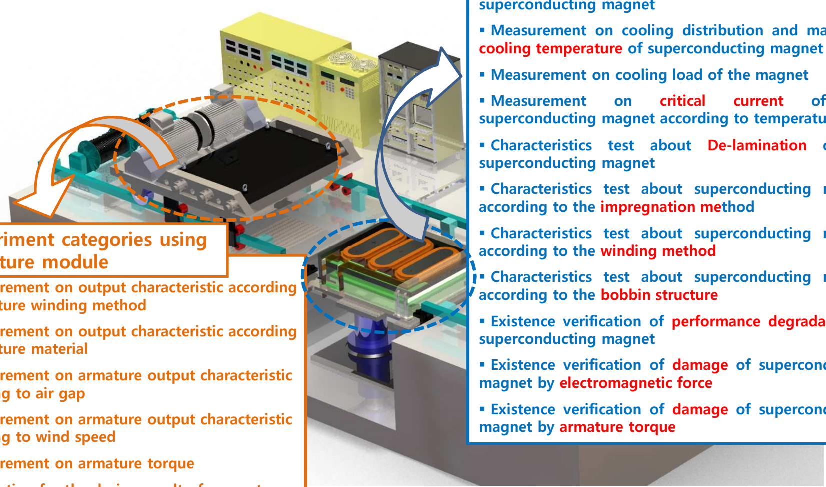


Characteristic evaluation device for HTS field coil



Characteristic evaluation device for HTS field coil

➢ Evaluation items using characteristic evaluation device



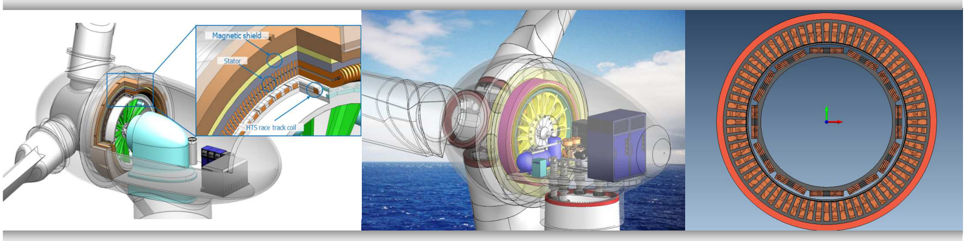
Experiment categories using superconducting magnet module

- Measurement on magnetic flux density of superconducting magnet
- Measurement on cooling distribution and maximum cooling temperature of superconducting magnet
- Measurement on cooling load of the magnet
- Measurement on critical current of the superconducting magnet according to temperature
- Characteristics test about De-lamination of the superconducting magnet
- Characteristics test about superconducting magnet according to the impregnation method
- Characteristics test about superconducting magnet according to the winding method
- Characteristics test about superconducting magnet according to the bobbin structure
- Existence verification of performance degradation of superconducting magnet
- Existence verification of damage of superconducting magnet by electromagnetic force
- Existence verification of damage of superconducting magnet by armature torque

Experiment categories using armature module

- Measurement on output characteristic according to armature winding method
- Measurement on output characteristic according to armature material
- Measurement on armature output characteristic according to air gap
- Measurement on armature output characteristic according to wind speed
- Measurement on armature torque
- Verification for the design result of generator using output waveform

Researches trend of superconducting generators for large-scale wind turbine



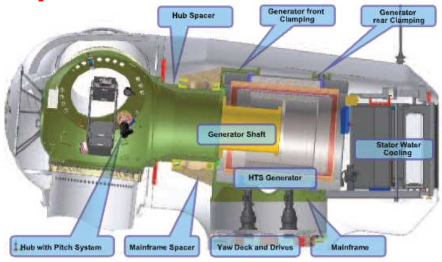
Researches trend of the superconducting wind turbine (World)

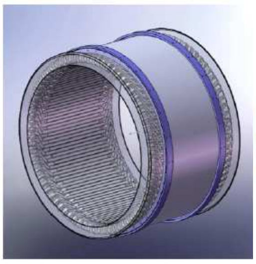
Ref. AMSC

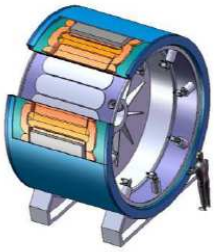
➢Sea Titan™– American Superconductor **(AMSC)**

▪ Generator properties

Rated power	10 MW
Poles	24
Diameter	5 m
Length	-
Rotation speed	10 rpm
Current density	-
Temperature	30-40 K
Maximum field	-
Field on stator	-
Output voltage	3.3 kV
Output current	0.6 kA
Voltage frequency	2 Hz







Technical characteristics

✓HTS superconducting field winding
✓Copper armature winding
✓Generator diameter; 4.5-5 m
✓Weight; 150-180 tons
✓Efficiency at rated load; 96%

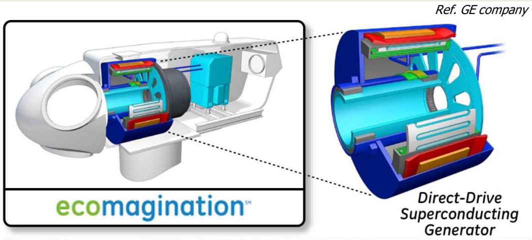
Researches trend of the superconducting wind turbine (World)

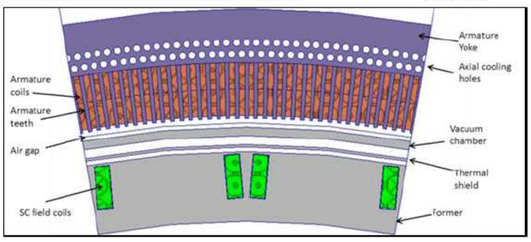
Ref. GE company

➢General Electric **(GE)**

▪ Generator properties

Rated power	10 MW
Poles	36
Diameter	4.9 m
Length	2.7 m
Rotation speed	10 rpm
Operating current	277 A
Temperature	6.08 K
Maximum field	7.35 T
Field on stator	2.2 T
Output voltage	3.3 kV
Output current	1.75 kA
Total length of SC wire	720 km
Total weight	93 ton
Volume	51 m^3





✓Complete a Hydrogenie superconducting generator (full rated load is 1.7 MW spinning at 214 rpm and operating at 43 K.)

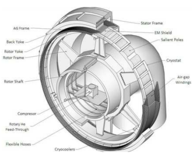
✓Start a project with funding from the US DOE to investigate a 10 MW- 15 MW direct-drive wind turbine with LTS technology

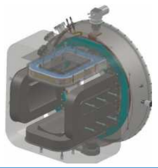
Researches trend of the superconducting wind turbine (World)

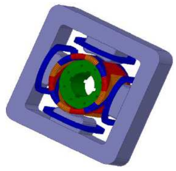
Ref. Superconducting light generator for large offshore wind turbines

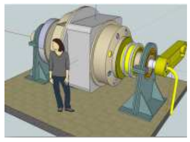
➢**SUPRAPOWER** project; **SUP**erconducting, **R**eliable, lightweight, **A**nd more **POWER**ful offshore wind turbine

2009-2012 | 2013 | 2014 | 2015 | 2016









2009-2012	2013	2014	2015	2016
• Generator concept development and patent by TECNALIA	• MgB2 wire manufacturing • Cooling system design	• First MgB_2 full scale coil construction and testing • 500 kW scale machine detailed design	• 10 MW generator design and integration • Cryostat first module testing • Scale machine construction	• Scale machine testing • Industrialization studies • Business plan

Technical characteristics

- ✓10 MW; 8.1 rpm & 11.8 MNm
- ✓Field coils constituted by a stack of MgB_2 double pancakes
- ✓Air-gap armature winding
- ✓11.9 m air-gap diameter
- ✓0.52 m stack length
- ✓Overall weight including structural mass ~ 200 t
- ✓Efficiency at full load over 95%

The present work describes the SUPRAPOWER project, and EU FP7 founded research project (€20m), that started in December 2012 and that it is expected to finish at the end of 2016.

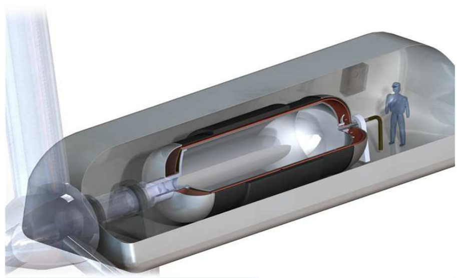
Researches trend of the superconducting wind turbine (World)

Ref. AML

➢Advanced Magnet Lab **(AML)**

Technical characteristics

- ✓10 MW fully superconducting wind generator
- ✓Rotating speed is 10 rpm and operating temperature is 20 K. (Helium gas is used as the coolant)
- ✓Superconducting field winding
- ✓Superconducting armature winding
- ✓Improvement in MgB_2 wire is needed.
- ✓Total length; 5 m & Total diameter; 2 m
- ✓At 10 MW of power, the generator's weight is less than 150 tons compared to 300 tons of PMSC.
- ✓A double-helix superconducting windings technology is used to minimize the AC loss on the armature coils.



Researches trend of the superconducting wind turbine (World)

➢EcoSwing project (3.6MW real operation)

European Commission

HORIZON 2020

EcoSwing

Project reference: 656024
Funded under: H2020-EU.3., H2020-EU.3.3., H2020-EU.3.3.2., H2020-EU.3.3.2.1., H2020-EU.3.3.2.2., H2020-EU.3.3.2.4.

EcoSwing - Energy Cost Optimization using Superconducting Wind Generators - World's First Demonstration of a 3.6 MW Low-Cost Lightweight DD Superconducting Generator on a Wind Turbine

From 2015-03-01 **to** 2019-03-01, ongoing project

Project details

Total cost:
EUR 13 846 593,75

EU contribution:
EUR 10 591 733,64

Coordinated in:
Denmark

Topic(s):
- LCE-03-2014 - Demonstration of renewable electricity and heating/cooling technologies

Call for proposal:
H2020-LCE-2014-2

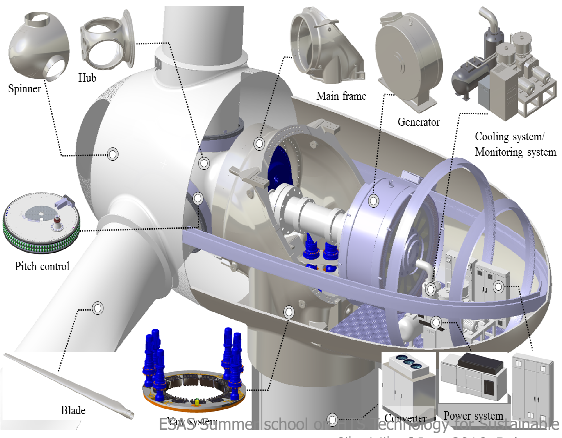
Funding scheme:
IA - Innovation action

Horizon 2020 European Union Funding for Research & Innovation

Researches trend of the superconducting wind turbine (Korea)

➢ Development of the 12 MW Superconducting Synchronous Generator
- 1st year; Optimal design of 12 MW class wind power generation system
- 2nd year; Design of cooling system / Fabrication and test of 10 kW SCSG
- 3rd year; **Detail design of 12 MW class SCSG including the cooling system**

✓ 12 MW class wind power generation system



Item	Value
Rated power (MW)	12.5
Operating temperature (K)	20
The number of rotor poles	24
Effective length (mm)	1,700
Rotation speed (rpm)	10
Turns of SC coil	850
The number of DPC layers	4
Field current of SC coil (A)	133
The number of slot	144
Turns of copper coil	18
Diameter (m)	5.2
Rated output frequency (Hz)	2
Perpendicular magnetic field (T)	5.1
Maximum magnetic filed (T)	7.8

Large-scale wind power generation system

➤Configuration of the 12 MW WPGS considering the superconducting generator