Superconducting Rotating Machines

1 History

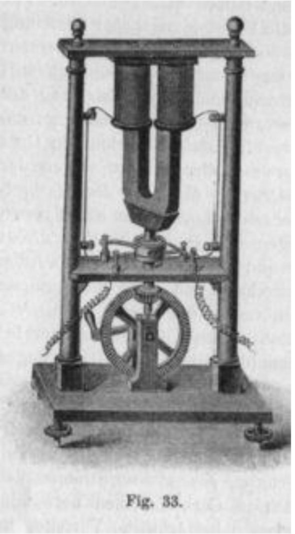
2 Structure and operating behavior of the synchronous machine
2.1 Structure
2.2 Stationary state (Phasor diagram, Torque, Performance chart)
2.3 Open loop-, Short-circuit characteristics
2.4 Summary

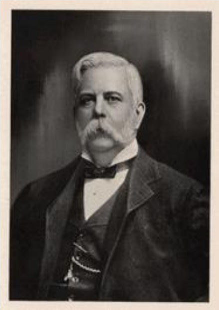
3 Functionality of other superconducting machines
3.1 Linear motor
3.2 Reluctance motor
3.3 Homopolar motor

4 State of the Art
4.1 Overview
4.2 Application examples
4.3 Future applications

Historie

- 1831 Michael Faraday – Electromagnetic induction
- 1832 Hippolyte Pixii – First AC electrical generator →
- 1849 Fa. Alliance - First industrial use of an AC generator
- 1851 Søren Hjorth- Dynamo-electric principle
- 1861 Anyos Jedlik – Dynamo machine
- 1866 Werner von Siemens – Dynamo machine
- 1888 Nikola Tesla – Induction motor
- 1895 George Westinghouse - First large-scale power plant on the grid in Niagara

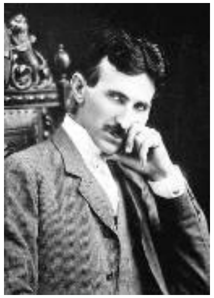




George Westinghouse
1846-1914

Anyos Jedlik
1800-1895

Werner von Siemens
1816-1892



Nikola Tesla
1856-1943

Michael Faraday
1791-1867

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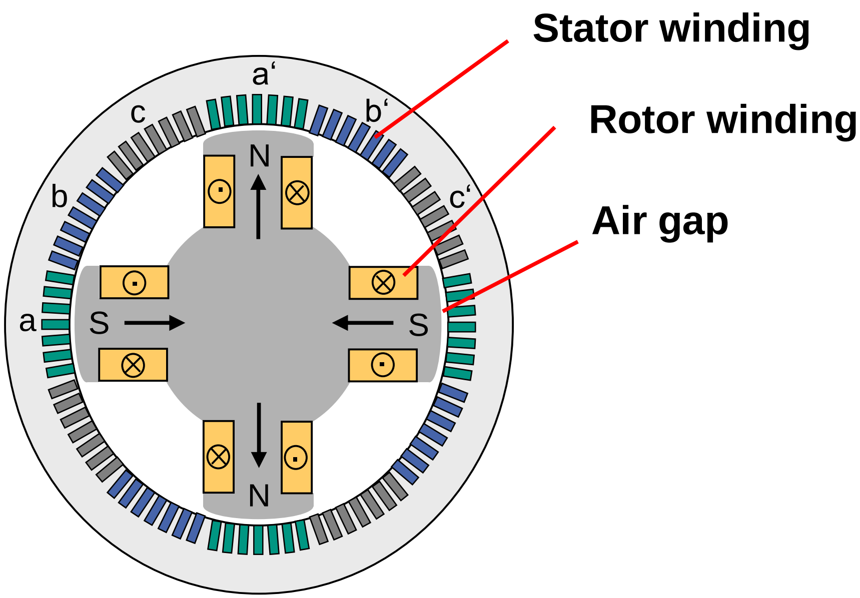
Synchronous machine

Conventional synchronous machine (4 poles, p=2)



- small air gap
- iron rotor
- stator winding in slots

Characteristics

Torque per length

$\sim n\, I_{stat}\, B_r\, r$

$\sim A_1\, r\, B_r\, r$

Power

$\sim A_1\, B_r\, r^2\, L\, n$

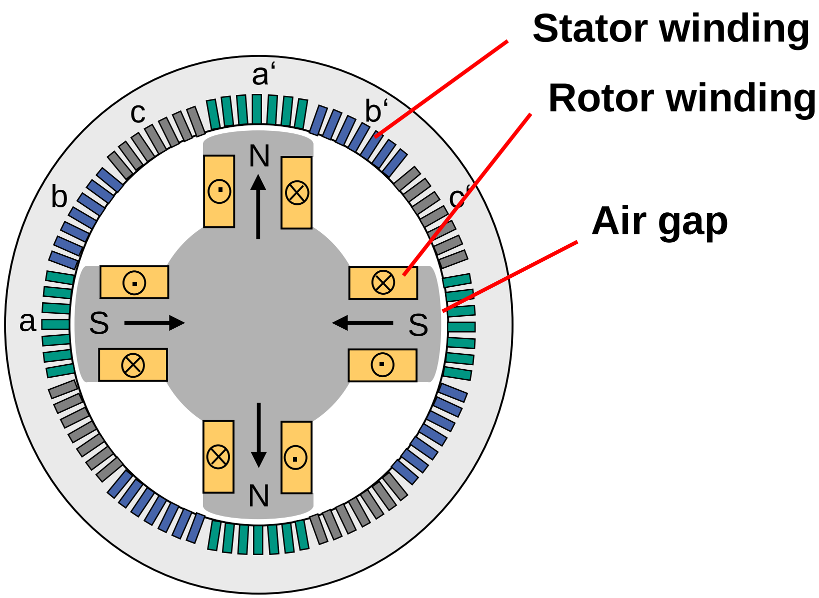
Power per volume

$\sim A_1\, B_r\, n$

What does the superconductor change?

Synchronous machine

Conventional synchronous machine
(4 poles, p=2)



- small air gap
- iron rotor
- stator winding in slots

Conventional

$B = 1\,T$

$A_1 = 1$ p.u.

$P = 1$ p.u.

<u>Losses</u>

$P_{Cu,stat} = 1$ p.u.

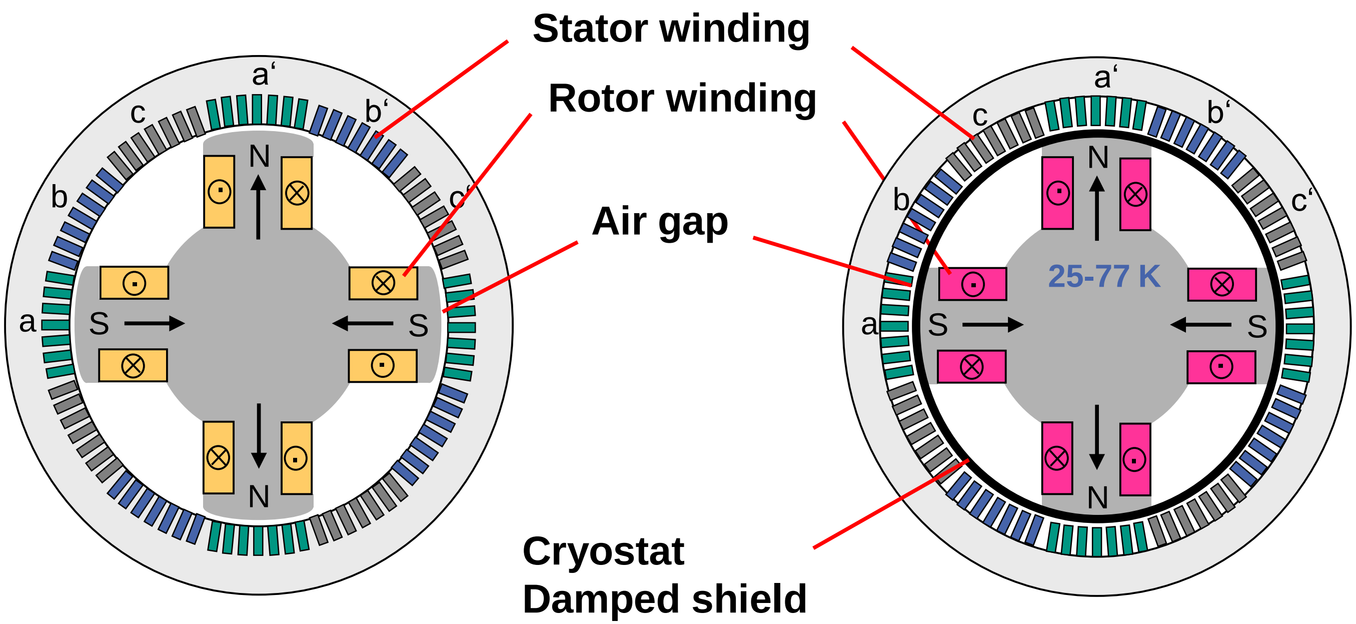
$P_{Cu,rot} = 1$ p.u.

$P_{Fe} = 1$ p.u.

Synchronous machine

Conventional synchronous machine (4 poles, p=2)

Superconducting synchronous machine (4 poles, p=2)

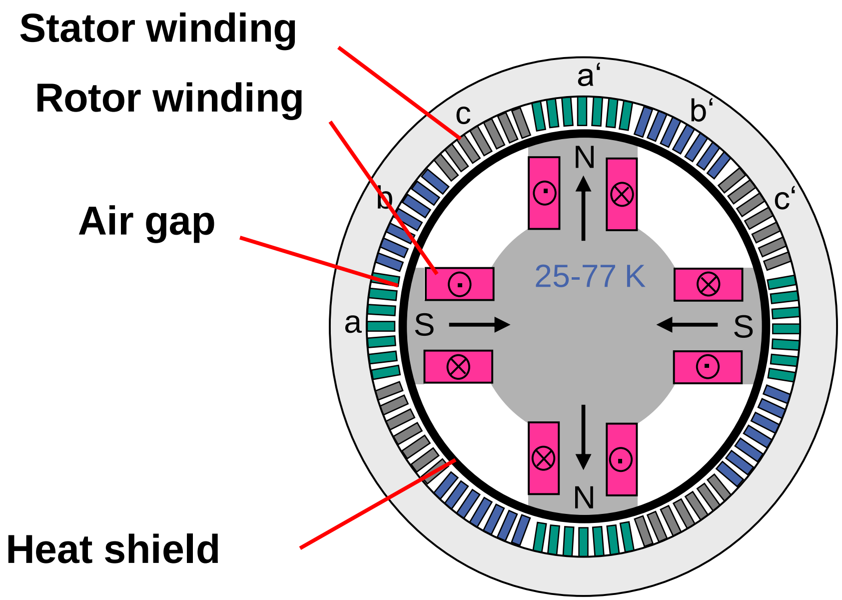


- small air gap
- iron rotor
- stator winding in slots

- stator winding conventional
- rotor winding superconducting
- rotor non-ferromagnetic
- slotless stator winding
- large air gap
- cryostat /damped heat shield

Synchronous machine

Superconducting synchronous machine (4 poles, p=2)

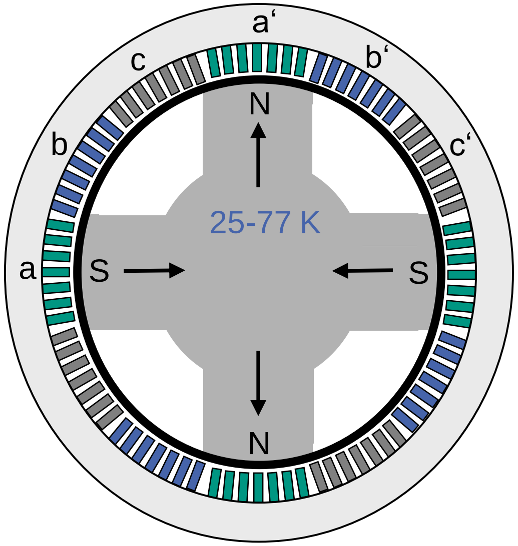


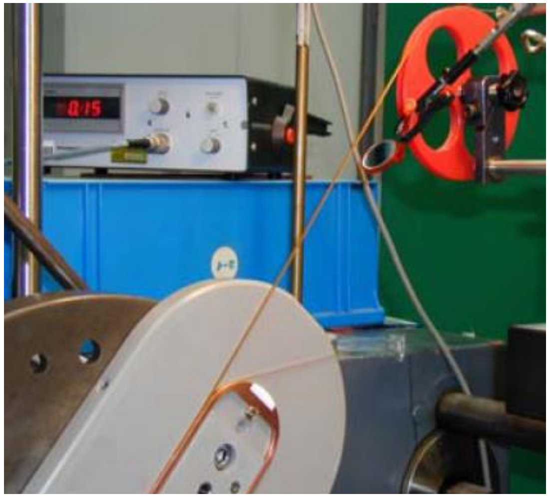
- stator winding conventional
- rotor winding superconducting
- rotor non-ferromagnetic
- slotless stator winding
- large air gap
- cryostat /damped heat shield

Superconductor	Conventional
$B = 2\ T$	$B = 1\ T$
$A_1 = 2$ p.u.	$A_1 = 1$ p.u.
$P = 4$ p.u.	$P = 1$ p.u.
Losses	Losses
$P_{Cu,stat} = 2$ p.u.	$P_{Cu,stat} = 1$ p.u.
$P_{Cu,rot} = 0$ p.u. + $P_{Cooling}$	$P_{Cu,rot} = 1$ p.u.
$P_{Fe} = 0{,}6$ p.u.	$P_{Fe} = 1$ p.u.

Synchronous machine

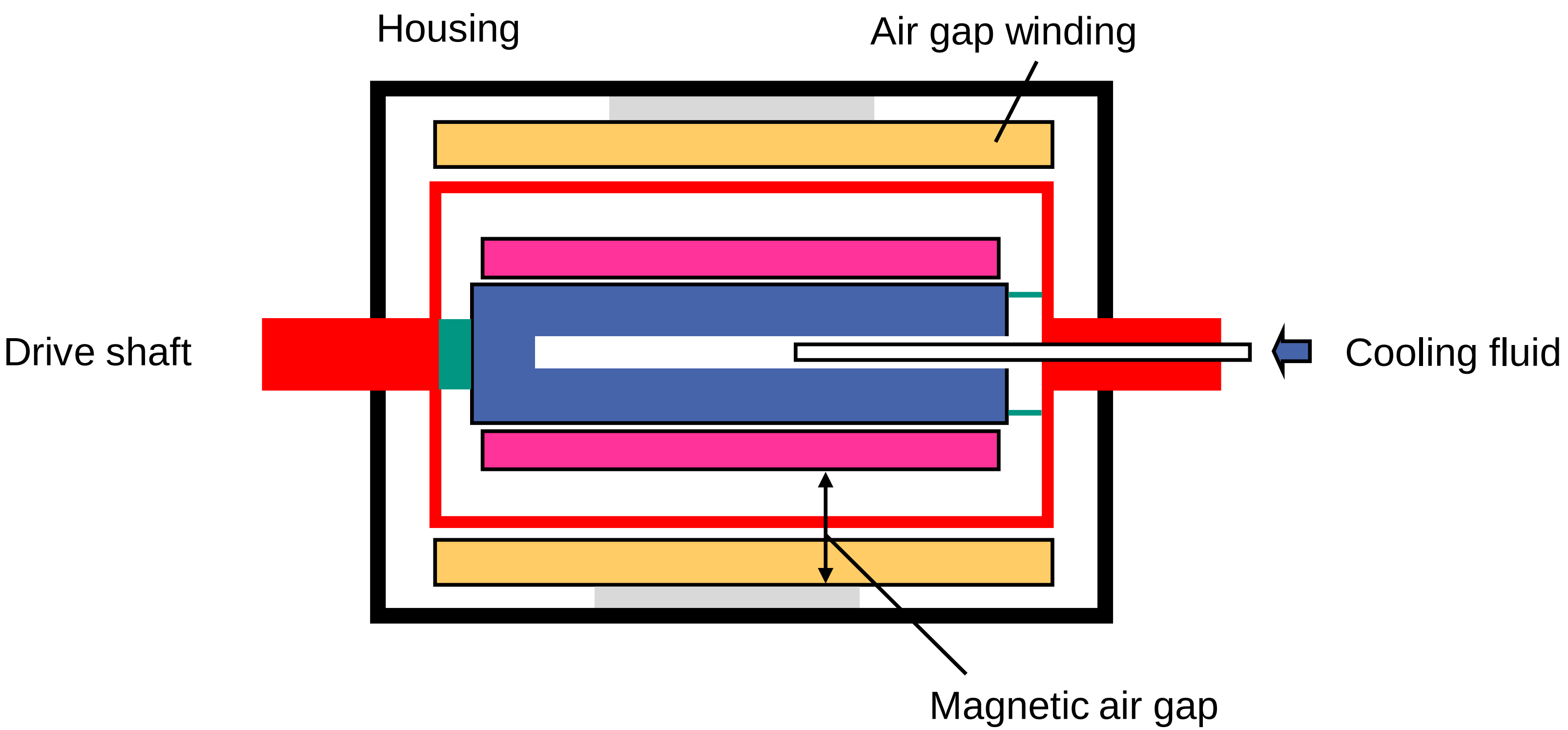
Practical execution of the HTS rotor winding (4 poles, p=2)





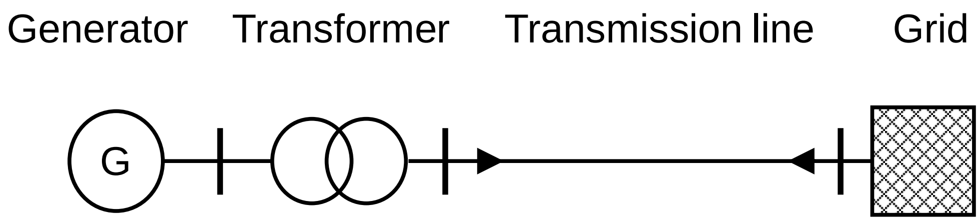
Photos: Siemens

Aufbau Supraleitende Synchronmaschine

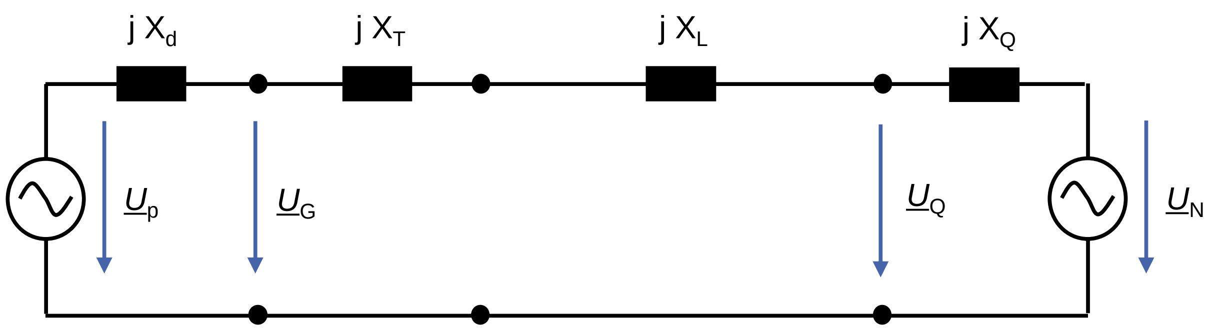


Superconducting Rotating Machines

Stationary state - single machine model

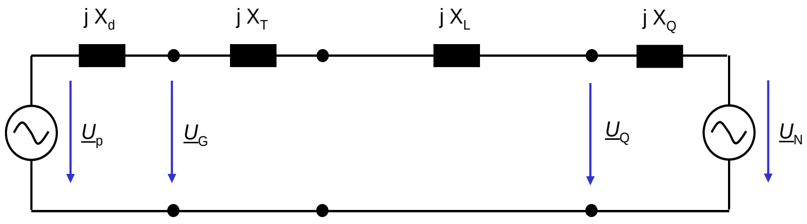


One phase equivalent circuit in stationary state (active resistance = 0)



$$X_N = X_T + X_L + X_Q$$

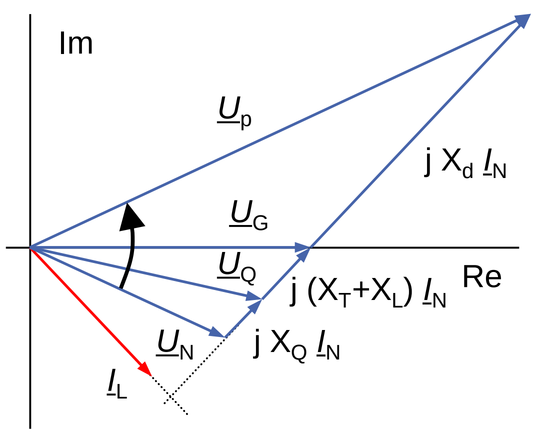
Equivalent circuit and phasor diagram of a synchronous machine in stationary state



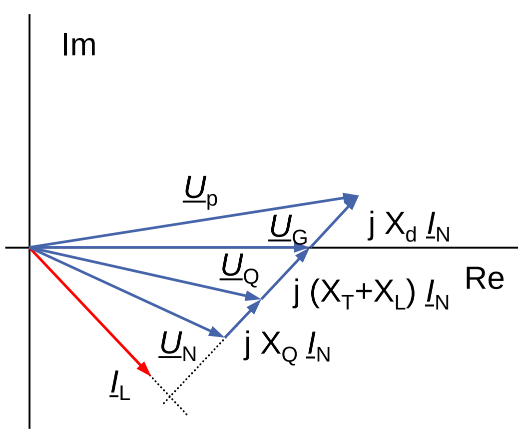
$X_N = X_T + X_L + X_Q$

Ohmic/Inductive Load

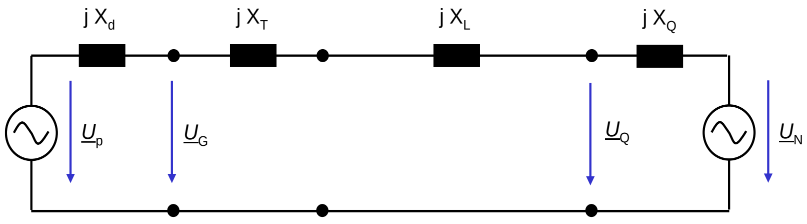
Conventional SM



Superconducting SM



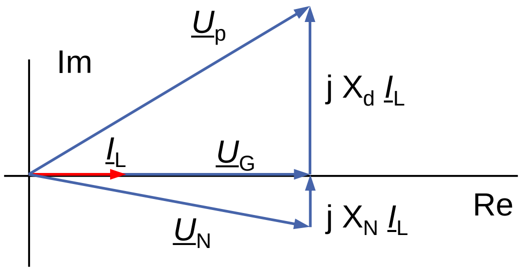
Equivalent circuit and phasor diagram of a synchronous machine in stationary state



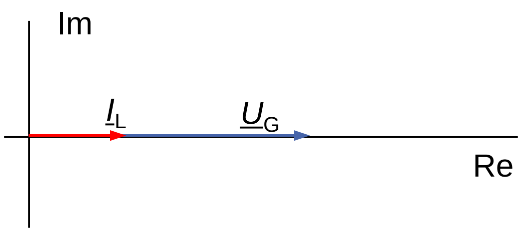
$X_N = X_T + X_L + X_Q$

Active load only

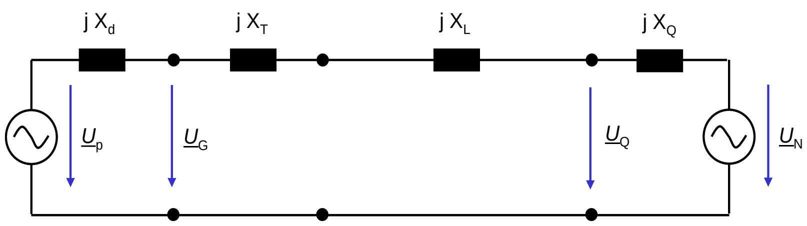
Conventional SM



Superconducting SM



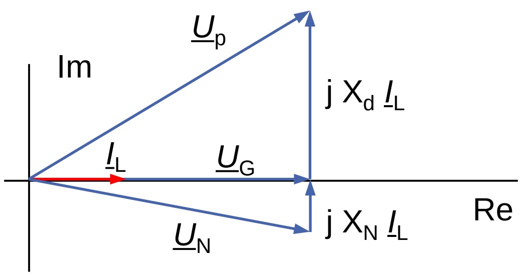
Equivalent circuit and phasor diagram of a synchronous machine in stationary state



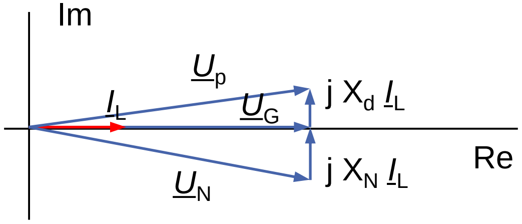
$X_N=X_T+X_L+X_Q$

Active load only

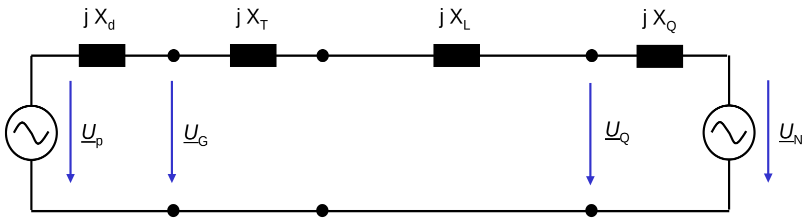
Conventional SM



Superconducting SM



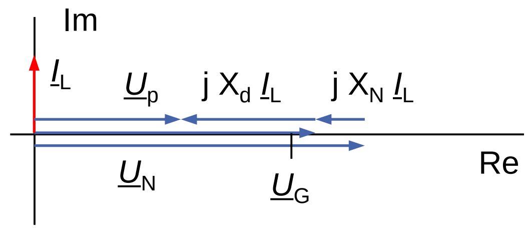
Equivalent circuit and phasor diagram of a synchronous machine in stationary state



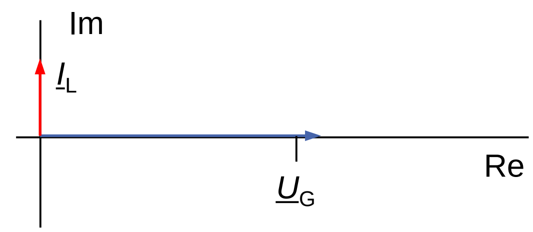
$X_N = X_T + X_L + X_Q$

Capacitive reactive load

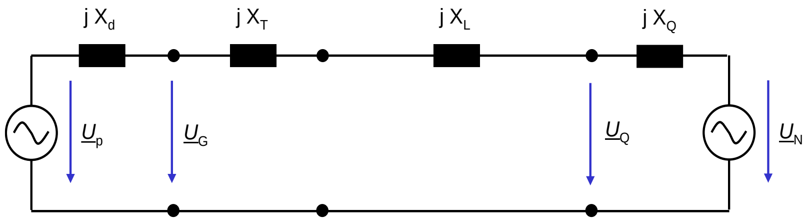
Conventional SM



Superconducting SM



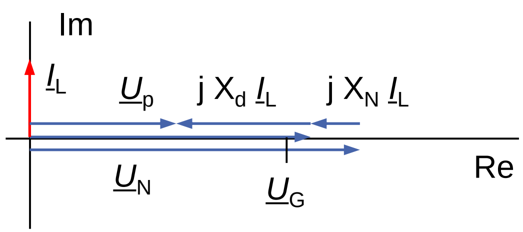
Equivalent circuit and phasor diagram of a synchronous machine in stationary state



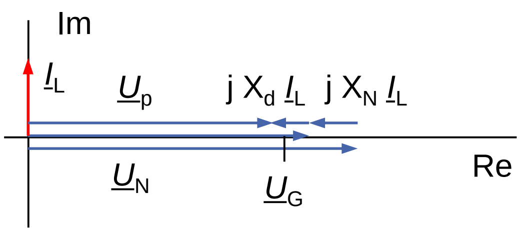
$X_N = X_T + X_L + X_Q$

Capacitive reactive load

Conventional SM



Superconducting SM



Torque calculation

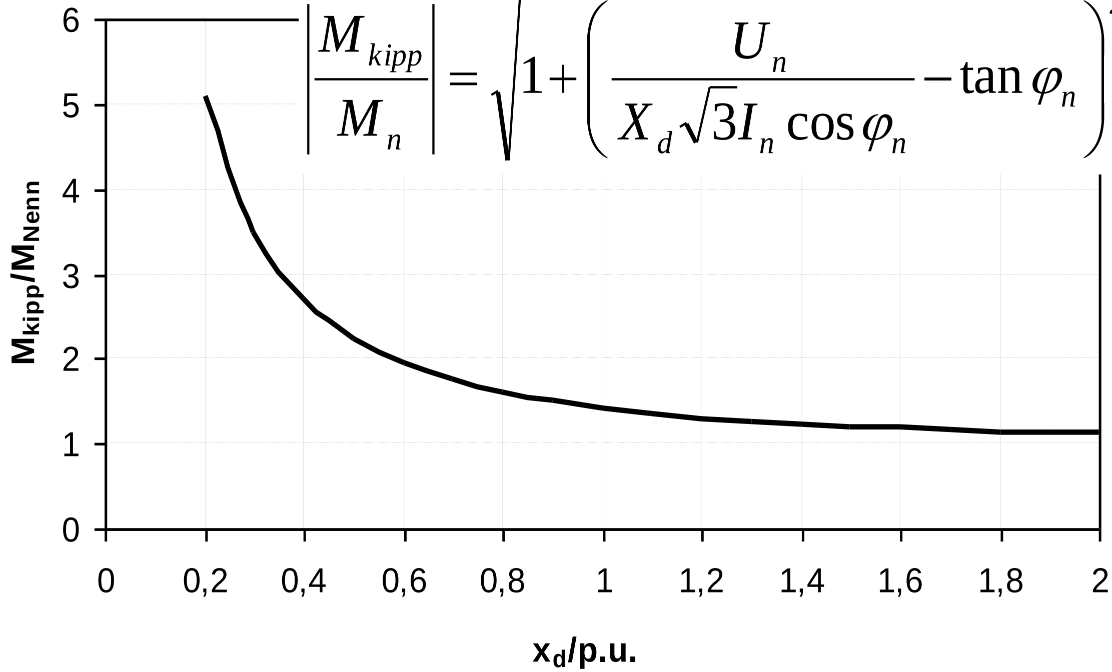
U$_p$ generated voltage
X$_d$ series armaturereactance
X$_q$ parallel armature reactance
δ angle between generated and terminal voltage
p number of pole pairs

Torque of a salient pole machine

$$M = \frac{P_{mech}}{2\pi n_0} = -\frac{3p}{\omega}\frac{U U_p}{X_d}\sin\delta - \frac{3p}{\omega}\frac{U^2}{2}\left(\frac{1}{X_q}-\frac{1}{X_d}\right)\sin 2\delta$$

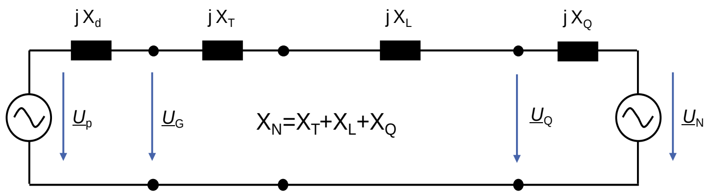
Ratio of breakdown torque to rated torque of synchronous machine

$$\left|\frac{M_{kipp}}{M_n}\right| = \sqrt{1+\left(\frac{U_n}{X_d\sqrt{3}I_n\cos\varphi_n}-\tan\varphi_n\right)^2}$$



Performance chart for conventional and superconducting generators

$$\underline{S}_N = 3\underline{U}_N \underline{I}_N^*$$



$$\underline{I}_N^* = \frac{\underline{U}_p^* - \underline{U}_N^*}{-j(X_d + X_N)}$$

$$\underline{U}_p = \frac{\underline{U}_p}{\underline{U}_N}\underline{U}_N = \frac{U_p}{U_N}\underline{U}_N\, e^{j(\varphi_{up} - \varphi_{uN})} = \varepsilon\, \underline{U}_N e^{j\delta_{pN}}$$

$$\varepsilon = U_p / U_N$$

$$\delta_{pN} = \varphi_{up} - \varphi_{uN}$$

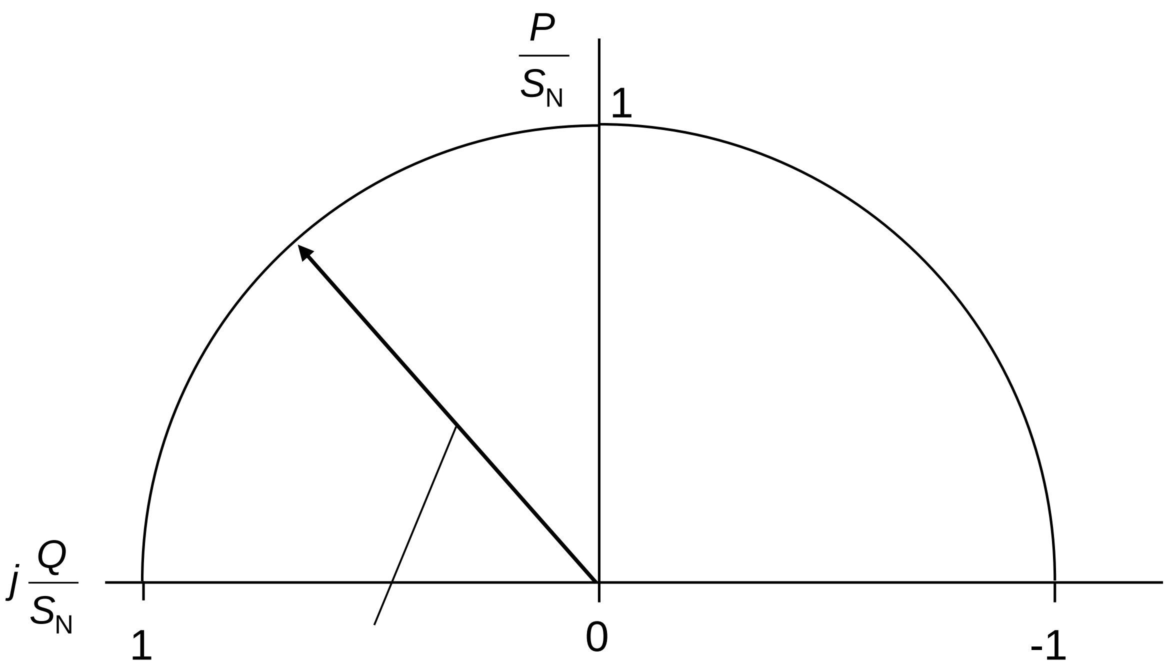
$$\underline{I}_N^* = j\frac{\underline{U}_N}{(X_d + X_N)}(\varepsilon\, e^{-j\delta_{pN}} - 1)$$

$$\underline{S}_N = j\frac{3U_N^2}{X_d + X_N}(\varepsilon\, e^{-j\delta_{pN}} - 1) = jQ_C(\varepsilon\, e^{-j\delta_{pN}} - 1) = P_N + jQ_N$$

$$\frac{\underline{S}}{S_N} = \frac{P}{S_N} + j\frac{Q}{S_N} = j\frac{Q_C}{S_N}\left(\varepsilon \cdot e^{-j\delta} - 1\right)$$

$$Q_C = \frac{3U_N^2}{X_d + X_N}$$

Performance chart for conventional and superconducting generators

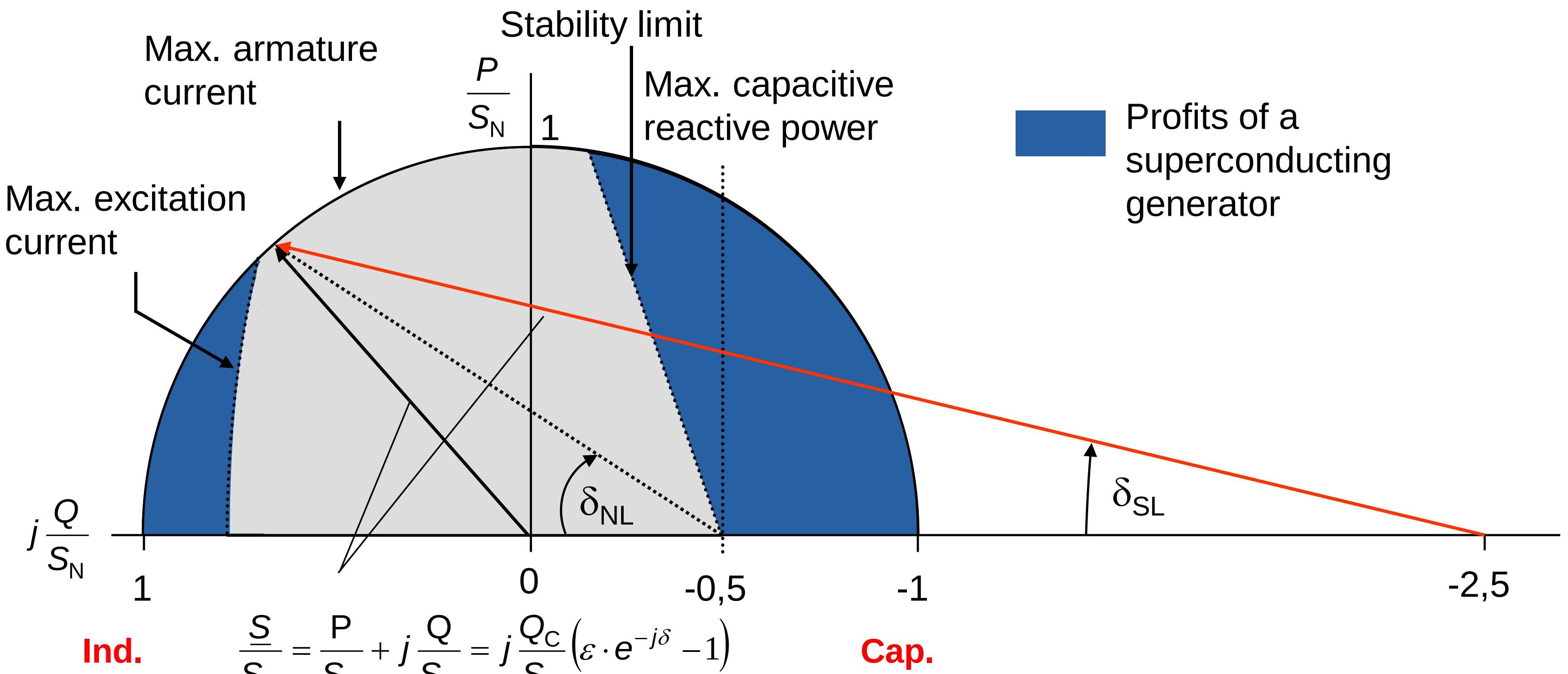


Ind.

$$\frac{\underline{S}}{S_N} = \frac{P}{S_N} + j\frac{Q}{S_N} = j\frac{Q_C}{S_N}\left(\varepsilon \cdot e^{-j\delta} - 1\right)$$

Cap.

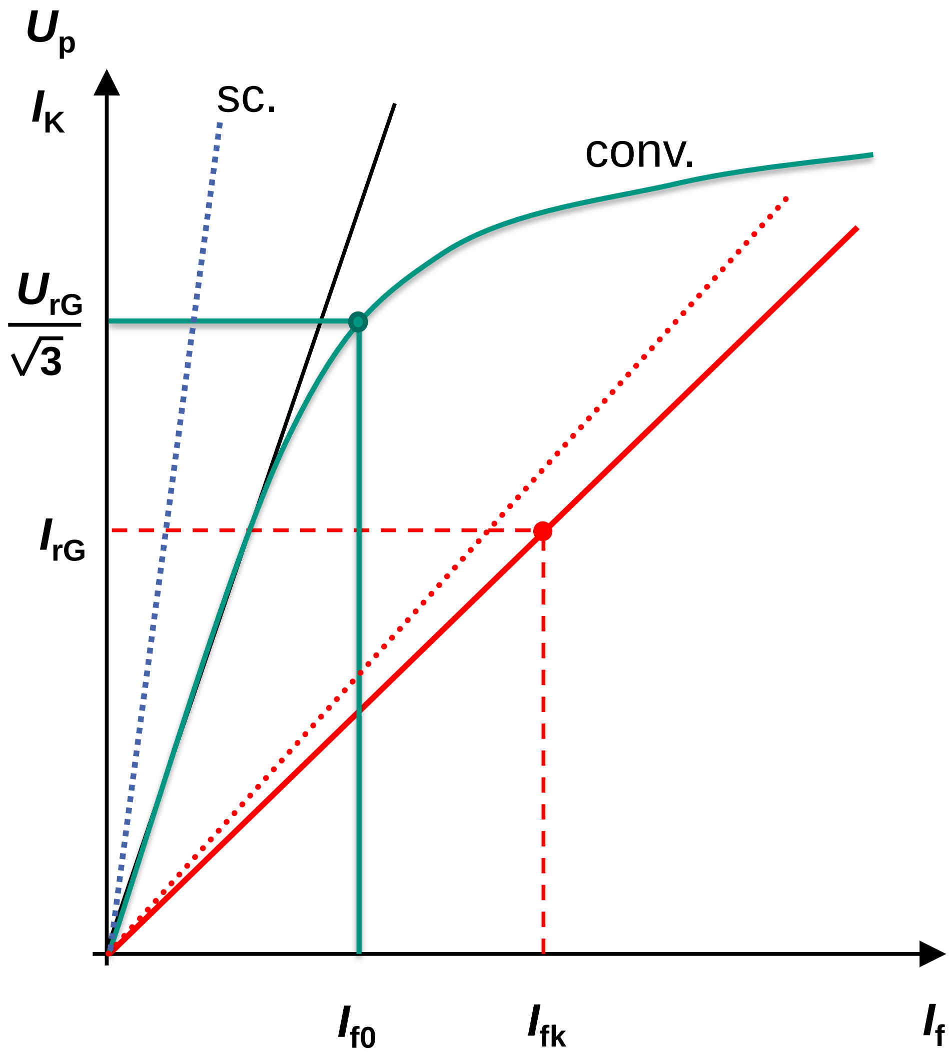
Performance chart for conventional and superconducting generators



$$\frac{\underline{S}}{S_N} = \frac{P}{S_N} + j\frac{Q}{S_N} = j\frac{Q_C}{S_N}\left(\varepsilon \cdot e^{-j\delta} - 1\right)$$

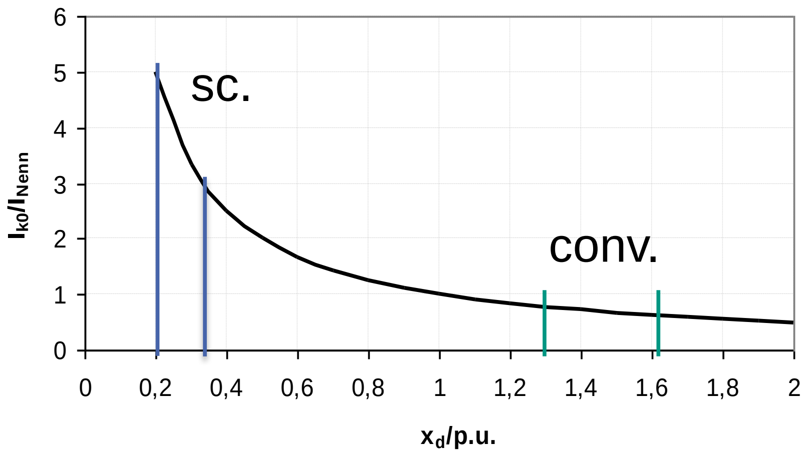
Superconducting Rotating Machines

Open loop- and short-circuit characteristics



Ratio open-loop short circuit

$$\frac{I_{f0}}{I_{fk}} = \frac{U_{rG}}{\sqrt{3}\, I_{rG}} \frac{1}{X_d} = \frac{1}{x_d}$$



Synchronous machine

Advantages of superconducting synchronous machines

- Small volume and weight ($V_{SC}/V_{CONV} \approx 0,5$)
- Small synchronous reactance ($X_{dSC}/X_{dCONV} \approx 0,2$)
  - Larger area for stable operation
  - Higher over load capacity $(M_{KIPP}/M_{NOM})_{SC} > 3$
  - Less sensitive to load fluctuations
- Higher efficiency (negligible excitation losses)
- Less noise and less vibration
- Higher speeds are possible

Challenges of superconducting synchronous machines

- Reliable SC material
- Cryogenic cooling
- Dissipation of losses in the stator winding
- Other operating characteristics for the user
- No unique selling proposition (competes with conventional machines)

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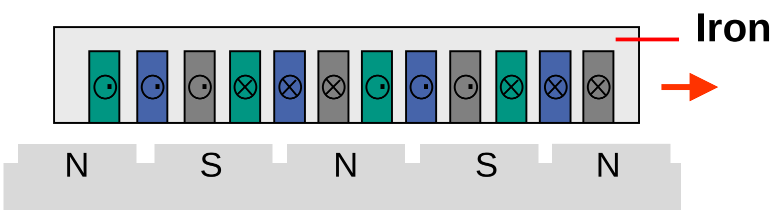
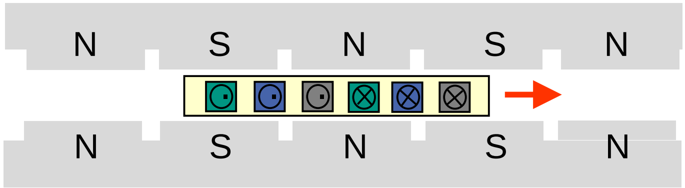
Linear motor

System with iron core (one-sided magnetic rail)

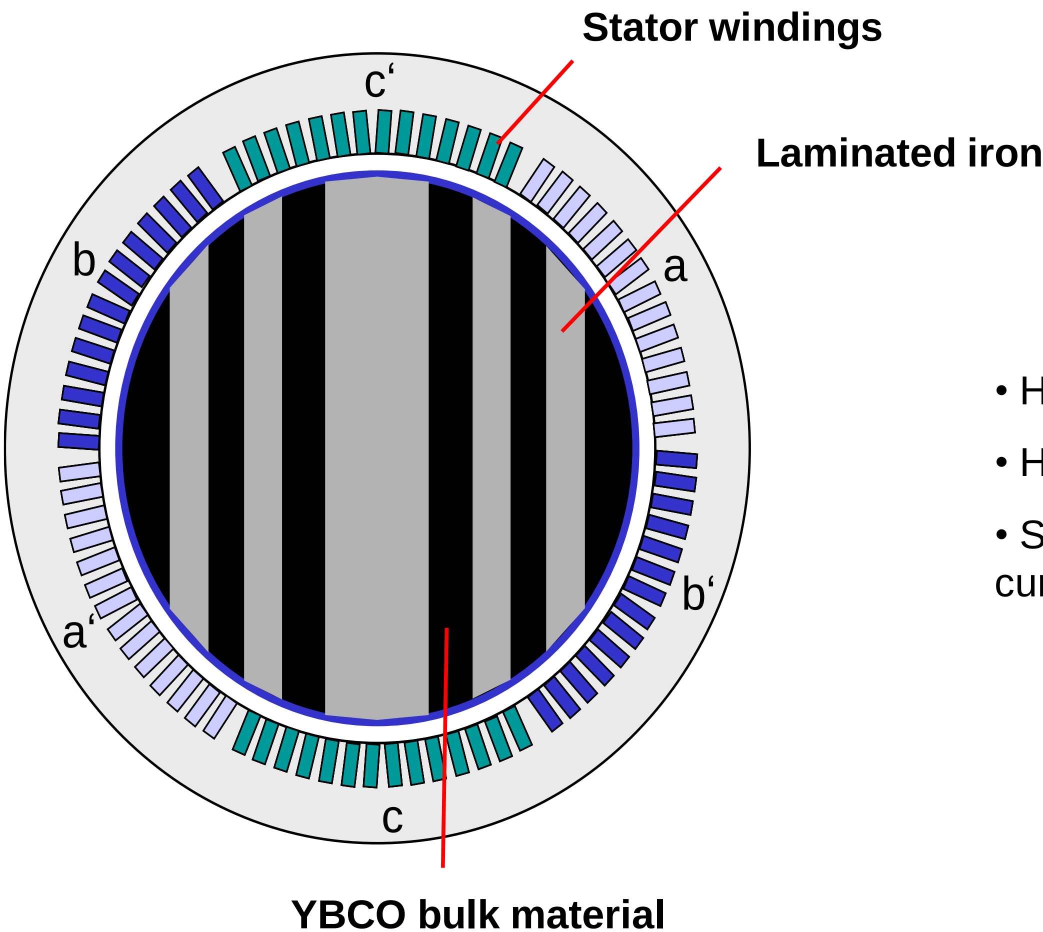


Iron less System (double sided magnetic rail)



Reluctance motor (2 poles, p=1)

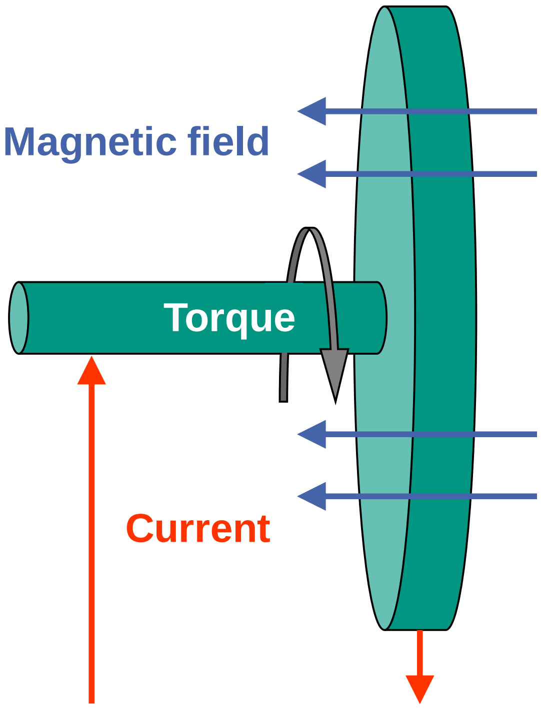
ZEBRA type according to Kovalev



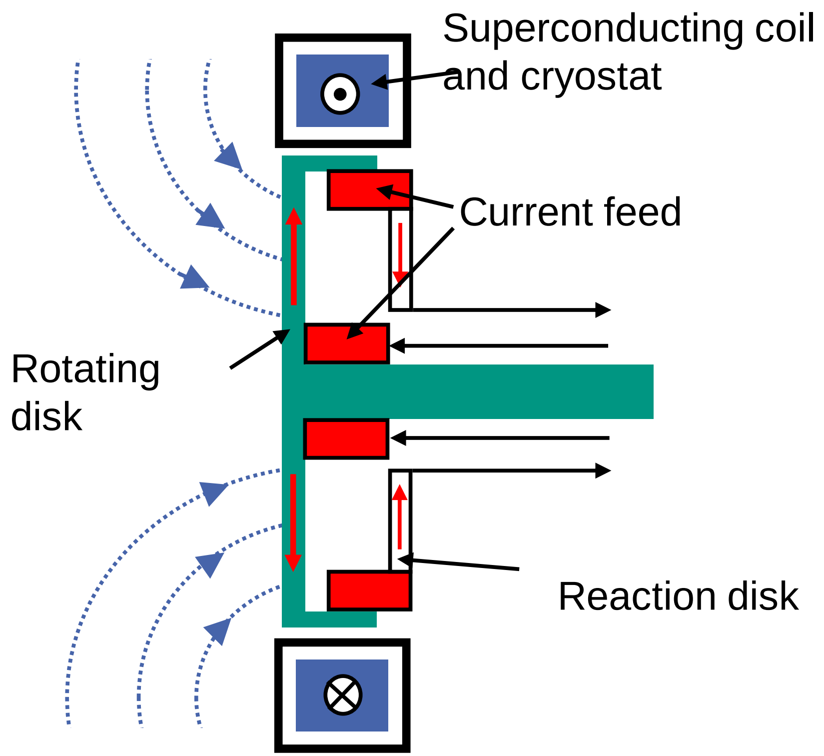
- Higher torque density
- Higher dynamic
- Simple concept, no excitation current in rotor

Homopolar machine

Principle



Disk type

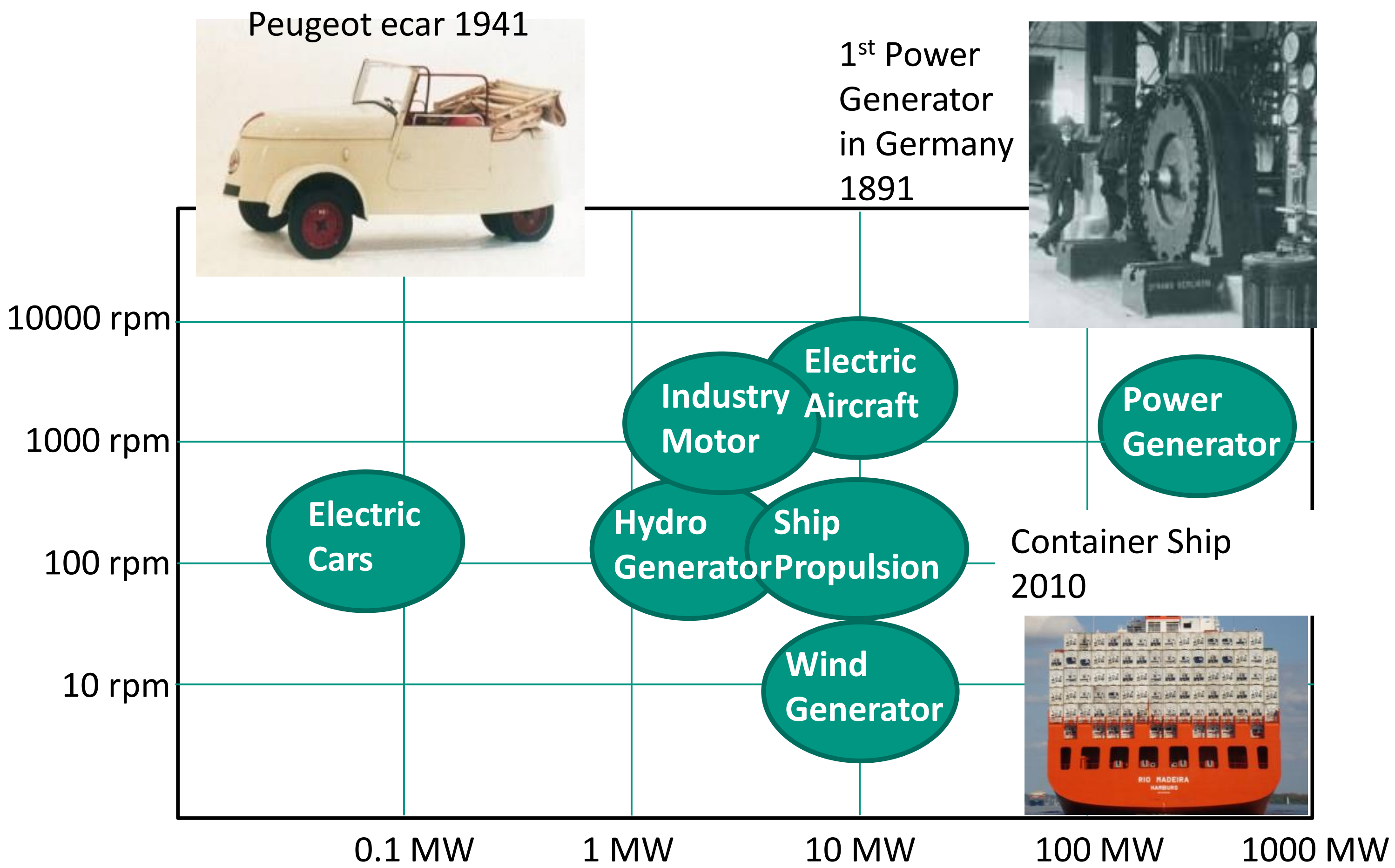


$$U = \frac{B_0 \, R \, v_{max}}{2} \qquad P = \frac{B_0 \, I \, R \, v_{max}}{2}$$

A simple variant of the homopolar machine

Superconducting Rotating Machines

Machines for which application?



State of the Art

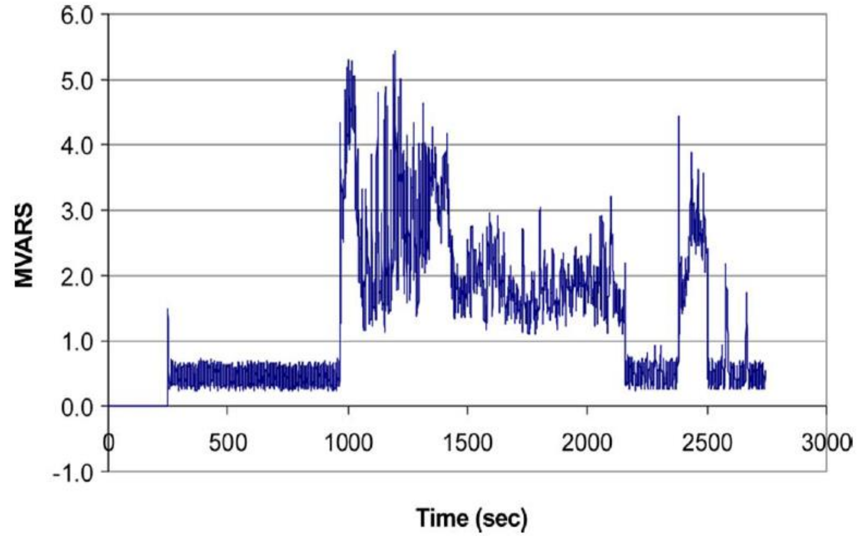
Country	Application	Rated power	RPM	SC	Year
US	Motor	200 kW	1800 rpm	BSCCO	1996
US	Motor	1 MW	1800 rpm	BSCCO	2000
US	Motor	3.7 MW	1800 rpm	BSCCO	2003
Korea	Motor	1 MVA	3600 rpm	BSCCO	2007
Japan	Ship propulsion	400 kW	250 rpm	BSCCO	2007
Japan	Ship propulsion	1 MVA	190 rpm	BSCCO	2008
Germany	Generator	4 MVA	3600 rpm	BSCCO	2008
Germany	Ship propulsion	4 MVA	120 rpm	BSCCO	2010
US	Ship propulsion	36.5 MVA	120 rpm	BSCCO	2010
UK	Hydroelectric generator	1.7 MVA	214 rpm	BSCCO	2012
Russia	Motor	200 kVA	1500 rpm	YBCO	2015
Russia	Wind generator	1000 kVA	-	YBCO	2015
EU (FP7)	Wind generator	500 kVA	-	MgB_2	2017
EU (H2020)	Wind generator	3,6 MW	15 rpm	YBCO	2018
EU (H2020)	Aircraft propuslion	1 MW	10000 rpm	YBCO	2020

Superconducting Rotating Machines

First field test

8 MVAR, 13.8 kV HTS Synchronous Condenser (AMSC)

MVAR during a firing cycle



Source: KALSI S et al., IEEE Trans. on Applied Superconductivity 17, No. 2, 1591-4 (2007).

Field test from October 2004 to November 2005 near an electric arc furnace at the Hoeganaes Steel Mill in Gallatin, Tenn.

Developments at Siemens

1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 …

HTS I

HTS II

HTS III

HTS II longterm operation

Model Machine

- 0.4 MW
- 1500 rpm
- 4-pole

Technology Demonstrator

Generator

- 4 MVA
- 3600 rpm
- High Speed
- 2-pole

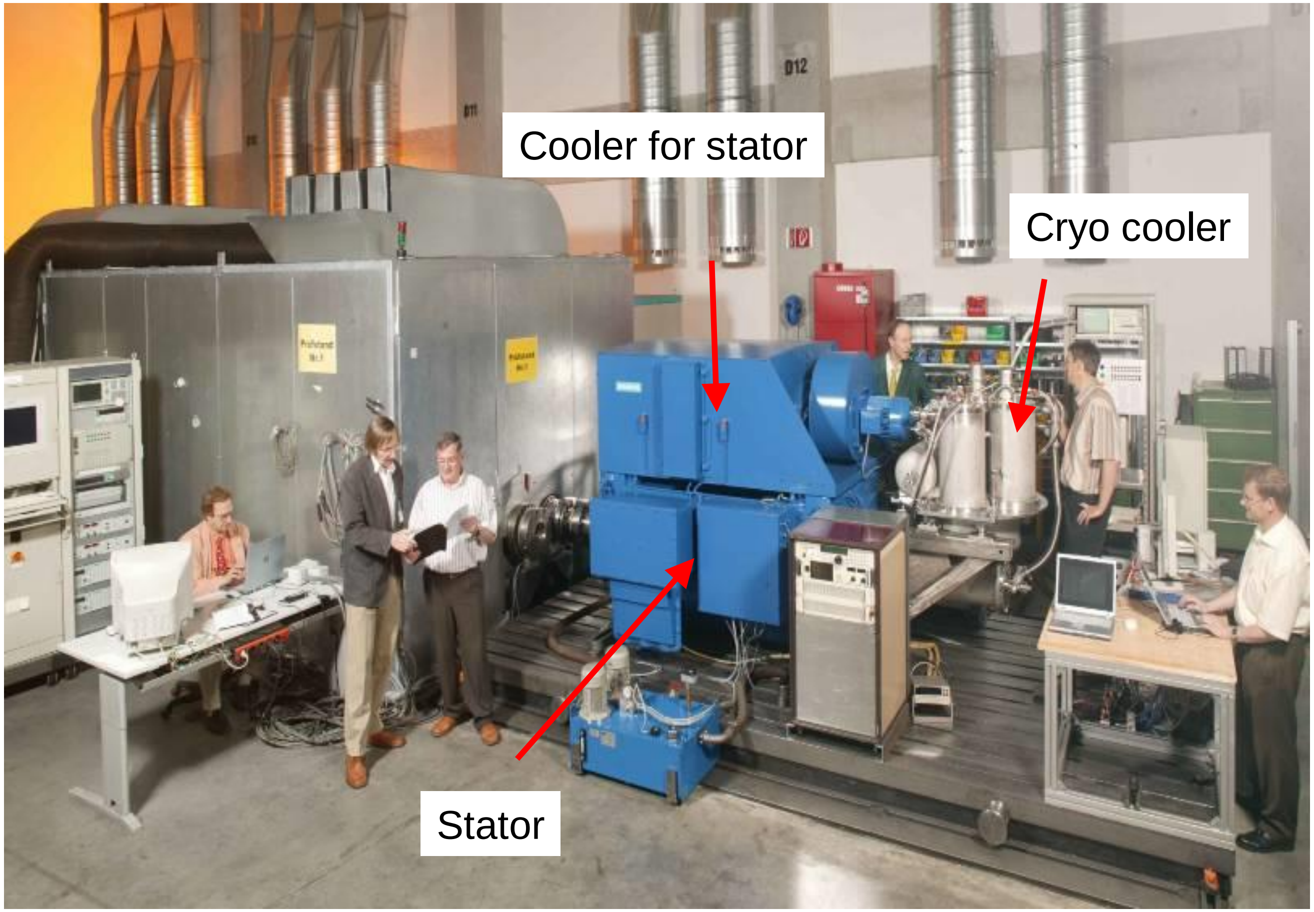
Application-oriented

Motor

- 4 MW
- 120 rpm
- High Torque
- 8-pole

Application-oriented

4 MW Synchronous machine (Siemens)



4 MW HTS synchronous machine at the test stand in Nuremberg (2006)

HTS	Conv.
2 poles	4 poles
3600 min^{-1}	1800 min^{-1}
1,9 x1,2 m^2	1,8x1,8 m^2
7 to	11 to
x_d=0,41 p.u.	x_d=2,2 p.u.

- rotor winding Bi-2223
- T_{op}= 25 K
- L_{Ne} cooling
- 2% better efficiency

4 MW Synchronous machine (Siemens)

4 MW HTS II – Long therm field test at Nuremberg

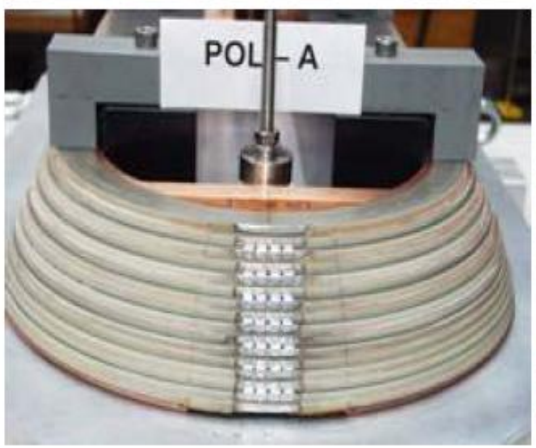
Figure: Siemens

Test results:

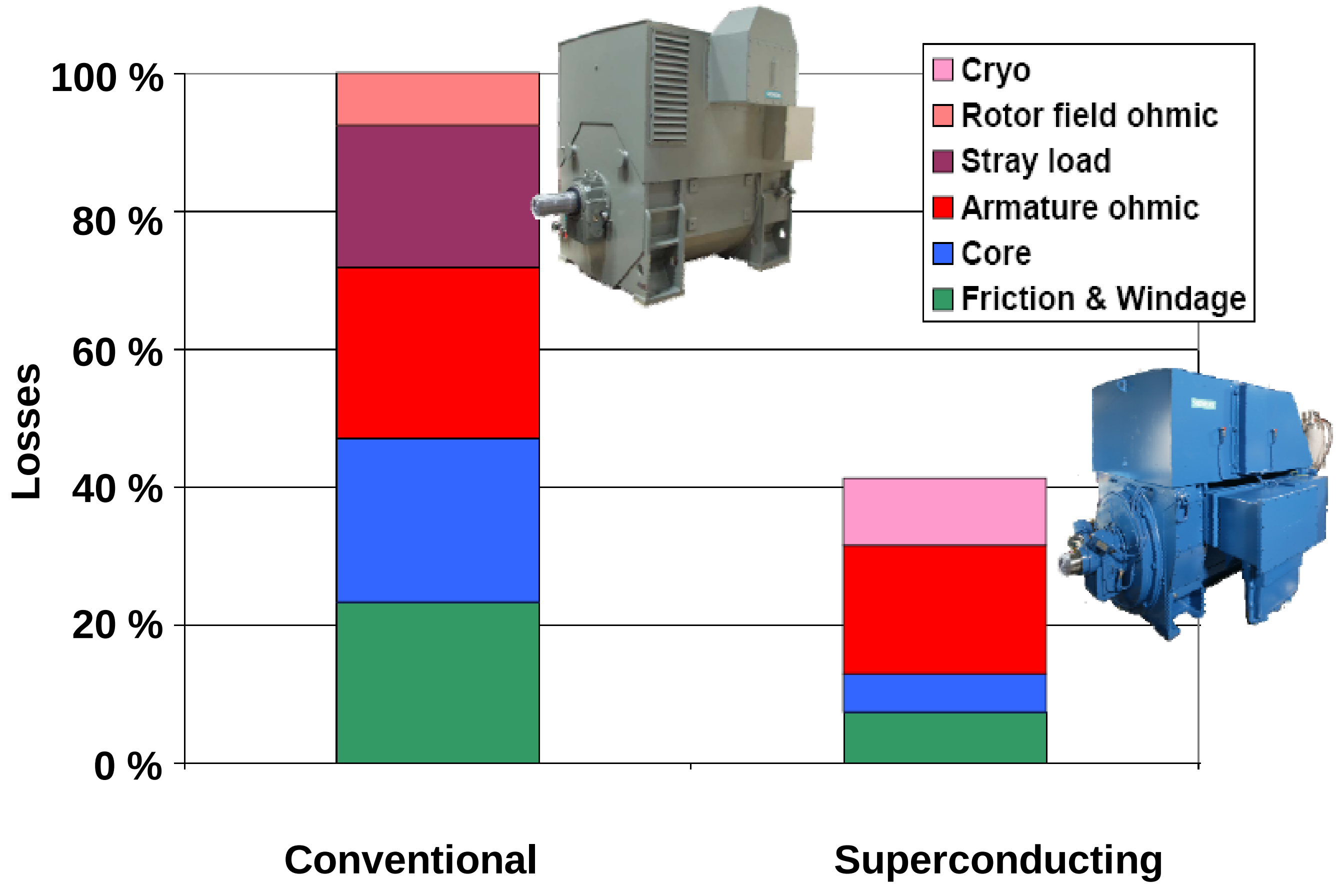
- Loss reduction 50 %
- Full capacitive reactive power
- High over load capacity
- Low voltage drop
- Low harmonics
- Over 7500 h operating hours
- Safe operation

No shutdown due to superconductor or cooling!
All operating and switching states safely controlled!

4 MW Synchronous machine (Siemens)



4 MW Synchronous machine (Siemens)



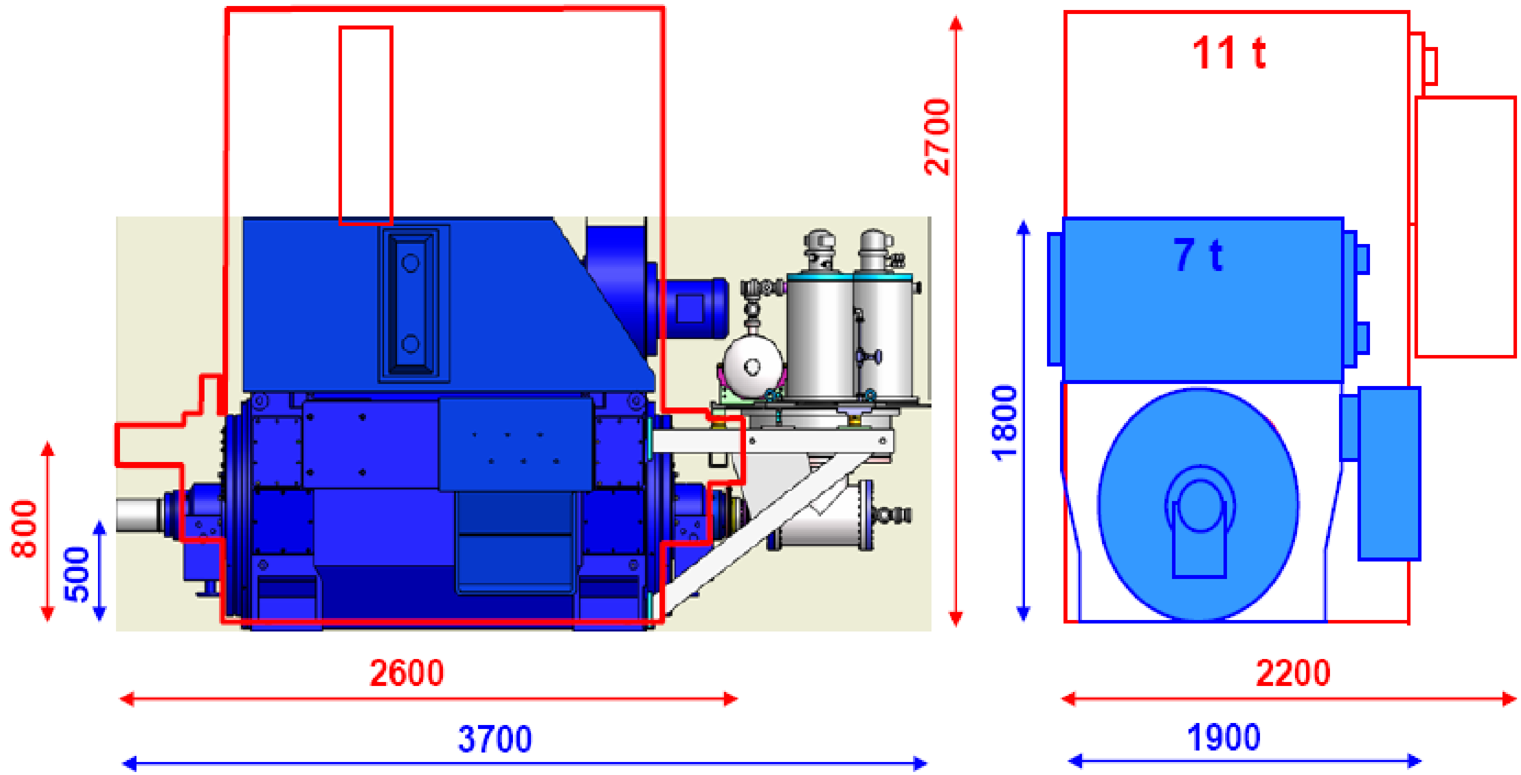
η=96,5 %

η=98,7 %

4 MW Synchronous machine (Siemens)

Conventional machine | **Superconducting machine**

Weight 11 to | **Weight 7 to**

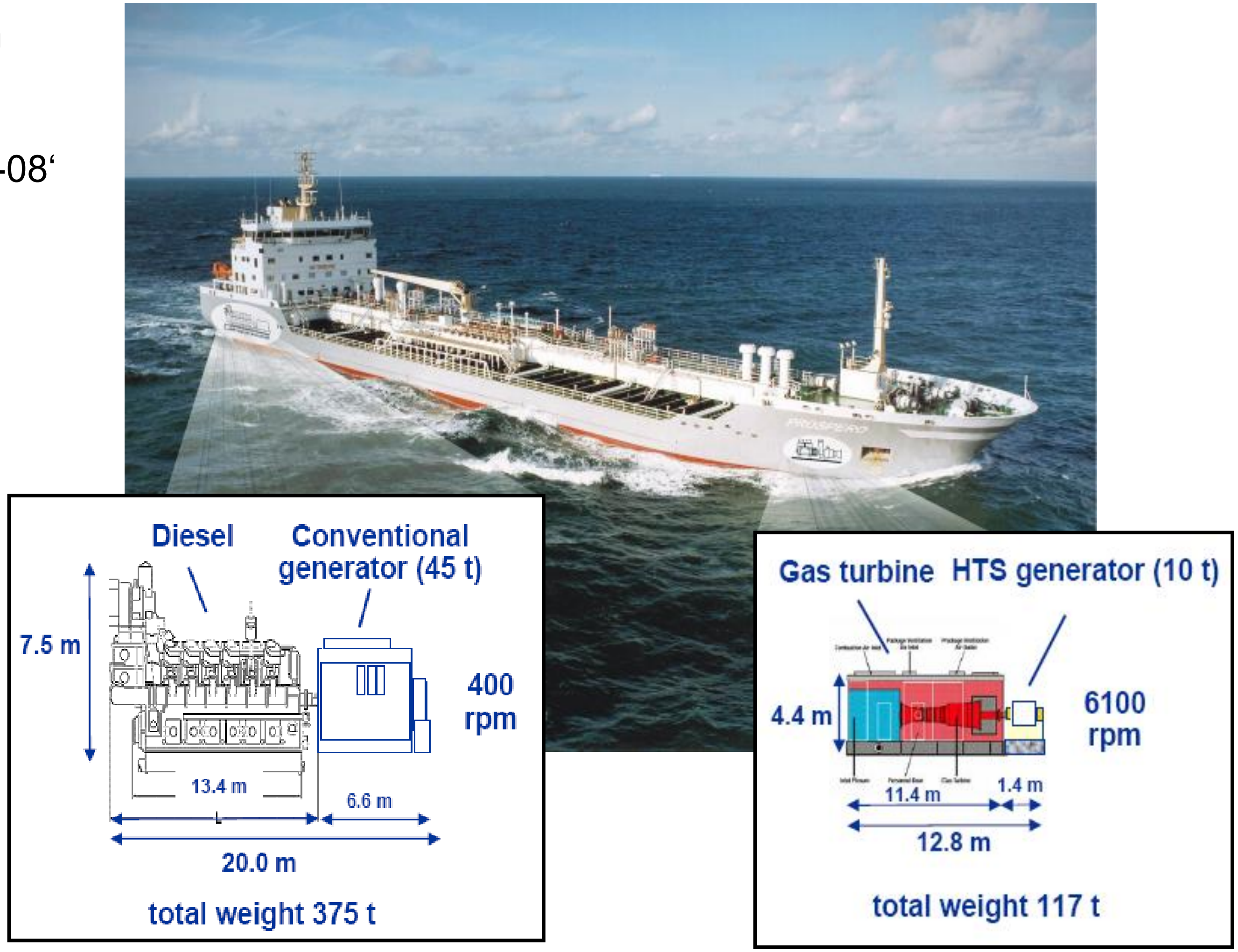


4 MW Synchronous machine (Siemens)

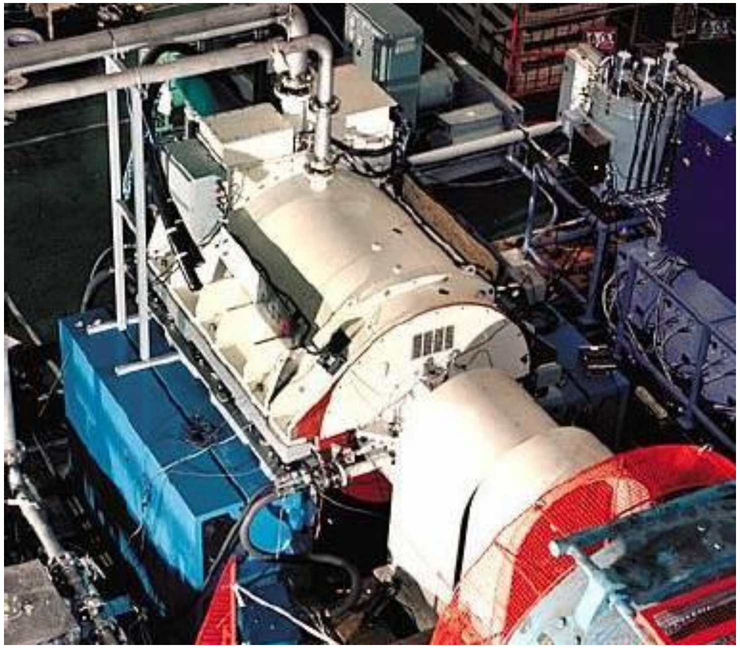
Speed: 120 U/min

Torque: 330 kNm

Development: 06‘-08‘



5 MW Synchronous machine (American Superconductor)



Power: 5 MW

Speed: 230 1/min

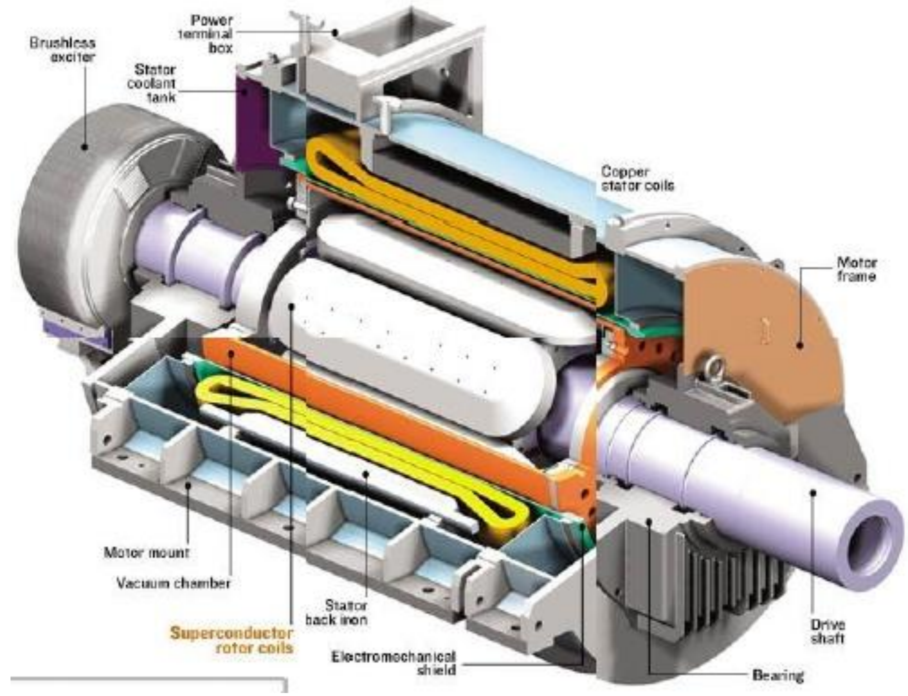
Torque: 207000 Nm

Weight: 23 t

Half the weight and volume of a conventional motor

Stator: Cu, 3 phases

Rotor: racetrack - HTS



5 MW Synchronous machine (American Superconductor)

Motor installation and finalisation at Alstom UK

Completed January 2003

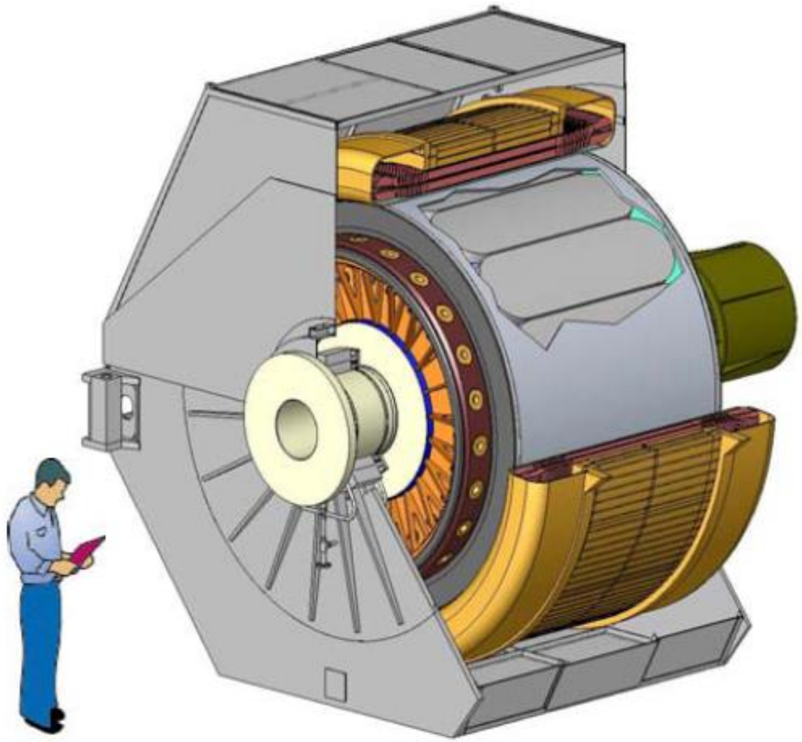
5 MW Synchronous machine (American Superconductor)

Test at ONR (Office of Naval Research) 2003

Rated power	5 MW
Rated voltage	4160 V
Rated current	722 A
Rated load factor	1
Speed	230 min^{-1}
Frequency	11,5 Hz
Synchronous reactance in d-direction	0,32 p.u.
Transient reactance in d-direction	0,24 p.u.
Subtransient reactance in d-direction	0,16 p.u.

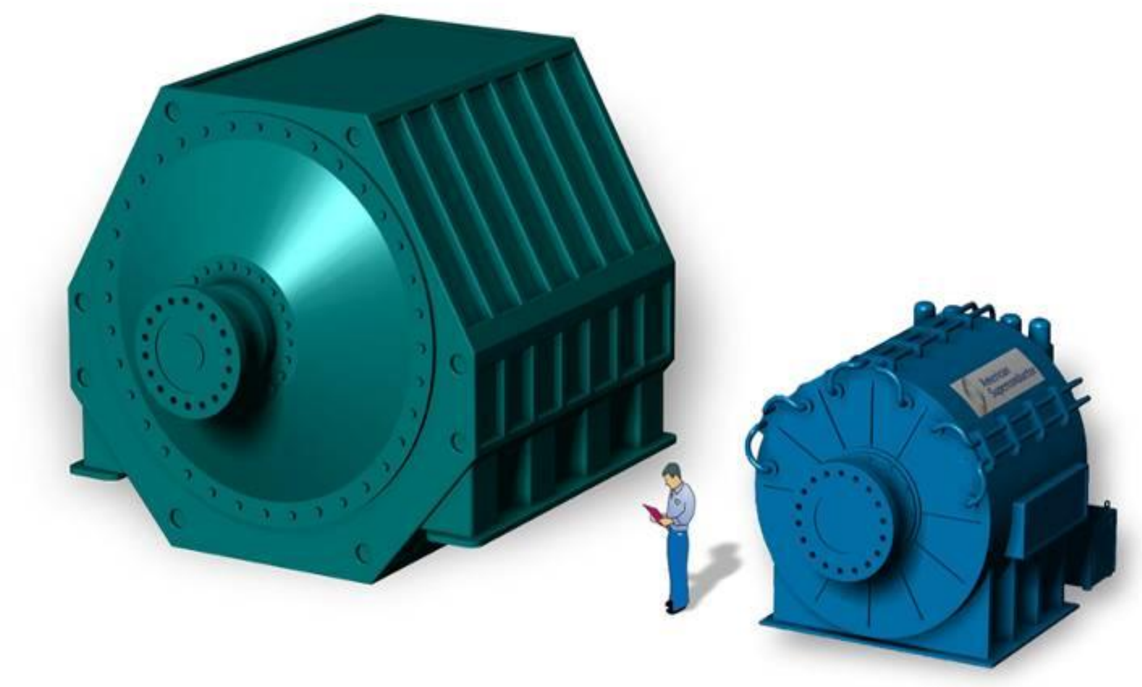
36,5 MW Synchronous motor (American Superconductor)

Power: 36,5 MW
Speed: 120 U/min
Voltage: 6 kV
Current: 1270 A
Number of pole pairs: 8
Weight: 75 to
Efficiency: > 97 %
Dimensions: 3,4 m x 4,6 m x 4,1 m
Operating time: Jan. 03‘- Dez. 06‘



36,5 MW Synchronous motor (American Superconductor)

Size comparison conventional motor – HTS motor



Conventional
280 to

HTS
75 to

36,5 MW Synchronous motor (American Superconductor)

Karlsruhe Institute of Technology

Manufacturing of superconducting race track coil

Finished rotor

36,5 MW Synchronous motor (American Superconductor)

Installation of the rotor in the stator

X_d	0,368 p.u.
X_d'	0,32 p.u.
X_d''	0,243 p.u.
η_{Motor}	97,1 %

Complete system

1 MW Ship propulsion (Nedo, Kawasaki)

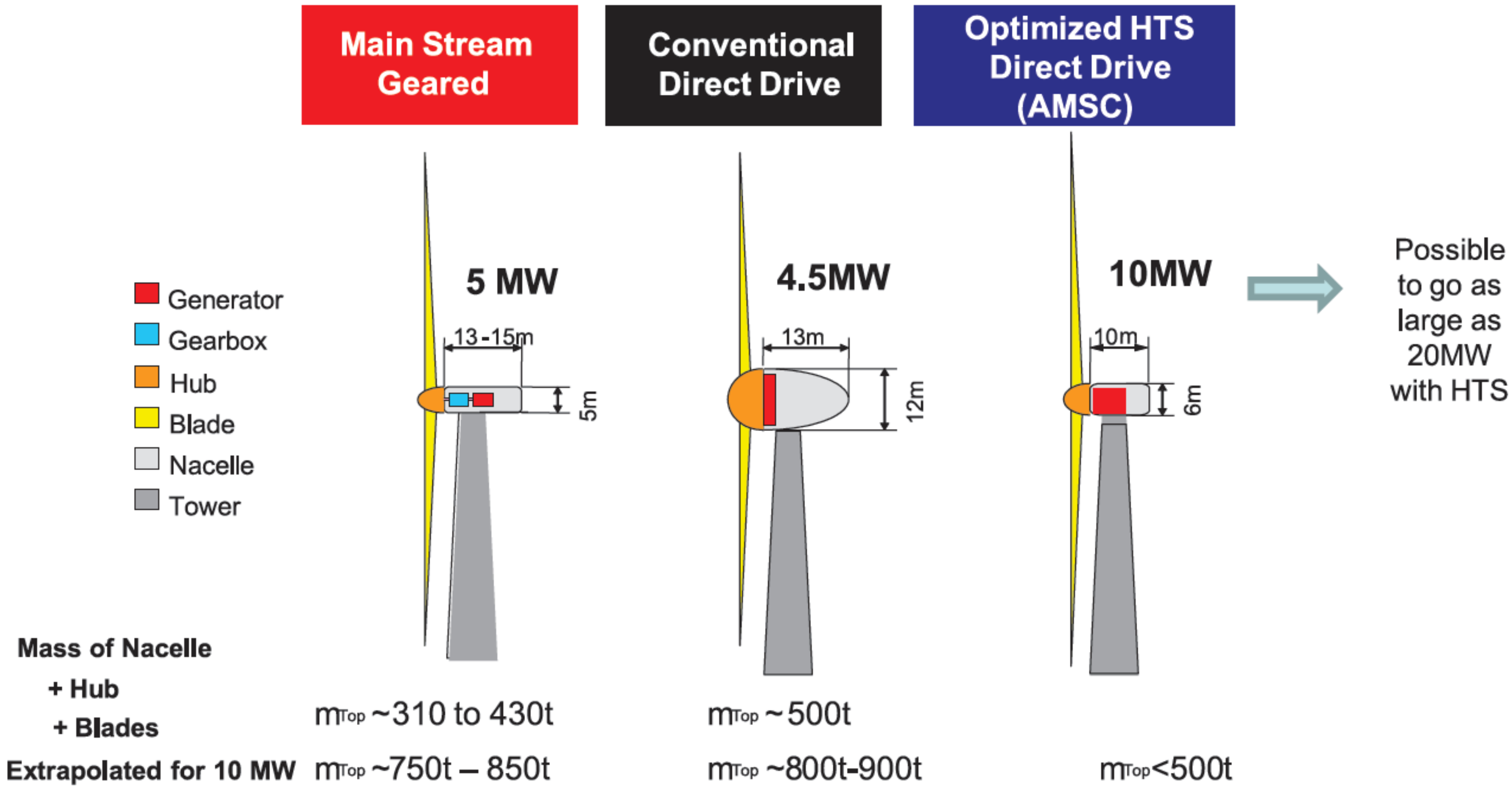
Stator

HTS rotor

Power	1 MW
Speed	190 rpm
No. of pole pairs	4
Voltage	1200 V
Stator current	675 A
HTS current	200 A
HTS	Bi 2223
HTS temp.	30 K
Efficiency	98 %

K Umemoto et.al, Development of 1 MW-class HTS motor for podded ship propulsion system, 9th European Conference on Applied Superconductivity (EUCAS 09) IOP Publishing, Journal of Physics: Conference Series 234 (2010) 032060 doi:10.1088/1742-6596/234/3/032060

Superconducting wind power generators



Picture from AMSC SeaTitan™ Data Sheet

A HTS wind power generator with 10 MW and 4000 full load hours earns 1.8 Mio. €[1] /a more than a conventional with 5 MW.

1) 1 kWh=9Eurocent

Key Project Figures

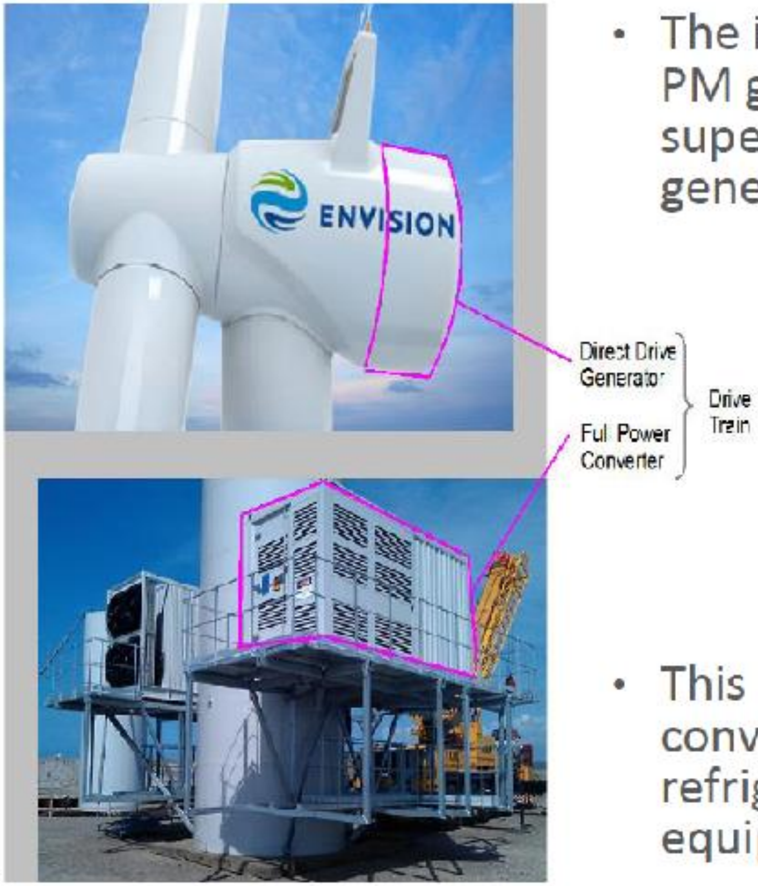
- **Program:** EU Horizon 2020
- **Reference:** 656024
- **Start Date:** 2015-03-01
- **End Date:** 2019-03-01
- **Total Cost:** EUR 13,846,594
- **EU Contribution:** EUR 10,591,734

Horizon 2020
European Union Funding
for Research & Innovation

"EcoSwing has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 656024." "Herein we reflect only the author's view. The Commission is not responsible for any use that may be made of the information it contains."

Platform for Technology Validation

ecoswing



- The idea is to replace a PM generator with a superconducting generator

- This includes power conversion and refrigeration equipment.

Horizon 2020
European Union Funding
for Research & Innovation

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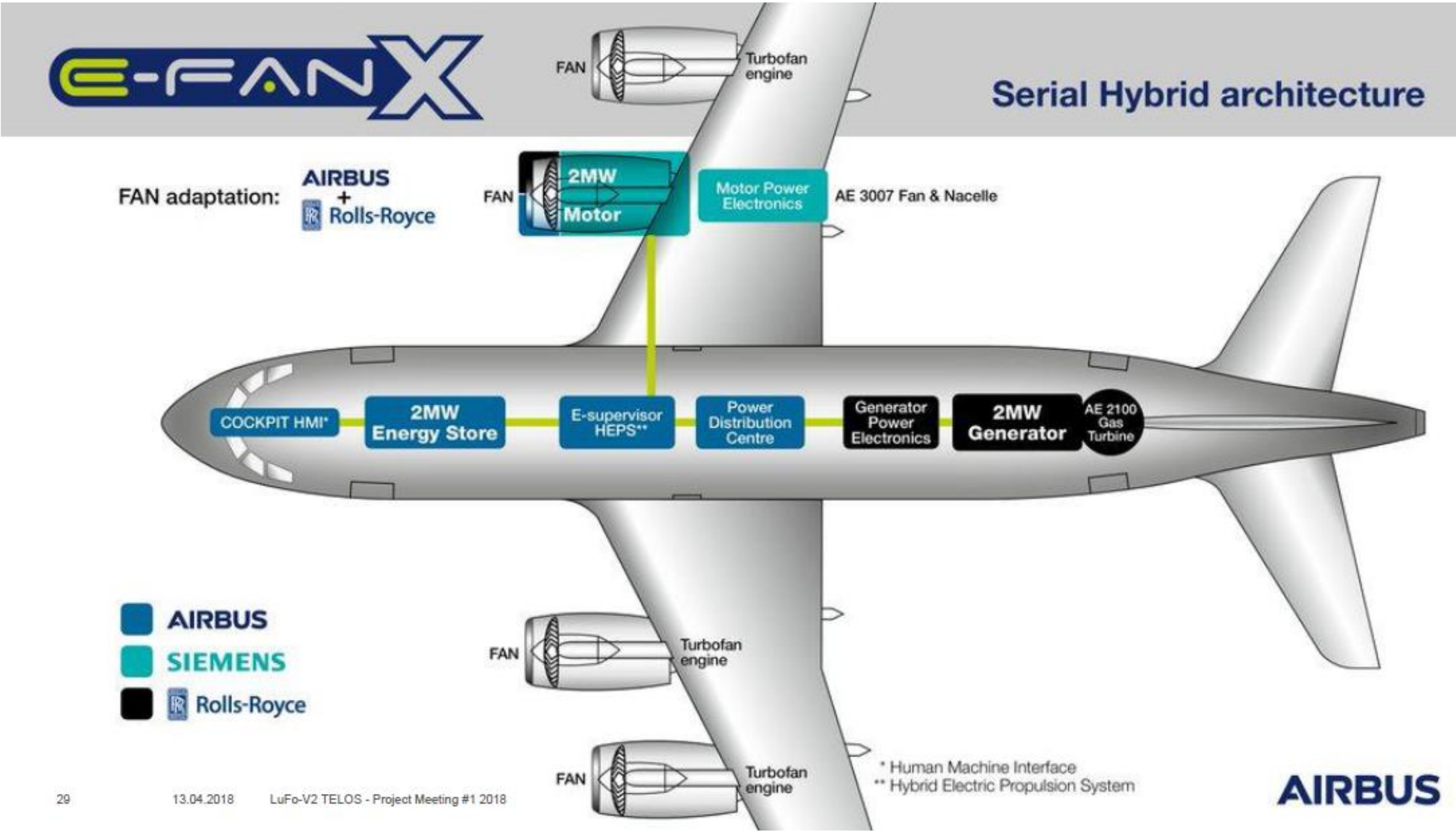
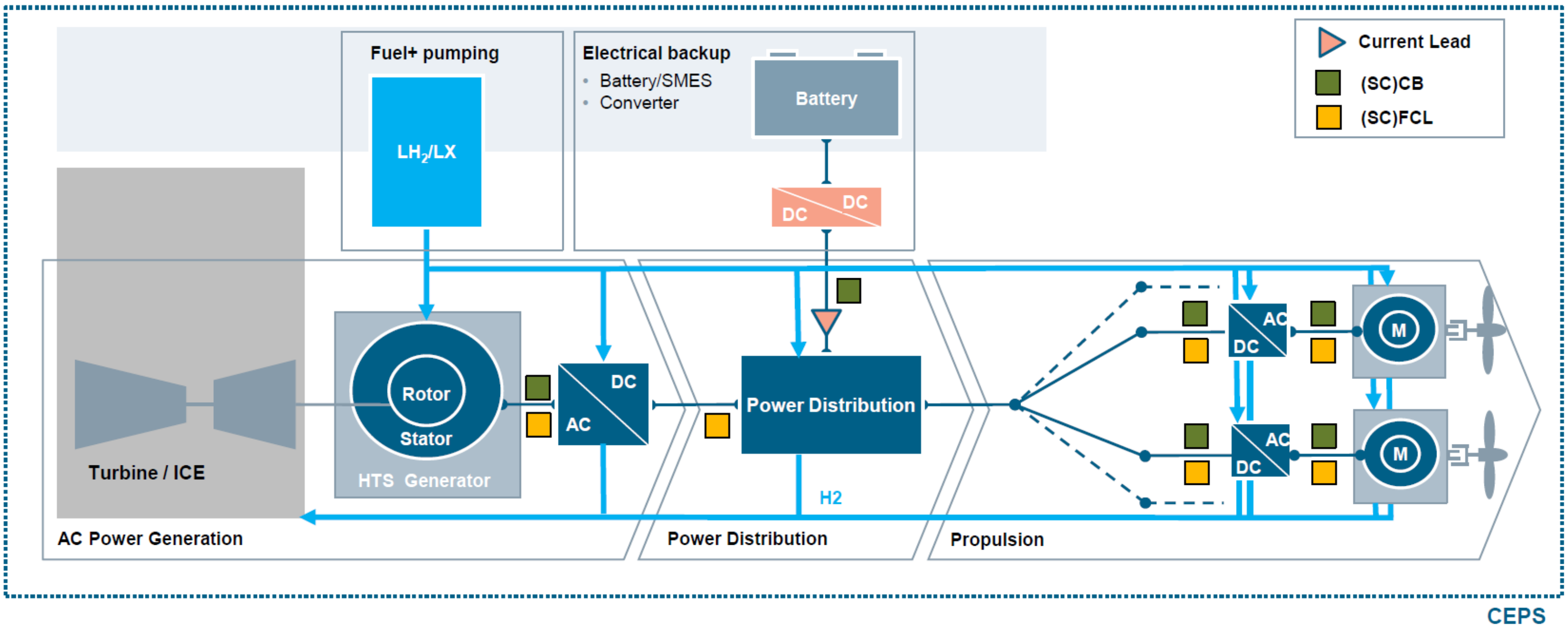
Electric Aircraft



P. Rostek, TELOS-project meeting, 13.04.2018

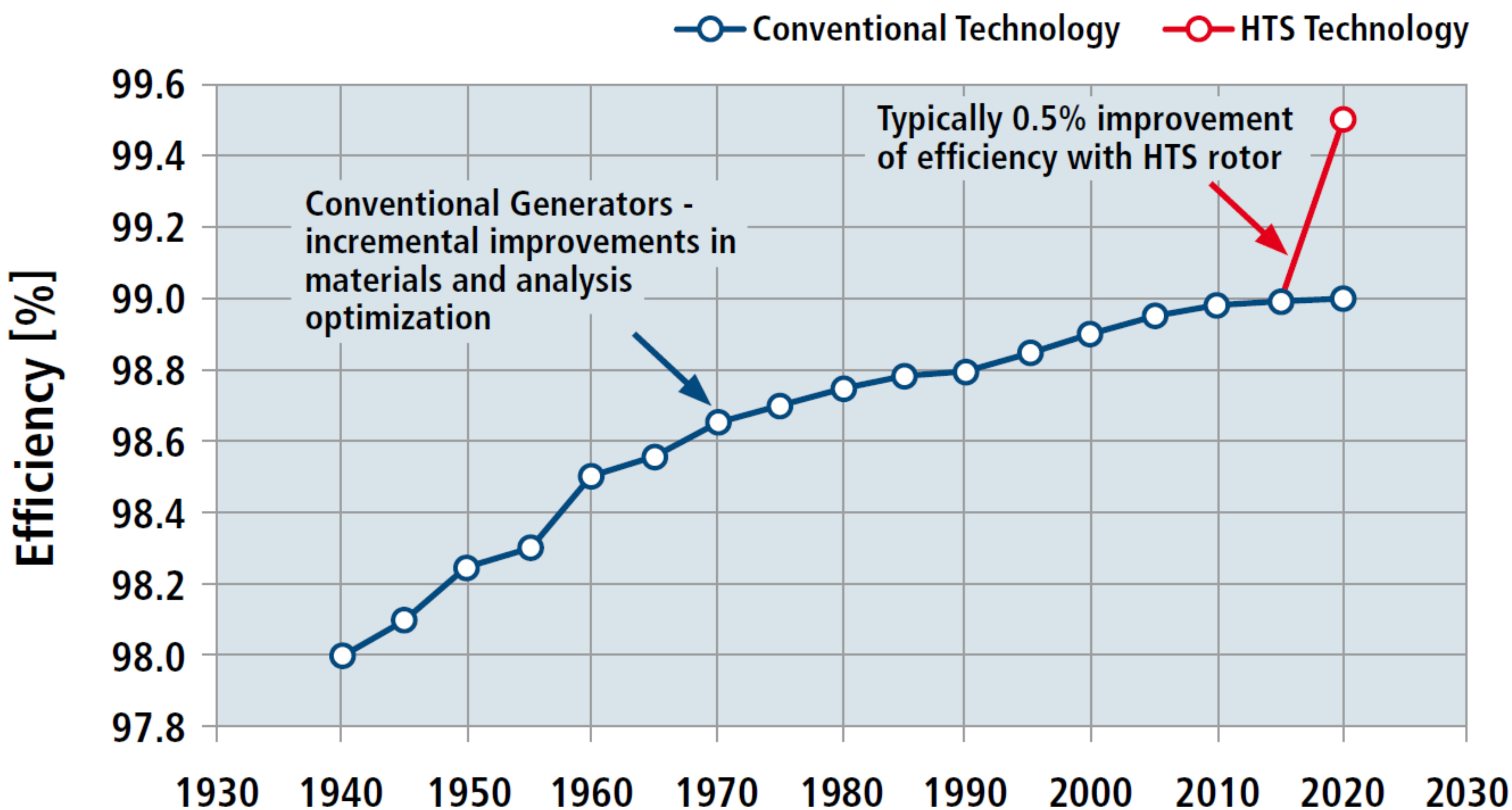
Electric aircraft

Architecture of a propulsion system with HTS generator



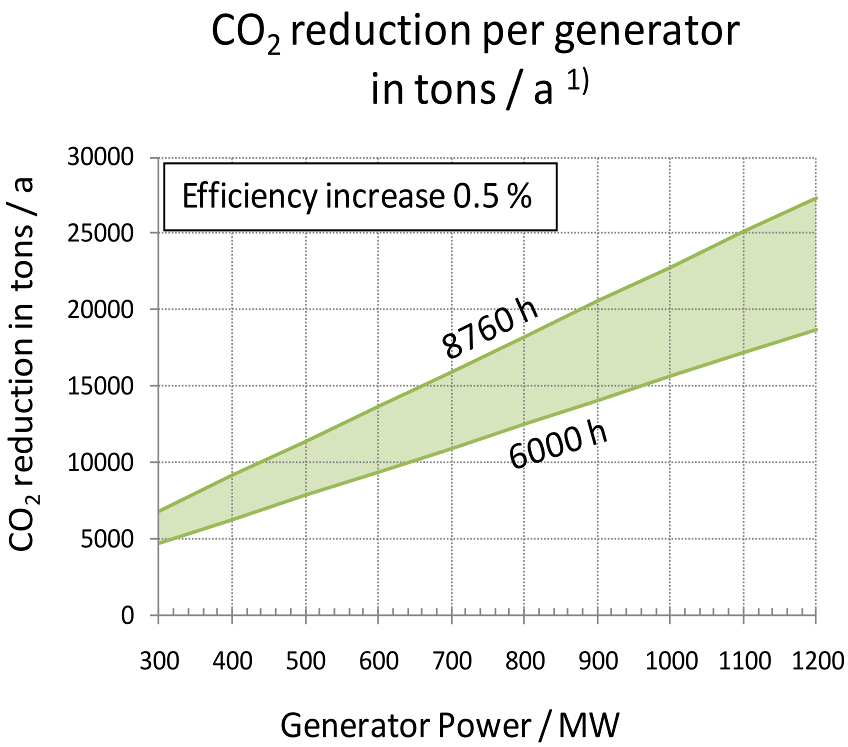
M. Boll, Siemens, ZIEHL, March 2018

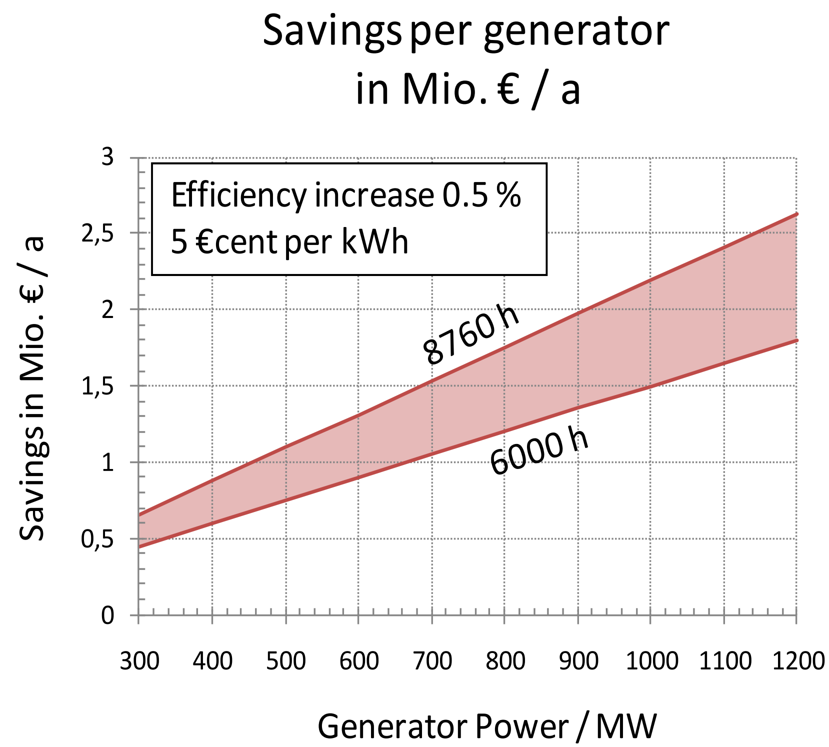
Superconducting power plant generators
Efficiency development



Source: High-Temperature Superconductivity for Power Engineering, Materials and Applications, Accompanying Book to the Conference ZIEHL II, Future and Innovation of Power Engineering with High-Temperature-Superconductors, 16-17 March 2010, Bonn, Germany

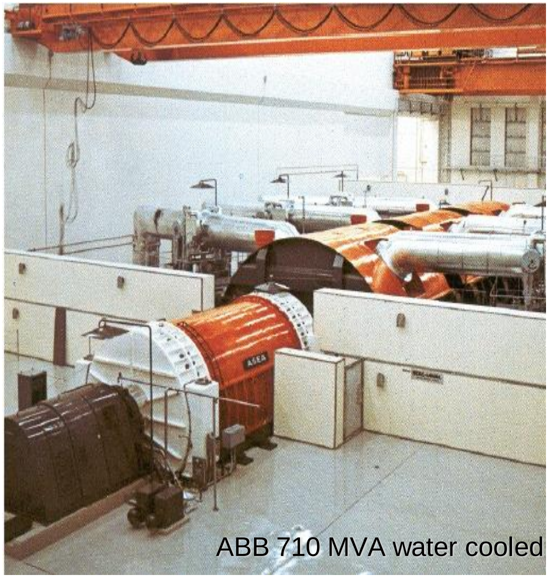
Superconducting power plant generators

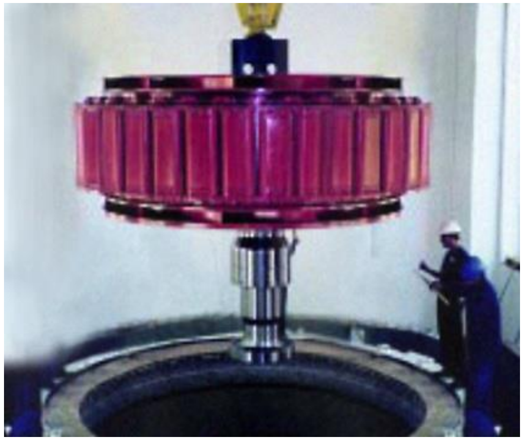




Future stationary generator applications?

e.g.
Wind power generators
Power plant generators
Hydroelectric generators
Microgrid generators





Future stationary motor applications?

e.g.
Steel industry
Paper industry
Compressors
Mining
Chemistry
Refineries
Power plants

Furture mobile applications?

e.g.
Marine drives
Rail drives
Wheel drives
Aircraft

Furture mobile applications?

Photo: Sumitomo, Toyota

Photo: NASA, CAPS