superconducting rotating machines

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www.oswald.de
Why can SC be useful in a motor/generator

- how do motors work
- what are today's limitations for motors
- where can SC be used in a motor

**topologies and examples**

cryogenic aspects
Karl Oswald und Sohn

foundation 1909
in Miltenberg am Main
Oswald Elektromotoren GmbH

50 kW ... 2 MW

customized motors/generators

... 200,000 Nm
motor / generator

functional principle of a homopolar motor

resulting lorentz force on current in external field
motor / generator

Entstehung eines Drehfelds aus einem dreisträngigen Drehstromsystem

Amplitude
- IU = 1
- IV = 1
- IM = 1

Phase
- pH/I = 90
- pH/V = 120
- ph/IW = -120

Lage
- allU = 0
- allV = 120
- allM = -120

http://www.fh-sw.de/sw/fachb/et/labinfo/em/iSEE/dreh.htm
motor / generator

spacial arrangement of coils

- number of slots
- number of poles
- number of phases
- connection
- power
- speed

\[ \begin{align*}
\gamma_1 &= 0 \\
\gamma_2 &= 2\pi(3p_f) \\
\gamma_3 &= 2\cdot2\pi(3p_f) \\
\text{Darstellung } 2p_f &= 6
\end{align*} \]
motor / generator

\[ M \sim A \cdot B \cdot d^2 \cdot l \]

- \( M \): Torque
- \( A \): Amp-windings
- \( B \): Flux in Airgap
- \( d \): Diameter
- \( l \): Length

\[ P \sim M \cdot f / p \]

- \( P \): Power
- \( f \): Frequency
- \( p \): number of pole pairs

- 3 m
- 60.000 Nm
- 2 tons
- 350 Nm
motor / generator

\[ P \sim M \cdot \frac{f}{p} \]

\[ M \sim A \cdot B \cdot d^2 \cdot I \]

rated operation

\[ n \text{ [rpm]} \]

Is

M

Up

U_{\text{max}}

U

P
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**Topologies and examples**

**Cryogenic aspects**
motor / generator

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motor / generator

\[ M \sim A \cdot B \cdot d^2 \cdot l \]

- \( M \): Torque
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- \( l \): Length

Flux in material

In air

External field
motor / generator

NdFeB: $B = 1,1 - 1,3T$
iron: $B_{\text{max}} = 2T$

magnetically hard
magnetically soft
motor / generator

PM-Synchronous motor:
All parts fit perfect together

NdFeB:
B = 1.1 - 1.3T

iron:
B_{max} = 2T

Flux density in Airgap:
B = 1T

80% coverage

50% coverage

M \sim A \cdot B \cdot d^2 \cdot l
motor / generator

Development of inverter technology: efficient asynchronous motors

DC motors until 80's
motor / generator
motor / generator

PM-synchronous motors

DC
AC asynchron
AC synchron
development of NdFeB-Magnets decisive for synchronous technology:

- increased force density (>20%)
- higher efficiency (some %)
- more compact (> 1 size)
- better dynamics (>30%)
- ...

motor / generator
motor / generator

power: 390 kW
 torque: 15500 Nm
 weight: 2310 kg

ca. 60 % Energy Saving

Quelle: Schuler/BMW
Advantages of PM-Motors:
- High force density
- Passive rotor
- High dynamics

... enables many new applications
motor / generator

next developments?

What is needed?

DC
AC asynchron
AC synchron

%
motor / generator

no nc solutions so far...
motor / generator

- new applications possible
- usage of new technologies and materials for building motors
- solutions for so far unfulfillable requests
- independance on critical resources
- improvement of operating parameters
- ...

Graphs showing data and trends related to motor performance.
motor / generator

- Standard Normmotor: 0.1 kW/kg
- Servomotor: 1 kW/kg
- Normleitender Flugzeugantrieb: 3-6 kW/kg
- HTS supraleitender Flugzeugantrieb: 12-15 kW/kg
motor / generator

EADS/Airbus concept: Paris Air show 2013

- superconducting transmission lines
- superconducting propulsion motors
- superconducting generator + turbine
- power electronics batteries
New applications are arising:
- Increased acceleration rate
- Reduced Size
- Increased power density

Common background:
even applications are in development years to come into market…
Why can SC be useful in a motor/generator
how do motors work
what are today's limitations for motors
where can SC be used in a motor
topologies and examples
cryogenic aspects
motor / generator

M~A·B·d^2·l

M: Torque
A: Amp-windings
B: Flux in Airgap
d: Diameter
l: Length

el. power

iron losses
p_{Fe}

stator

rotor

friction, iron losses
p_R

mech. power

p_2

Copper losses
p_{Cu1}

Copper losses

**motor / generator**

- number of turns
- current
- geometric parameters

Limiting factors:
- available space for magnetic system
- space needed for application
- cooling system

Engineering current density: \[ j \sim \frac{NI}{A} \]
## Motor / Generator

<table>
<thead>
<tr>
<th>$j / \text{A/mm}^2$</th>
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<tbody>
<tr>
<td>2 - 4</td>
<td>0.05</td>
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Quelle: Superpower
## motor / generator

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[Image of motor/generator]

*Quelle: Superpower*
motor / generator

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current density:

- superconducting layer  
  > 60,000 A/mm²
- tape  
  > 600 A/mm²
- engineering  
  > 150 A/mm²
motor / generator
motor / generator

trade off:

- critical current
- operating temperature
- availability
- price
- dimensions
- losses
- ...
Why can SC be useful in a motor/generator

- how do motors work
- what are today's limitations for motors
- where can SC be used in a motor

**topologies** and examples

cryogenic aspects
motor topologies

AC – nc asynchronous rotor

nc – rotor sep. excited – sc

all sc motor

nc – PM-Rotor – sc

nc – reluctance rotor – sc

reference motor

... and some more:

homopolar
axial flux
transversal flux
...
reluctance motor

- Diamagnetic rotor
- Passive rotor – no power transmission
- Cold rotor
- Iron in rotor obligatory and close to SC
- Relative low force density
- No limitations in operation
- Complex rotor structure – speed limitations

Force density:
130% compared to nc PM-Motor
excited Synchronous Motor

- Active SC coils in rotor (DC application)
- power transmission (many kA!)
- Cold rotor
- Iron in rotor (partially) useless (>2T?)
- Active influence on excitation
- Complex rotor structure – speed limitations and minimum sizing (-> MW)

Force density:
> 200% compared to nc PM-Motor
**PM motor**

- Active SC coils in stator (AC application)
- Passive rotor system
- Cold stator
- Iron in stator (partially) useless (>2T?)
- Flux control for high speed
- Cryostat for rotating fields

**Force density:**
> 250% compared to nc PM-Motor
fully SC motor (exc. rotor)

- Active SC coils in stator (AC application)
- Active SC coils in rotor (DC application)
- Cold stator and rotor
- Iron in stator and rotor (partially) useless
- Power transmission to rotor (many kA!)
- Active influence on excitation
- Complex rotor structure – speed limitations and minimum sizing (-> MW)

Force density:
> 300% compared to nc PM-Motor
fully SC motor (bulk rotor)

- Active SC coils in stator (AC application)
- Bulk SC in rotor (DC application)
- Cold stator and rotor
- Iron in stator and rotor (partially) useless
- Passive rotor
- Magnetizing device needed
- Flux control for high speed or dynamic adaption of magnetization

Force density:
> 300% compared to nc PM-Motor
Homopolar motor

- Active SC coils in stator (DC application)
- Rotor made of conductive material
- Cold stator
- Iron in stator and rotor (partially) useless
- Power transmission (many kA!) at least one at large diameter !!!
- Easy speed control

Force density:
> 200% compared to nc PM-Motor
Why can SC be useful in a motor/generator
  how do motors work
  what are today's limitations for motors
  where can SC be used in a motor

topologies and examples

cryogenic aspects
# SC motors / generators

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Country</th>
<th>Power / MVA</th>
<th>Speed / rpm</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converteam</td>
<td>UK</td>
<td>1,79</td>
<td>214</td>
<td>hydro generator</td>
</tr>
<tr>
<td>Siemens</td>
<td>Germany</td>
<td>4</td>
<td>120</td>
<td>ship propulsion motor</td>
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<tr>
<td>Converteam</td>
<td>UK</td>
<td>8</td>
<td>12</td>
<td>wind generator</td>
</tr>
<tr>
<td>AMSC</td>
<td>USA</td>
<td>36,5</td>
<td>120</td>
<td>ship propulsion motor</td>
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<tr>
<td>Siemens</td>
<td>Germany</td>
<td>4</td>
<td>3600</td>
<td>industrial generator</td>
</tr>
<tr>
<td>Converteam</td>
<td>UK</td>
<td>0,5</td>
<td>nn</td>
<td>demo generator</td>
</tr>
<tr>
<td>IHI marine</td>
<td>Japan</td>
<td>0,365</td>
<td>200</td>
<td>ship propulsion motor</td>
</tr>
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<td>Doosan, KERI</td>
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<td>5</td>
<td>230</td>
<td>motor</td>
</tr>
<tr>
<td>Oswald</td>
<td>Germany</td>
<td>0,2</td>
<td>650</td>
<td>industrial motor</td>
</tr>
</tbody>
</table>
motor topologies

increase of „B“ by SC-excitation coils in the rotor

\[ M \sim A \cdot B \cdot d^2 \cdot I \]

- „R=0“, only inductance of excitation coil
- feeding of high rotor currents
- flux guidance in yoke and teeth (saturation!)
- mech. power transmission
- ...

M: Torque
A: Amp-windings
B: Flux in Airgap
d: Diameter
I: Length
motor topologies

increase of „B“ by SC-excitation coils in rotor

SC specific features:
- thermal insulation of rotor
- feeding of coolant
- temperature drop > 200K

advantage: DC-application

⇒ no losses in SC
SC – motors:
GE

1970’s - Westinghouse
5 MW, 4.5 K
NbTi Superconductor

1980’s - General Electric
20 MW, 4.5/8 K
NbTi/Nb3Sn Superconductor

1990’s – Westinghouse STC
1 MW, 20 K
BSCCO Superconductor
HTS I:
1999 - 2002
400 kW
1500 rpm
technology demonstrator

HTS II:
2002 - 2007
4 MVA
3600 rpm
high speed longterm operation since 2009

HTS III:
2006 - 2010
4 MW
120 rpm
high torque: 300 kNm

SC – motors: Siemens
SC – motors: Siemens

HTS I:
1999 - 2002
400 kW
1500 rpm

technology demonstrator

Synchronous motor
Bi2223/AG tape
Air gap copper stator

Operating temperature 27K
„plug and play“ Ne cooling system

HTS Motor
SC – motors:
Siemens

HTS I:
1999 - 2002
400 kW
1500 rpm

technology demonstrator

a demonstrator, not a prototype!
HTS I:
1999 - 2002
400 kW
1500 rpm

technology demonstrator

SC – motors: Siemens

- GM cold head RGS120T (Leybold): 40W @ 25K (poss. to be exchanged by pulse tube cooler in the future)
- heat transfer by thermosiphon (with slope)
- working fluid: Ne (operation) or N₂ (cool down)
SC – motors:
Siemens

HTS II:
2002 - 2007
4 MVA
3600 rpm

high speed
longterm operation
since 2009
Siemens 4MW HTS II 2007 at test rig:

- rotor at 25K (fl. Ne)
- motor weight -30%
- coils made of Bi-2223

- first grid synchronization 2009
- efficiency +2%
- losses -50%
- > 5000 hours of operation without degradation of SC
GE Hydrogenie:
2006 - 2013
1,7 MW
214 rpm
HTS-coils on rotor
cooling with He-gas-feedthrough in shaft

SC – motors:
GE
SC – motors: AMSC

AMSC ship propulsion:

36,5 MW
120 rpm
SC – motors: Oswald

SDYN110:
400 kW
77 K, IN₂
reluctance type motor
power density 130%
compared to nc PM-motor
SC – motors: Oswald

Plastic:  
\[ P_o = 229 \text{ kW} \]
\[ P_a = 470 \text{ kVA} \]

Ideal SC:  
\[ P_o = 345 \text{ kW} \]
\[ P_a = 400 \text{ kVA} \]

Real YBCO:  
\[ P_o = 256 \text{ kW} \]
\[ P_a = 420 \text{ kVA} \]
SC – motors: wind power

Superturbine: 10MW offshore by 2020

ecoswing: 3MW onshore retrofit

Quelle: tecnalia
SC – motors: DC-application in rotor

advantage SC motors:

- volume -40…60%
- weight -50…70%
- power density +100…150%
- dynamics +150…200%
- efficiency ...99,9%

Quelle: Siemens

Quelle: AMSC

Quelle: eco5
motor / generator

increase of „A“ by SC-field coils in the stator

SC specific features:
- cooling in the not moving parts
- AC-application of SC:
  many constraints!

\[ M \sim A \cdot B \cdot d^2 \cdot I \]

- M: Torque
- A: Amp-windings
- B: Flux in Airgap
- d: Diameter
- I: Length
SC – motors: Oswald

SLIN:
45 kN
77 K, In$_2$
stator coils BSCCO
power density and acceleration: 200%
SC – motors: Oswald

SMFS:
40 kW, 665 rpm, 575 Nm
77 K, IN$_2$
PM-motor with SC stator
power density 200% compared to nc PM-motor
Why can SC be useful in a motor/generator
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topologies and examples
cryogenic aspects
SC losses in AC application

low temperature – SC:

in mixed phase flux lines through SC
with each elementary flux quantum:
\[ \frac{h}{2e} = 2.07 \times 10^{-15} \text{ Tm}^2 \]
**SC losses in AC application**

- Transport current causes Lorentz force on flux lines.
- Drifting movement consumes energy, appearing as el. resistance.
- Defects in crystal lattice can pin flux lines.
- Flux lines are pinned until critical current density, resistance disappears.
SC losses in AC application

losses in single tape can be calculated analytically

good analytical approximation for ideal stack

behavior in coil shape, with ext. fields, alternating current, shielding, ...?
SC losses in AC application

Losses in single tape in selffield can be calculated

Approximation for stack (part of coil in slot):

- Losses due to current transport in selffield:

\[
P_{\text{trans}} = \frac{16\mu_0 j_c^2 w^2 h^2}{\pi} \left[ \left( 1 - \frac{I}{I_c} \right) \ln \left( 1 - \frac{I}{I_c} \right) + \left( 1 + \frac{I}{I_c} \right) \ln \left( 1 + \frac{I}{I_c} \right) - \frac{I^2}{I_c^2} \right]
\]

- Losses due to external magnetic field:

\[
P_{\text{Hyst}} = \frac{2\mu_0 D^2}{\pi wd} \int_0^{H_m} dH_a (H_m - 2H_a) \times \ln \left[ 1 + \frac{\sinh^2(\pi w/D)}{\cosh^2(H_a/H_0)} \right]
\]

Nach Clem et al.

Influence on crit. current

Nach Mawatari et al.
SC losses in AC application
SC losses in AC application

Calculation of magn. Flux within SC
SC losses in AC application

with material data and boundary conditions (ext. field, current, temperature, ...): losses in SC can be estimated.
with material data and boundary conditions (ext. field, current, temperature, ...): losses in SC can be estimated.
SC losses in AC application

calorimetric measurement of SC losses:
- ext. magn. field
- current transport
- self field
- temperature dependence
SC losses in AC application

losses with current transport in Racetrack-coils in selffield: measurement (kalorimetric und elektrical) vs. calculation

Additional losses (quench)
SC losses in AC application

Cooling technology:

- Direct contact / heat conduction
- Cooling with Gas, Liquid, ...
  - heat capacity, evaporation energy, ...
  - closed, open loop, ...
SC losses in AC application

Cooling technology:
- Direct contact / heat conduction
- Cooling with Gas, Liquid, ...
  heat capacity, evaporation energy, ...
  closed, open loop, ...

![Diagram of cooling system with cryocooler, heat exchanger, and superconducting coils]
cooling system of SC in stator

optimal operation point depends on:
- SC material properties
- recooling of losses
- specifications
- size
- ...

Diagram showing a cryocooler, heat exchanger, superconducting coils, and a fan.
cooling system of SC in stator

cryocooler

Quelle: Sumitomo

cooler: input power/cooling power

best value at the moment
assumed value
best value in theory (Carnot)
SC losses in AC application

Quelle: CryoZone
SC losses in AC application
SC losses in AC application

1. Ventilating system
2. Cold head
3. Power terminal (warm)
4. Transfer lines to motor
5. Sensoric terminal (cold)
6. Power terminal (cold)
7. Power transmission (cold-warm)
8. Heat exchanger
SC losses in AC application
operation temperature depends on load:

- losses
- cooling capacity

cooling system of SC in stator
SC – motors: Oswald

Our goal: Turn white fog into black box
SC – motors:
Oswald

power: 40 kW
speed: 665 rpm
torque: 575 Nm
efficiency: 99.6 %
dynamics: >10,000 rpm/s
YBCOocc-tape: 400 m
potential of SC-motors:

- power density > 200%
- dynamics > 300%
- weight/size 40…60%
- efficiency …99.7%
- availability of material

applications:

- mobility (ship, vehicle, plane)
- generators
- industrial drives