10,000+ hours of Operating Experience with HTS Machines
Content

- Overview on Siemens HTS Machines & Focus for today
- The 4 MVA HTS-Generator at a glance
- Setup for the 10.000+ project
- Typical operation
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Wind Power
Offshore DD Wind Turbine HTS Generator

SC Generator Advantages
- Compact: Reduced volume and mass
- Increased efficiency
- Unlimited reactive power (p.f. = 0) available
- Stiffness: Low voltage dip at load changes
- Very low Total Harmonic Distortion (THD)

But: Full advantages only with stator air-gap winding
Amount of Superconductor scales with $2p$ as exponent!

Why Superconductors for Wind?
- Significant volume and mass advantages expected >10MW
- System cost advantage for complete turbine expected because of reduced mass and volume
- Maybe enabling technology because of mass restrictions and logistics
- Market size extremely attractive → High attention in HTS community

Potential enablers
- Hybrid machines without air-gap winding
- Stationary field winding (simple cooling) with inexpensive LTS and rotating armature winding
- Advances in converter and switch gear technologies for very low el. frequencies, enabling air-gap designs
- New superconductors (like $\text{MgB}_2$) or improved price-performance ratio for HTS for high $2p$ air gap designs

Potential enablers addressed by many talks throughout today’s program
Experience & focus for today`s talk

**Development of three machines for industrial applications (BMBF & BMWi)**

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Details</th>
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<tbody>
<tr>
<td>400 kW 4 MVA Generator</td>
<td>Three machines successfully built and tested. Covering spectrum from 2-pole Generator (4 MVA, 3,600 1/min) to high torque VSD (320 kNm, 30…120…190 1/min). Long-term test 4 MVA –Generator for more than 10,000 hours at the Siemens 20 kV industrial grid in Nuremberg; operated as synchronous condenser; test platform for new components. Design and specification aiming towards offshore (shipbuilding) application → harsh environment.</td>
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<tr>
<td>4 MW Motor 320 kNm</td>
<td></td>
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<tr>
<td>Grid experience</td>
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Feasibility proven in a commercially interesting range
Variable Speed Drive, Converter Operation; Generator; Synchronous Condenser
The 4 MVA Generator

2 pole, high speed (3600rpm) machine

Test results

- Losses halved
- Compact & lightweight
- Operation at p.f. = 0 possible
- Low voltage dip at load changes

\[ \eta (\cos \varphi = 0,8) \quad 96,1 \% \quad 98,4 \% \]
\[ \eta (\cos \varphi = 1,0) \quad 97,0 \% \quad 98,7 \% \]
Starting point for the 10.000+ project

Mission goals and framework

Setup

- Synchronous Condenser → No prime mover, fuel cost… but full loads except torque (anyway small, it’s a high speed machine)
- Grid operation at Siemens Nuremberg converter and motor plant
- Power controlled by facilities’ grid operators, not by HTS experts
- 1st goal: Experience long-term interaction and interdependency machine – system – grid on site
- 2nd goal: Platform for testing new components, system control, optimization

→ More than simply operating hours at preferably high MVAr
Implementation (BMWi 03SX253)
Data Acquisition

Impressions from data acquisition (remote access & control possible)

54 parameters recorded
- Speed
- Several temperatures
- Current (Rotor & Stator)
- Voltage
- Vibrations
- Setpoints
- …
A typical day

What was the typical operation of the machine?

Key findings

- Frequency (speed) and voltage fluctuating within grid tolerances
- Execution of grid operator’s demands without problems
- Grid voltage stabilization as required
- Positive impact on “smoothening” of grid voltage though quite often large loads (MVAs) are switched / ramped at the nearby system test center
FAQ, Part I

What if… the cryogenic rotor cooling fails?

**Event & key findings**

- Sudden shutdown of cryocoolers forced by interruption in cooling water supply
- Immediate detection, ramp down sequence of field current after a couple of seconds intended delay (now we are underexcited!)
- Fast disconnection from grid at non-critical field current
- As the grid is the machines’ driver, the rotor decelerates and comes to standstill after ~3 min

**Sequence works well, no problem**

Remark: machine can be operated for minutes w/o cryocooler if required
What about aging of the new technology rotor?

**Process & result**

The experts opinion on aging: Due to low, constant operating temperature **no aging**

After 4000+ operating hours

- Drag rotor, open it and inspect it
- Reassemble rotor
- Repeat all initial lab measurements (zero operating hours)

The expert is not refuted: **nothing has changed** within measurement accuracy

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**V-I-curves**

**After 4000+ hours**

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**Initial measurement**
And robustness?

**Storyline (“test for robustness”)**

$t < t_1$

Weekend, low load to compensate, Grid Control Center (GCC) and Machine System Control (MSC) in automated operation

$t = t_1$

Suddenly, a plain and nice “0A” field current $I_f$ is reported from the rotor (though the current was not changing in reality)

MSC: “$I_f$ zero, below GCCs’ request. Ramp up $I_f$!”
FAQ, Part III (2)

And robustness?

**Storyline (“test for robustness””)**

$t=t_2$

GCC: “Reactive load overcompensated. Reduce $I_f$ to no load excitation!”

MSC: “$I_f$ zero, below request. Ramp up $I_f$!”

$t=t_3$

GCC: “Voltage leaving tolerable region. Reduce $I_f$ to no load voltage excitation! Going to open breakers!”

MSC: “$I_f$ zero, below request. Ramp up $I_f$! …Breakers opening?!?”

The generator brakes on the secondary of the (primary open) transformer within <30s while complex transient events occur.

At that moment, it was at >120% nom. load
Summary

What are the lessons learnt, what are the measures

**Periphery**
- Several challenging events triggered by simple things like door breaker, water supply, UPS etc.

**Rotor and Generator**
- Always served well

**Control**
- At beginning of project, GGC sends MVAr requests to the MSC. MSC executes via control of $I_f$. Background: Lack of experience with HTS field windings. Controlling $I_f$ pretends you are in control of the rotor (HTS) current.
- Testing new components and “optimizing” control $\rightarrow$ increased complexity $\rightarrow$ number of events like “test for robustness” increasing
- Best result (achieved at the project last phase): operate the rotor completely blind (no signals used for control!). Experiencing the rotors’ robustness needed to dare…

Trust, not fear
Thank you for your attention

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