Speedy_HTS – An HTS Rotor for an Uprated Mid-Speed Wind Power Generator

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***Abstract*—This work reports on the status of the project Speedy_HTS, focusing on an HTS rotor in an oil-cooled conventional stator of an existing wind power generator. The HTS rotor replaces a permanent magnet rotor, thereby increasing the machine's power rating, improving the power factor, and facilitating grid integration. The mid-speed, three-stage, integrated planetary gearbox results in a reduced demand and cost of HTS. The cooling concept for the rotor combines a neon thermosiphon and a copper cold bus. The approach for preparing the HTS windings involves vacuum-pressure impregnation of non-insulated turns. The research path is divided into the development of a machine for extensive characterization on a test stand and the basic design of selected technology bricks for a "real product" machine. The electromagnetic design results in a doubling of the power density, roughly. The cooling concept indicates that a single cold head (≈ 130 W cooling power) is sufficient to operate the final machine.**

***Index Terms*—Cryogenic cooling, high-temperature superconductors, non-insulated turns, superconducting coils, wind power generation.**

I. Introduction

The generation of electric energy by wind power is a significant contribution to the decarbonization of the energy system. Using superconducting wires in a quasi-DC environment is an option to reduce the size of the machine for the requested power rating.

Therefore, numerous projects have been conducted and are partly still active to elaborate on the use of superconductivity in wind power generators, a list of instructive selected projects and activities may encompass: "Innwind" [1], "SupraPower" [2], activities by GE [3], [4], "SupraGenSys" [5] and "Speedy_HTS", the project in focus of this work.

In the EU-project "Innwind", among other technologies, replacing the permanent magnet excitation in a direct drive wind power generator by coils based on second generation high-temperature superconducting tapes (2G-HTS) was studied in theory and experiment. In the EU-project "SupraPower" the conductor of choice was MgB_2, and the cooling provided by rotating cold heads was studied. The funded and industrial activities by GE are focusing on using established technology bricks out of healthcare (MRI magnets) as a stationary field winding by low-temperature superconductors (LTS), and transferring the electric power of the rotating armature winding (normal conducting) by means of slip-rings. The German project "SupraGenSys" represents a multi-step approach to design a fully superconducting generator based on 2G-HTS while minimizing the ac-loss in the machine.

In contrast to the above-mentioned endeavors, the German project "Speedy_HTS" develops a mid-speed generator described in the next sections. Due to the low rotational speed and the large size of (even partly of fully superconducting) direct drive wind power generators (see (1)), the amount of required 2G-HTS tape is enormous, which weakens the business case. The basic design equation

$$P \propto n_{rot} \cdot \hat{A}\hat{B} \cos\delta V \tag{1}$$

relating the power P to the rotational speed n_{rot}, the current loading in the stator A and the air gap magnetic field B, the internal power factor $\cos\delta$, and the volume V clearly shows the option to reduce the machines volume by increasing the rotational speed. (This is done in the existing commercial conventional products, e.g., reducing the need of rare earth materials by a factor of > 10 when raising the rotational speed from 15 rpm to 600 rpm). For maintenance reasons, a three-stage gearbox is an established option in commercial products.

II. Motivation for Mid-Speed Wind Power Generators and Approach of "SPEEDY_HTS"

The reference machine for "SPEEDY_HTS" is a conventional commercially available so-called HybridDrive generator by the company Winergy with an integrated 3-stage planetary gearbox– see Fig. 1 and Table I. This machine encompasses a rotor providing the excitation by rare-earth-based permanent

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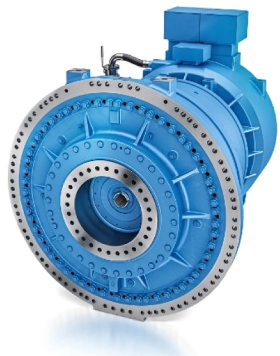

Fig. 1. Conventional hybrid machine HybridDrive (generator with integrated 3-stage planetary gearbox).

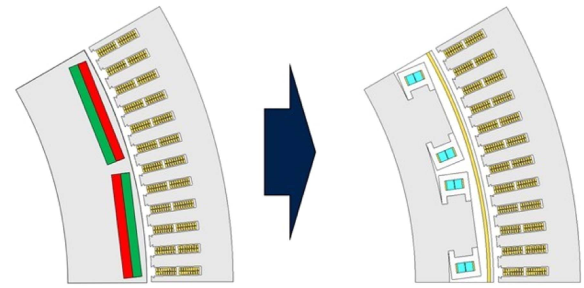

Fig. 2. View of the cross section of one pole pair of the conventional machine (left, with RE-PM) and the 2G-HTS machine (right, with double coils replacing the RE-PM assembly). The stator is unchanged.

TABLE I
DETAILS ON THE MID-SPEED GENERATORS (*: LIMITED BY TEST STAND)

Quantity	**Unit**	**Conventional reference machine**	**SPEEDY_HTS test stand**	**SPEEDY_HTS product**
max. power	MW	6	>4*	13
speed	rpm	600		
Stator voltage rms	V	750 line-to-line		
Stator current density rms	A/mm²	5…20		
Number of poles	n.a.	24		
Magnetic field	T	1.2		
Rotor diameter	mm	1500		
Excitation	n.a.	Fixed	Slip-rings	Wireless
dynamic requirements	%/s	<30		
Mass	kg	9600	Tbd.	10600
Power factor	n.a.	0.8	1.0	1.0
Rare earth permanent magnet mass	kg	250	n.a.	n.a.
2G-HTS amount	km	n.a.	<2.5	<2.5
Efficiency	%	97	tbd.	97%
Number of cold heads	n.a.	n.a.	4	1

magnets (RE-PM), and an inverter-operated stator with a proprietary oil-cooled copper armature winding. The latter increases the current loading capabilities to a great extent. However, the fixed and limited excitation by RE-PM does not fully exploit the potential of the stator. When increasing the current loading A of the stator, the $\cos\varphi$ of the RE-PM machine is decreasing dramatically (to values of 0.5) and thus yielding unsatisfactory low efficiency values. The RE-PM machine is a "rotor-limited machine". Using HTS-excited rotors, the current loading A is increased by a factor of two at $\cos\varphi = 1$ and following (1), the power (density) is increased accordingly (even for the same $B \approx 1.2$ T). This partial HTS machine becomes "stator-limited".

To introduce superconductors into this type of machine, we retain the stator and the magnetic circuit (stator yoke and teeth) completely, and replace the RE-PM rotor with a 2G-HTS rotor.

As the rotational speed is maintained, the projected demand of 2G-HTS is considerably reduced compared to a direct drive generator, and the option to change the excitation offers the possibility to address the full power potential of electric machines with oil-cooled stators. This approach is not the most appropriate one to harvest the full potential of HTS of two to fourfold power increase [6], as the magnetic field is still limited by the use of iron, but it is of low development risk and will allow a direct comparison to the conventional machine/ product.

The project approach to develop this type of machine is split into two research paths: 1) designing, building, and testing a machine suitable to be characterized on a test stand and to build a base for a detailed design of a product later on, and 2) addressing selected technology bricks relevant for the final product.

In research path 1), the basic design of the machine 2) is already addressed, too.

III. DESIGN OF THE 2G-HTS MACHINES

The detailed design of the test stand machine is not yet frozen (some data from suppliers is still missing), so we will report on intermediate results here.

A. Electromagnetic Design

As already pointed out in Section II., the magnetic circuit in the stator is maintained. Therefore, the design of the test stand rotor is similar to the geometry of the conventional rotor – see Fig. 2.

Double coils (racetracks with convex legs) enable the realization of poles in the 2G-HTS rotor without inner joints and are connected in series by resistive copper contacts. To meet the dynamic requirements, a single 12 mm-wide 2G-HTS tape was chosen to maximize operating current and minimize the number of turns (and thus the inductance). The design is neither aggressive in terms of air gap magnetic field (see Fig. 3) nor in harnessing the full potential of partial superconducting machines. Still, it fits the existing conventional oil-cooled stator.

The machine for the test stand will use slip rings to get the excitation current into the rotor for focusing the research work on the machine itself. However, this leads to a considerable ohmic heat load to the cryogenic rotor – see next subsection.

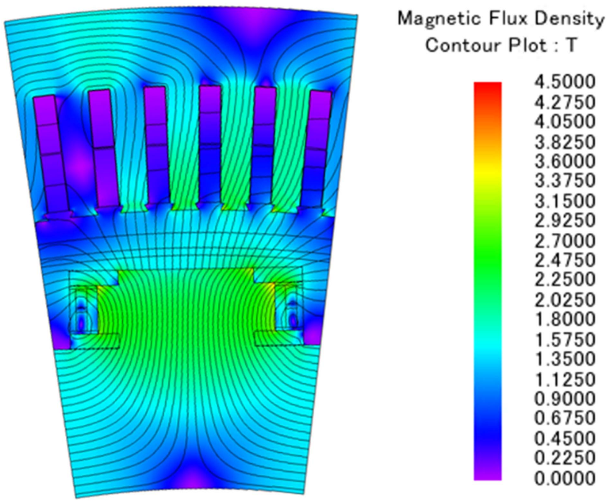

Fig. 3. Flux density profile of one pole across HTS-rotor and stator (13 MW operation) (simulation by FE program JMAG).

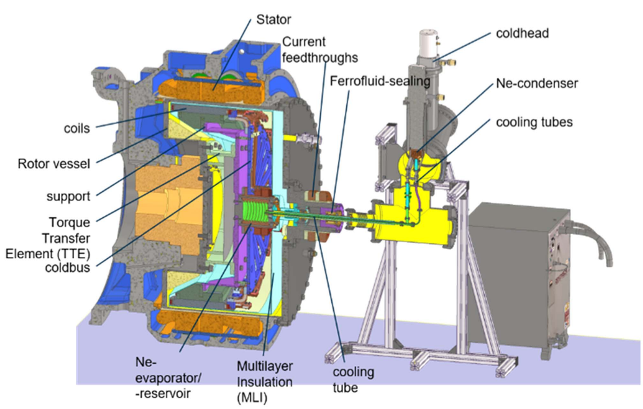

Fig. 4. The general outline for the test stand machine, including the stationary cooling system.

B. Cooling Design

The goal of the cooling approach is twofold: first, it must fulfill the requirements at the test stand (e.g., fast cool-down, extreme operational conditions, safe operation), and second, it must be easily transferable to the "real product" machine. Therefore, we decided to have a stationary cooling system (comprising compressors and a set of cold heads) and a neon thermosiphon with a rotary feedthrough and a cold reservoir inside the rotor – see Fig. 4.

The stationary cooling system ensures easy access, for example, for annual maintenance. The neon reservoir in the rotor provides a thermal anchor (temperature $T \approx 27$ K) at the rotors center as long as the maximum cooling power of the cold heads is not exceeded. The neon condensers are equipped with individual heaters to adapt the net cooling power to the rotor's needs and to ensure constant temperature operation. In combination with a (quite massive) copper cold bus (blue parts of rotor in Fig. 4), only small radial temperature gradients are expected and an operating temperature of $T_{op} = 30$ K is envisaged for the 2G-HTS coils (operating at $\leq 55\%$ of the respective critical current).

TABLE II
Main Maximum Heat Loads on the Cryogenic Rotor of the Test Stand Machine (Total ≈ 260W)

Source	Heat load [W]	Type of load
TTE	25	Steady: heat conduction
Radiant Heat	10	Steady: radiant heat
Current leads	184	Steady: conduction & varying: ohmic, depending on excitation current
Current bus	16	Varying: ohmic, depending on excitation current
Coil contacts (all resistive ones, including pole-to-pole)	22	Varying: ohmic, depending on excitation current
Eddy current loss	<3	Transient: in rotor iron, is mostly reduced by a copper damper shield in the cryostat wall

Numerous heat loads must be considered during the machine's operation – Table II provides a summary.

The torque produced by the gears has to be transferred to the cold rotor. This is done by a torque transfer element (TTE), which is made in the shape of a rim using fiber-reinforced plastics. As the TTE is a compromise between high torque transfer capability and high heat flow resistance, it might be the most critical component in the final product; therefore, the current leads will be replaced in the final product.

The cold rotor of the test stand machine is designed to provide comprehensive data from more than 50 sensors (temperature and voltage). These signals will be transmitted by a wireless data transmission system developed in the framework of the project "Speedy_HTS".

The heat loads in Table II indicate that for the test stand machine four coldheads (each $\approx 130\mathrm{W}_{\mathrm{cold}}$ cooling power) are suitable operating the machine steadily under full load.

C. Prospects on the Product Machine

The product machine shall be operated with one cold head, only. So, considering the maximum heat loads in Table II, this requires the replacement of the current leads by a wireless excitation system (either based on conventional solutions and/or semiconductors [7], an HTS transformer, or an HTS dynamo [8]) – which is out of scope of the present project.

For some nacelle installations of wind power generators, a central feedthrough for the pitch control system of the blades is required – if not feasible, this might turn out to be a showstopper. For this special challenge on a cryogenic rotor with a central cold supply by a neon thermosiphon, a basic solution has been designed. Realization and test may be subject to further research work.

IV. First Results in 2G-HTS Coils

Unfortunately, there was a delay as the preparation of the first coils was postponed to accommodate an unplanned intermediate experiment in the project. However, the first coils have been wound - see Fig. 5.

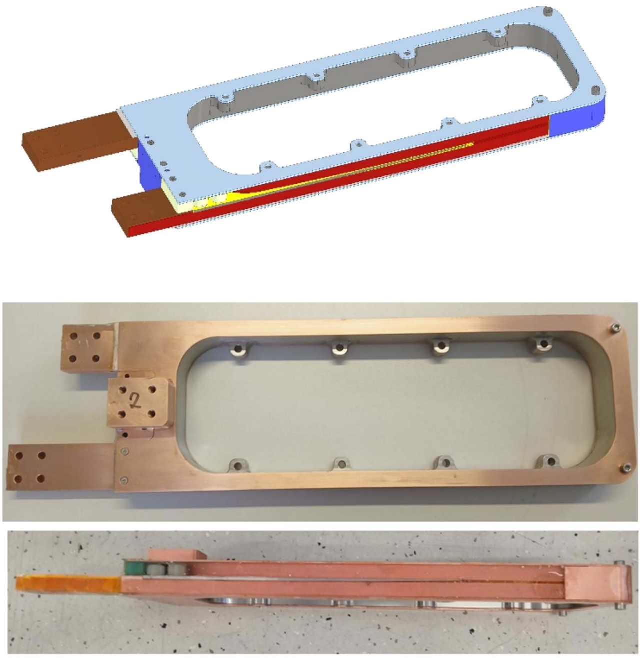

Fig. 5. Full size 2G-HTS double coils. Top: CAD drawings with copper contacts (brown), 2G-HTS (red), thermal connectors (dark blue) and copper cooling plates (light blue). Middle: Bottom-view with electrical and thermal connectors. Bottom: Inclined side view (the inner steel former is visible).

TABLE III
DETAILS OF THE VPI DOUBLE COIL NI-WINDINGS

Quantity	Unit	Value
Number of turns	n.a.	37 (× 2)
Nominal current	A	1000
Nominal temperature	K	30
Axial length of coil	mm	440
Transverse width of coil	mm	146

The double coils are produced according to a novel vacuum-pressure-impregnated (VPI) no-insulation (NI) process. For the details of the coils, refer to Table III.

The goal of the VPI-NI-approach is to ensure mechanical integrity, high thermal conductivity throughout the winding package, and a constant turn-to-turn resistance during operation and lifetime. Previous experiments on this type of coils have revealed successful operation well beyond the critical current (increasing the operational safety margin) and contact area specific turn-to-turn resistivity values of 18 $\mu\Omega/\mathrm{cm}^2$ (using 4 mm-wide 2G-HTS). This resistivity value is well in line (slightly below) the values of other NI-coils without VPI. The use of 12 mm-wide 2G-HTS might lead to a slightly increased value. Due to the quite low number of turns in the coils, it is expected that the time constant of the VPI-NI-coils is compatible to the excitation dynamics (e.g., 10% in 30 s), but has to be confirmed later on.

V. Conclusion and Outlook

In the project "Speedy_HTS" we are close to freezing the detailed rotor design. To double the power density of an existing mid-speed wind power generator, the conventional RE-PM rotor is replaced with a 2G-HTS rotor. The machine exhibits a combination of unique features in superconducting wind power generators, including mid-speed operation, the use of VPI-NI coils, a combination of a stationary cooling system and a neon thermosiphon with an internal copper cold bus, and a high-current-density AC stator based on oil-immersed copper windings.

The mid-speed operation results in a considerably reduced need for 2G-HTS, and, in addition to the uprating and enlarged power diagram, this indicates a sound business case.

For this use case, the following benefits materialize:

- Increased power density compared to conventional RE-PM generators.
- Reduced weight and volume allow for more compact designs or higher efficiency at the same size.
- The power factor 1.0 minimizes dimensioning of cables and size of the converter.
- Innovative grid connection methods, including cost-effective diode rectifiers and direct DC grid coupling.
- Eliminated need for permanent magnets.

The project "Speedy_HTS" will deliver insights by the test-stand machine which will strongly influence the electromagnetic and cryogenic design of a follow-up "real product" machine as well as the excitation technology.

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