Published in *Journal of Physics Conf. Series* (*SuST*) **234**, 032040 (2010)

# Development and construction of an HTS rotor for ship propulsion application

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**Abstract**. A low-speed high-torque HTS machine is being developed at Siemens on the basis of previous steps (400kW demonstrator, 4MVA generator). The goal of the programme is to utilize the characteristic advantages offered by electrical machines with HTS-excited rotor, such as efficiency, compact size, and dynamic performance. To be able to address future markets, requirements from ship classification as well as potential customers have to be met. Electromagnetic design cannot be focused on nominal operation only, but has to deal with failure modes like short circuit too. Utilization of superconductor requires to consider margins taking into account that the windings have to operate reliably not only in "clean" laboratory conditions, but in rough environment with the stator connected to a power converter. Extensive quality control is needed to ensure homogenous performance (current capacity, electrical insulation, dimensions) for the large quantity of HTS (45 km). The next step was to set up and operate a small-scale "industrial" manufacturing process to produce HTS windings in a reproducible way, including tests at operating conditions. A HTS rotor includes many more components compared to a conventional one, so tough geometric tolerances must be met to ensure robust performance of the system. All this gives a challenging task, which will be concluded by cold testing of the rotor in a test facility. Then the rotor will be delivered for assembly to the stator. In following machine tests the performance of the innovative HTS drive system will be demonstrated.

## 1. Introduction

The development efforts at Siemens to utilize the properties of HTS (high temperature superconductors) for efficient and compact electric machines (motors and generators) were performed in steps. At first a model machine was designed, built and tested extensively [1]. Its purpose was to check the basic concepts and to convince ourselves that there are no real roadblocks. The result of successful testing of the 400kW (1500 rpm) model machine in generator and motor configuration (connected to an inverter) was to initiate a 2$^{nd}$ more application-oriented project.

The 4MVA (3600 rpm) HTS generator was intended to demonstrate a potential ship application. It was successfully put into the test field in 2005 and proved the advantages addressable with such HTS machines in a realistic size [2]: better efficiency while requiring a smaller footprint compared to a conventional state-of-the-art machine, and further advantages: very low harmonic content of generated voltage, little structure-borne noise, stability even at small power factor, this allowed to use the machine as a source of reactive power.

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The 3rd step – as presented here – was to design, develop, build, and test a low-speed, high-torque ship propulsion motor, to be driven by a variable frequency inverter.

## 2. Definition of parameters

The concept chosen for the machine (see [3], overview of basic concepts and also competitors' approaches) was the same as in the preceding projects: a radial-flux synchronous machine with HTS field winding, supported by a cold (~30K) magnetic iron core.

The specifications were set with a view to possible market requirements, and after performing a lot of numerical optimizations to determine geometric dimensions, field current, needed HTS quantity, resulting efficiency and losses. The application for ship propulsion needs an extremely robust machine; therefore realistic margins must be included. Ship-specific requirements also have to be met, and a classification company ("Germanischer Lloyd") must be included in the project to prepare future release of a potential product. The main parameters are listed in the following table.

**Table 1.** Main parameters of machine (with focus on HTS rotor)

| | | | |
|---|---|---|---|
| Nom. Power | 4 MW | Superconductor | Bruker HTS (former EHTS) Bi-2223 (type: BHT-RM) |
| Nom. Speed | 120 1/min | Rotor cooling | GM coolers (Cryomech AL 325) |
| Speed Range | 30 – 190 1/min | Excitation | Electronic (brushless) exciter also serving as rotor data transmission |
| Nom. Torque | 320 kNm | | |
| Number of poles | 8 | | |
| Stator | Air-cooled stator with air-core winding (air to water heat exchanger) | | |

## 3. Electromagnetic design process

An iterative process is adopted. At first an analytical design of the machine's geometry is carried out. As second step, numerical analyses follow in order to increase the accuracy of the forecast or to perform detail optimizations. A third stage is system simulation, which treats the complete drive, i.e. the electrical machine, the inverter and possibly more components of the system together. This section focuses on the numerical analysis of the HTS rotor.

### 3.1. Calculation of nominal operation

A starting point is given by magnetostatic 2D-FE calculations using the cross section of the machine. The resulting magnetic flux densities can be used to fine-tune the magnetic circuit (see figure 1).

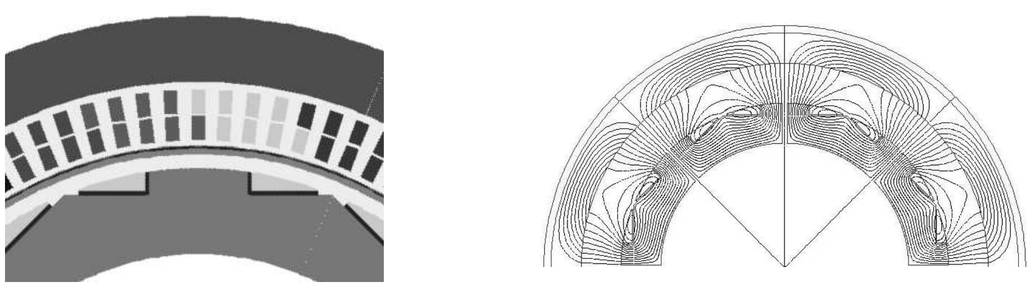


**Figure 1.** left: 2D model section, right: flux line plot for rotor excitation only (right)

For calculation of derived quantities like torque, induced stator voltage (see figure 2) or eddy current losses an effective machine length has to be used. But while for many conventional machines the iron stack length is a reasonable approximation, the configuration of the HTS machine requires the investigation of a 3D model to determine a realistic equivalent length.

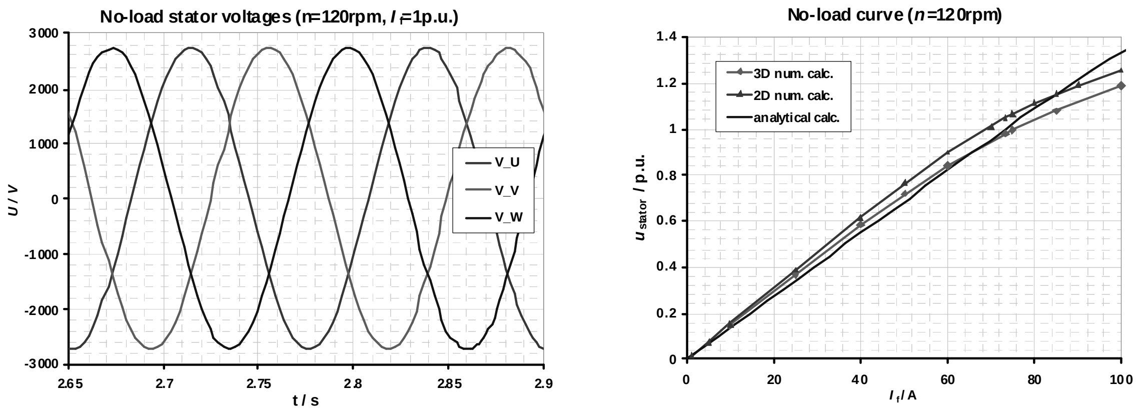



**Figure 2.**
left: back-emf wave form (phase to star point) at rated speed and rotor current (2D calculation),
right: no-load curves (rms value of fundamental harmonic) for different calculation models.

To a first approximation this can be found by integrating the axial distribution of magnetic flux. More precise results can be determined using a 3D model including stator winding geometry. Such 3D static FE calculations were also performed to check the geometry of the rotor iron and coils and especially the critical current capacity of the HTS: the flux density perpendicular to the broad face of the HTS tape is the limiting parameter (see figure 3).

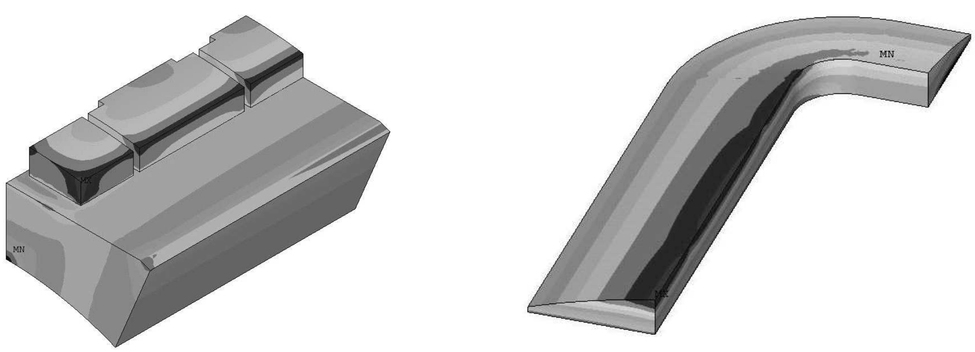


**Figure 3.** results of 3D magnetostatic FE calculation for nominal excitation
left: magnetic flux density, absolute value [T] on surface of rotor iron
right: magnetic flux density [T] orthogonal to HTS tape

3.2. Failure mode analysis

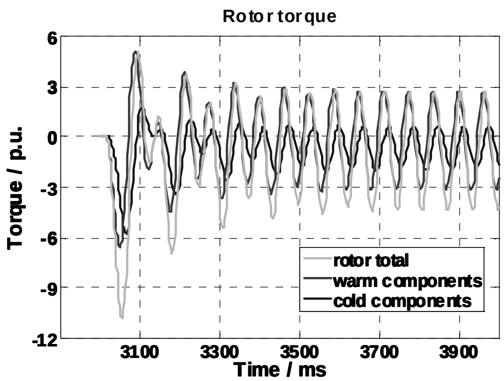
Sudden short circuit incidents generate serious mechanical and thermal loads on machine components like rotor and stator windings, damper, and torque transmission elements, and are critical to be considered in design. The highest torques are found in a 2-phase sudden short circuit.

To analyse the impact of such an event, a multi-domain analysis is required: a transient electromagnetic simulation is performed using the electromagnetic FE model coupled to time-dependent electric components. The induced eddy current distributions generate mechanical force densities, these serve as input loads for a transient structural analysis to determine and assess mechanical loads and displacements.

The simulations show that the HTS machine exhibits only slightly larger loads than in the case of a conventional machine, but the components to carry these loads are quite different:

- the cryogenic rotor structure supported by a torque transmission tube, and
- the room temperature cylindrical hull of the rotor (vacuum cryostat) which was also designed for damping.

One feature of the damping cylinder is to screen the cold mass from harmonics generated in the stator, this requires high conductivity material (e.g. Cu). However, to deal with short circuit loads in a reliable way, it must be strongly reinforced with steel (see chapter 7). This configuration was analyzed and optimized in order to avoid critical stresses. Figure 4 shows some results: transient torque development, and hoop stresses of the damping screen in case of a 2-phase short circuit.



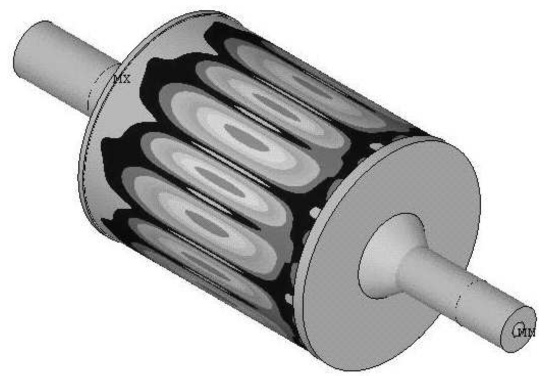




**Figure 4.**
calculation results for 2-phase short circuit
left: transient torque on warm (=damper) and cold rotor structures as function of time
right: hoop stresses of the damping screen at time of maximum

## 4. Superconductor

The rotor coils are wound using Bi-2223 superconducting tape from BHTS (Bruker HTS, Alzenau, Germany). In total ~45 km of conductor is needed, with piece lengths ranging from 300 m to 1250 m. Not only the critical current under operating conditions is important but also width and thickness of the tape must be in a narrow range for successful coil production. The insulation should be as thin as possible to reach a high current density in the winding package, but on the other hand the break through voltage has to be sufficient. The challenge was to ensure that the whole conductor lot meets the specification. Thus an intensive program was set up, together with the manufacturer, to perform measurements on the conductor during the entire production process from bare tape to conductors ready for coil winding. In this section this quality assurance program is described with the focus on the critical current. The most important conductor specifications are listed in Table 4.1.

**Table 4.1** Conductor specifications

| | |
|---|---|
| $I_c$(30 K, 2 T) [A] (field vertical to tape) | ≥ 108 (criterion 1µV/cm) |
| $I_c$(77.35 K, self-field) [A] | ≥ 90 |
| $I_c$(30K, 2T) / $I_c$(77.35K, S-F) | ≥ 1.20 |
| dimensions bare tape [mm] | 0.19…0.24 × 3.80…4.10 |
| dimensions insulated tape [mm] | 0.27…0.32 × 3.92…4.22 |
| Insulation material | PEEK |
| break through voltage [V] | ≥ 600 |

The determination of critical current under operating conditions (30 K, 2 T) can only be done on short samples in a time consuming procedure. Thus an approach was developed to assess the performance along the length of each conductor based on a limited number of 30 K measurements and continuous $I_c$ measurements in liquid nitrogen.

During production the conductor is heat treated in batches of a few billets. From each of these batches, two billets are chosen for 30 K measurement. The critical current at liquid nitrogen temperature is also measured for these samples and the scaling factor, $I_c$(30 K,2 T)/$I_c$(77.35 K,S-F) is calculated. The minimum value of scaling factor for each batch is selected to be used.

In total 31 adjacent short samples of bare tape were measured both at BHTS and Siemens. The average and standard deviation of critical currents and scaling factor are shown in Table 4.2. The mean value is above the minimum required; the scaling factor is slightly below the specification. However, when the standard deviations are considered, it is clear that part of the samples have values below specifications. The standard deviations are comparable and the mean of scaling factor is identical. The standard deviations are larger than the measurement uncertainty (1…2%), they indicate the spread in conductor properties over all the measured samples.

**Table 4.2** Mean value and standard deviation of short sample $I_c$ measurements and scaling factor.

| | $I_c$(77.35 K,S-F) [A] | $I_c$(30 K,2T) [A] | Scaling factor |
|---|---|---|---|
| specification | ≥90 | ≥108 | ≥1.20 |
| Mean value, Siemens | 93.6 | 111.3 | 1.190 |
| Std. deviation, Siemens | 5.5 | 7.1 | 0.04 |
| Mean value, BHTS | 96.0 | 114.1 | 1.190 |
| Std. deviation, BHTS | 5.7 | 7.9 | 0.05 |

With this (conservative) estimate of the scaling factor for a heat treatment batch, the scaled $I_c$(30 K, 2 T) was calculated for each billet in the series using the $I_c$ profile from the continuous measurement in liquid nitrogen. If a scaling factor < 1.20 has to be used, an $I_c$ in liquid nitrogen >90 A is needed to fulfill the $I_c$ spec at operating conditions. From each billet the parts with sufficient performance over the desired length were selected and delivered to Siemens.

In order to check this procedure, samples of the delivered conductor were selected in a receiving inspection and tested at 30 K/ 2 T and 77 K/ self-field. In total 19 samples were measured and met the $I_c$(30 K, 2T) specification of 108 A, taking into account the uncertainty of the experiment. The results of this process assure us that the quality of the total lot of 45km of HTS tape used is sufficient and thus the winding of coils has correct starting conditions.

## 5. HTS coil manufacture

A dedicated coil winding and pole manufacturing facility was set up with the goal to be developed towards an efficient high-quality production, scalable for the future. This included:

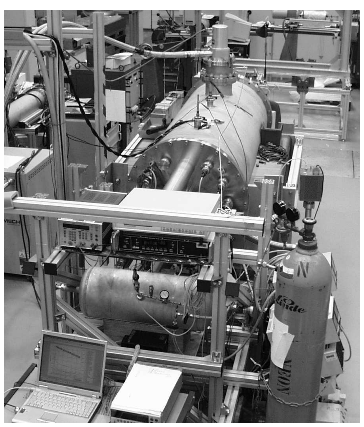
- A tape recorder-like conductor test rig to control HTS geometry (width and thickness as function of length) for pieces up to 1.5km, as well as to allow check of the insulation quality (figure 5)
- A winding machine including a set of toolings for fabricating wet-wound double racetrack coils with continuous control of winding tension and data recording
- Tools for quality control of wound coils, to check geometric dimensions and insulation
- A set-up for precisely stacking coils to create the HTS rotor poles
- A test facility for testing the superconducting performance of stacked rotor coils at operational conditions

**Figure 5.** Conductor test set-up to check HTS width, thickness, and insulation

**6. Cold test of rotor poles**

This task was defined in order to be able to localize degraded HTS coils under operational conditions, in time before rotor assembly, so they could be replaced by additional coils.

The test rig (see figure 6, left) includes a cryostat with a cold iron core, to which the stack of rotor coils is mounted, and a flux return path of laminations outside of the cryostat. The geometry of the iron components is designed to generate a magnetic flux distribution in the region of the HTS coils comparable (deviation within some %) to the operating conditions in the real rotor. Iron core and stacked coils are cooled using a GM cooler.



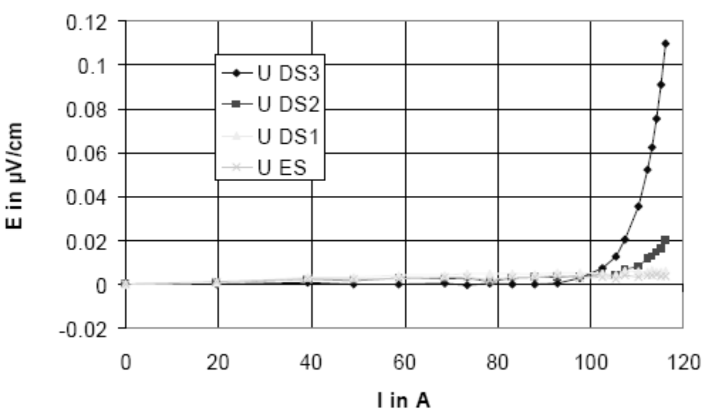



**Figure 6.**
Left: facility for testing HTS rotor pole stacks under operational conditions
Right: electric field (voltage per length) vs. current for rotor pole

The measurements allowed to determine the superconducting performance of the rotor coils under operational field currents and above at different temperatures, and thus to check the superconducting current margin as well as its decrease with slightly elevated temperatures. Figure 6 (right) shows a typical electric field vs. current profile of a rotor pole demonstrating a “pole critical current” of ~115A (with criterion 0.1 µV/cm). After testing all coils and replacing some degraded ones we thus can be sure of the current-carrying capability of the rotor field coils.

**7. Mechanical components**

From mechanical point of view the rotor includes a warm (room temperature and above) and a cold (~25K) part. Each of these in turn consists of several subcomponents. For the warm part these are the two flanged shafts (drive-end DE and non-drive-end NDE side) connected by the damper tube. Together these form the outer surface of the rotor as well as the outer cryostat wall for the insulation vacuum.

The damper is manufactured with a screening copper layer confined by reinforcing steel. The total thickness affects the magnetic air gap, preferably it is as thin as possible. It forms the vacuum barrier and must be designed to be safe against buckling, but it must also be capable to withstand the large stresses in case of a short circuit event. The copper layer is defined by the necessary screening quality. The thickness of the reinforcement is a function of the electromagnetic loads (output of numerical simulations, see chapter 3) and properties of the steel. For that reason we used high strength material.

The cold part inside the rotor consists of the magnetic rotor core, carrying the superconducting coils as well as the cooling bus components. This cold-mass is connected to the flange shafts by two FRP devices. On the NDE side only support against gravity is needed. Thus a comparatively thin-walled FRP tube is chosen, with a sliding fit to compensate for thermal contraction of the cold mass. On the opposite side the mechanical torque (320 kNm) has to be transferred to the warm DE shaft. This task is fulfilled by a FRP torque-transmission tube. This device should be as thin-walled as possible to minimize the heat leak, but on the other hand it has to be strong enough to transfer the oscillatory peak torque acting in case of an electrical short circuit incident.

Cooling of the cold mass is achieved by thermal conduction using a "cooling bus" (central Cu tube) cooled by a Neon thermosiphon as already successfully demonstrated in our two preceding machines. This interfaces to a set of condensers attached to GM cryo-refrigerators (4x Cryomech AL325, with corresponding compressor units, delivering 100W@25K per unit). By absorbing heat from the copper tube the liquid Ne is vaporized, and gaseous Ne transferred to the condensers where it is re-liquefied. The rest of the machine is cooled only by thermal conduction to the heat bus. No coolant neither liquid nor gas is in direct contact to coils or rotor core. (Further details of the cooling system are not part of this paper.)

However a peculiarity of the ship propulsion motor compared to the two previous machines is in the diameter of the cold part. While in case of the smaller machines the cooling tube was shrink-fitted into the iron core, this is no solution for the actual machine. Here the tube has to be held in position by a spoke-wheel-like structure. The cooling path to the coils is formed by Cu plates. Additional Cu bars are used for thermally anchoring the rotor iron to prevent temperature gradients.

**8. Rotor assembly**

The rotor assembly was done twice. In a first "test assembly" all components except the HTS poles were mounted in order to verify that the parts were matching to each other. When assembled, the rotor bearing seats were ground and the structure was fixed using dowel pins in order to be able to reassemble it later accurately. Also vacuum leak tests were performed at this stage.

After this the parts were disassembled again, and the HTS poles were mounted to the rotor iron. Also instrumentation was attached. In total about 130 temperature sensors and voltage taps are installed in the rotor and wired to 8 multi-pin feed-through flanges. In a further step the rotor was bandaged with glass tape and impregnated to fix and protect the HTS coils (see Figure 7).

**Figure 7.**
left: rotor core after bandaging of mounted HTS pole windings
right: rotor core after mounting torque tube and inserting thermal insulation

Then radiation shielding and multilayer insulation were attached. The rotor assembly was concluded again by a vacuum leak test. Finally the brushless exciter unit was mounted to the NDE flange shaft of the rotor, rendering the rotor ready for final cold-testing.

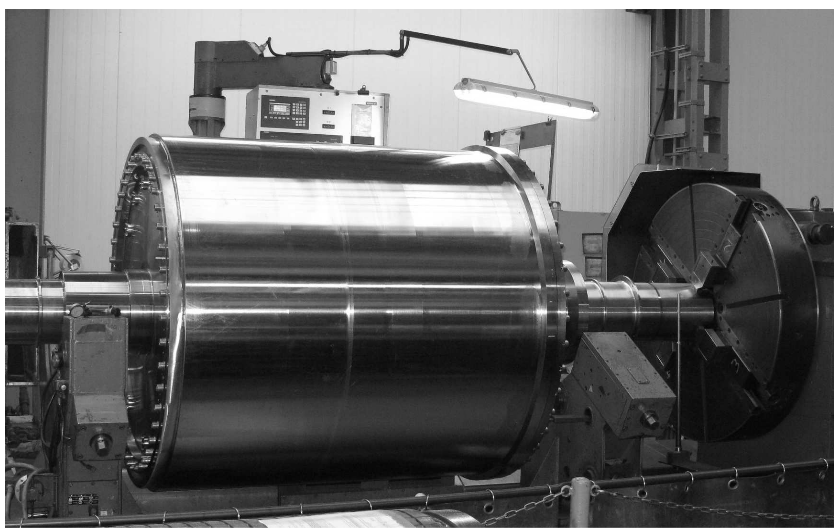


**Figure 8.** HTS rotor after grinding of bearing seats

**9. Next steps**

The very next task will be to connect the cooling system to the HTS rotor, cool it down and energize the coils in an arrangement without stator and outer iron yoke. Although the magnetic configuration is not identical to that in the complete machine, this will provide valuable information:

- Operation of the cooling system
- Cool-down behavior of the rotor
- Superconducting performance of rotor HTS coils,
- Allows to adapt the electronic exciter unit to the reactances of the rotor

After this experimental rotor check the whole machine can be assembled. It will be placed in a test field for commercial drive systems in Berlin. Standard type testing will be done (no-load and short-circuit characteristics), then load tests will be performed connected to the inverter.

These tests shall provide a unique possibility to check and analyze the interaction of the newly designed components in detail, to optimize the performance, but also to demonstrate the capability of this 4MW HTS machine as prospect for future HTS drives.

## 10. Conclusion: discussion of future of HTS machines

After our risk-minimizing, stepwise developmental effort we have arrived at a decisive stage: will HTS excited electrical machines find their way to market - maybe in the field of ship propulsion? It might be helpful to review the progress made in the past years. Explicit listing of the critical items should help to focus the efforts.

Compared to what was commercially available at the onset of our projects 10 years ago Bi-based HTS wire (1G = $1^{st}$ generation) has made tremendous progress. But a new type of HTS conductors (2G) manufactured by economic coating technology is now coming on the market. These are making tremendous progress; however, they still have to achieve the respective long lengths performance homogeneity and insulation quality, to be seen as a technical and cost-effective replacement.

Cryogenic cooling systems (GM refrigerators) have also demonstrated good progress. We now have robust units available commercially for more than 100W @25K. In addition there exists a growing experience in using such systems in long-term tests subject to realistic conditions as a test bed for future industrial application of HTS drives or on a ship.

Another critical step is the development of reliable and robust brushless exciter systems that can deal with the specifics of HTS windings. Also the inverters for driving the HTS motor have to be adapted, as the HTS machine with its air-core stator presents quite different terminal characteristics compared to a conventional machine. Together with the definition of the HTS machine this opens a field for optimization efforts.

But, assuming all these “ingredients” are there: will HTS machines win a competitive position? The key point is how the customers assess the advantages of the innovative technology, in short: compactness, efficiency, stability. But in order to enhance chances to convince potential customers we have to set up “realistic” demonstration projects, like the 4MW machine for which the innovative HTS rotor presented here was successfully manufactured and is now entering the tests.

## Acknowledgments

This work was partly supported by Federal Ministry of Economics and Technology (BMWi), project 03SX221

We would like to express thanks to the technical staff at Siemens CT PS 3, especially Messrs. Otto Batz, Werner Herkert, Heinz Schmidt, Harald Müller, Johann Rothfischer, and also the collegues at Berlin, who invested lots of commitment and all their skills to make it possible to build the challenging designs conceived by us physicists and engineers.

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