Superconductor Science and Technology

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To cite this article: H W Neumüller *et al* 2006 *Supercond. Sci. Technol.* **19** S114

INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. **19** (2006) S114–S117 doi:10.1088/0953-2048/19/3/016

Advances in and prospects for development of high-temperature superconductor rotating machines at Siemens

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Received 17 November 2005
Published 15 February 2006
Online at stacks.iop.org/SUST/19/S114

Abstract
We report on the successful manufacture and testing of the Siemens 400 kVA HTS synchronous motor, which has been in operation for over 3 years, and on the progress of the 4 MVA synchronous motor/generator, which has been manufactured and is now in a phase of extended testing. Furthermore, the benefits of HTS machines will be discussed with emphasis on applications in ships. The development of future marketable products will be strongly dependent on the progress of secondary technologies, such as wire performance and efficient cost-effective refrigerators.

1. Introduction

HTS rotating machines are of great interest at present all over the world. In the past few years a growing number of research programmes aimed at the development of a new generation of motors and generators have been launched. Theses machines cover the range from some kW up to several hundred MW. Also the possible applications cover a wide field ranging from low-speed motors for ship propulsion to 3000/3600 rpm generators as well as fast-running generators for airborne applications.

In this context Siemens has designed, built and tested a 400 kW HTS machine in order to show the feasibility of the corresponding concepts. Based on these results a 4 MVA, 60 Hz machine was designed and built. This machine is currently under test in the Siemens system test facility in Nuremberg. In the following section some general considerations about superconducting machines and their benefits will be outlined. Then the two Siemens machines will be described in some detail in the next sections. After that, some general remarks on possible applications for such machines will be given and some general requirements will be outlined.

2. General advantages

HTS rotating machines have several benefits compared with conventional machines. These will be named and discussed in some detail.

Due to the higher current densities of superconducting windings compared with conventional copper windings superconducting rotors can supply higher B-fields to the stator windings. This in turn results in an increased power density of the HTS machine compared with the conventional one. Therefore for a given amount of output power a superconducting machine can have a smaller volume. Due to its smaller size a superconducting machine can also be of lighter weight.

Additionally, due to the higher flux density produced by the rotor no iron teeth must be used in the stator winding. These would give rise to large eddy currents and hysteretic losses and therefore have to be omitted. This results in a so-called air-core stator winding which has no iron teeth but a non-magnetic, non-conducting support structure. Due to this feature additional weight can be saved. So superconducting machines will have lower specific weight compared with conventional machines.

Table 1. Technical data for the 400 kW Siemens model machine.

Nominal torque	2600 N m
Rated speed	1500 rpm
Nominal power	400 kW
Power overload capability	150%/15 min
Torque overload capability	700%
Rated voltage	3–50 Hz AC 400 V
Synchronous reactance	0.15
Rotor cooling power	~25 W at 25 K

The efficiency achieved was 96.8% including the cryogenic refrigerator, compared with 95.7% for a conventional machine (state of the art)

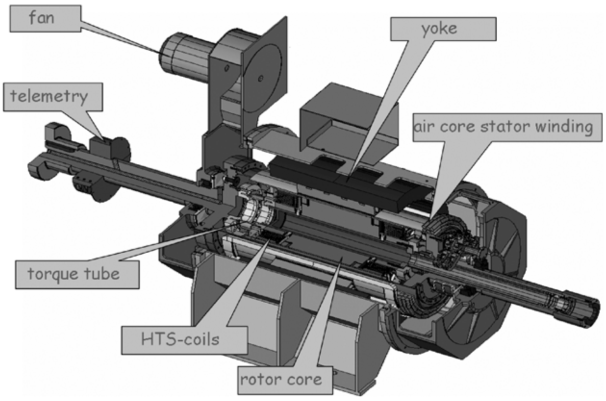

Figure 1. Schematic drawing of the essential components of the 400 kW model machine.

Figure 2. Photograph showing the 400 kW HTS machine in the test bed. The cooling-system with the cryocooler is located on the left side. The motor itself is mounted in a normal welded housing from a synchronous generator with a shaft height of 355 mm.

Stator losses originate from ohmic losses of the air-core stator winding and eddy currents in the stator winding itself, plus the losses produced in the iron yoke. Since the superconducting rotor has negligible ohmic losses, only heat leaks and losses due to operating conditions have to be covered by the rotor cooling system. Even taking into account the performance of the cryocooler (refrigerator), as a net result the losses of a superconducting machine can be considerably lower than those of conventional machines and so superconducting machines provide a higher efficiency.

Besides these obvious advantages superconducting machines exhibit a rather small synchronous reactance. This feature has several outcomes. First, such machines operate at small load angles which in turn results in a very large overload capacity. For example, our 400 kW machine has a synchronous reactance of only 0.15 p.u. (per unit) resulting in a load angle of 8° and an overload capacity of about 700% compared with ~30–40% for a conventional machine. Another manifestation of the small synchronous reactance is a very stiff electrical behaviour. In the case of our 400 kW machine switching on or off of the nominal load in generator mode results in a voltage change of only ~3% with fixed excitation. Conventional machines exhibit voltage changes of 20% and more under the same conditions. The small synchronous reactance in turn causes a large short circuit current in the case of a fault and so easily allows the detection and selective switch-off of faulty sections of the grid. Furthermore, the small synchronous reactance allows such machines to operate stably anywhere in the real/reactive power diagram. This leads to the concept of HTS machines that are designed solely to supply reactive power as in the case of the synchronous condenser delivered by the American Superconductor Corporation to TVA [1].

Last but not least, such synchronous rotating machines exhibit a considerably lower level of noise and vibration than conventional machines. The voltage generated is more perfectly sinusoidal and has a lower harmonic content.

3. The Siemens 400 kW model machine

Starting in 1999 a superconducting synchronous four-pole machine was designed and built at Siemens. Some characteristic technical data for this machine are given in table 1.

This machine was not intended to be a prototype but to be a development carrier to show the feasibility of all the components that had to be designed. Starting with the rotating cryostat ranging over the torque transmission tubes and ending with the racetrack HTS coils these components cover all the major parts of the machine. Additionally a reliable thermosyphon-based cooling system was designed.

Figure 1 shows a CAD sketch of the machine and its main components whereas figure 2 shows the real machine in the test bed. The cooling system is described in detail elsewhere [2].

Figure 3 shows the no-load and short circuit characteristics of the machine and in figure 4 the stiffness of the generated voltage during load switching is presented. During a test and demonstration phase of more than 3 years this machine has proven the feasibility of the new techniques and the reliability of the new components.

4. The Siemens 4 MVA machine

After successful demonstration of the 400 kW machine a machine ten times more powerful was tackled. The machine was completed in June 2005 and the first preliminary results will be given in the following paragraphs.

This machine was designed to be close to a possible application onboard a marine vessel and therefore the rules of a ship classification company (Germanischer Lloyd) were implemented. Table 2 gives the main data for the machine.

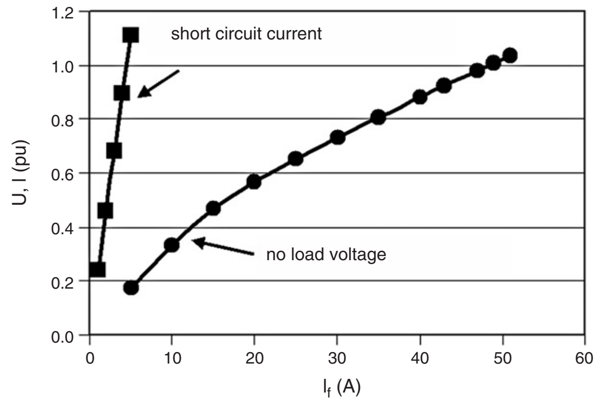

Figure 3. No-load and short circuit characteristic of the 400 kW HTS machine.

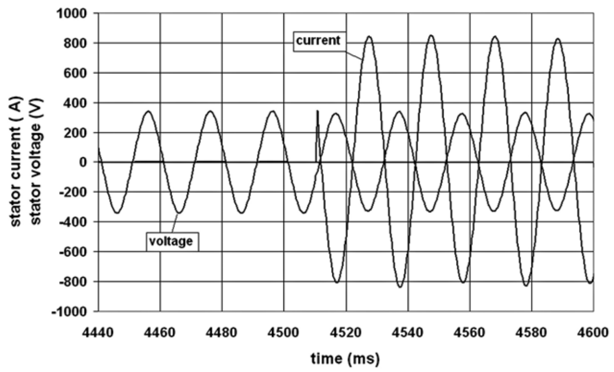

Figure 4. Plot of stator voltage and current for a single phase during switching of a resistive load 0–380 kW.

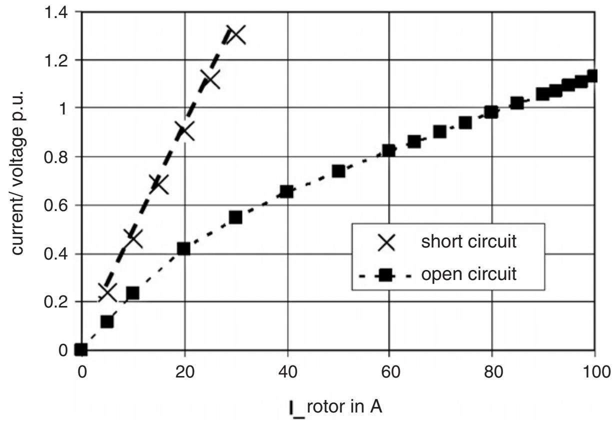

Figure 5. No-load and short circuit characteristic of the 4 MVA HTS machine.

Table 2. Design parameters for the 4 MVA Siemens machine.

Nominal torque	10.6 kN m
Rated speed	3600 rpm
Nominal power	4 MVA
Rated voltage	3–60 Hz AC 6.6 kV
Rated current	350 A
Degree of protection	IP 44
Bearings	Sleeve bearings
Rules	Germanischer Lloyd
The total dimensions of the machine carried out (including cryo-cooler) are	
$L \times W \times H$	3.7 m × 2.5 m × 1.8 m
Shaft height	500 mm
Foot print $L \times W$	1.9 m × 1.2 m
Total weight	6.9 t

Based on the proven design from the 400 kW machine for the racetrack coils the rotor coils of the 4 MVA machine were wound from Bi-2223 HTS tape procured from European Advanced Superconductors GmbH & Co KG (EAS).

The stator consists of a copper Litz wire winding with a class F (155 °C) electrical insulation and a fibre-reinforced plastic support structure. It is split into two halves in order to enable either 6.6 kV operation on the grid or 3.3 kV operation with an inverter. The stator is monitored by means of about 30 thermocouples. Under full load operation the hot spot temperature was proven not to exceed 150 °C in accordance with previously performed computational fluid dynamics calculations.

Figure 5 shows the short circuit and open circuit characteristics for the 4 MVA machine. From this data a synchronous reactance of 0.4–0.5 p.u. can be derived. The efficiency of the machine was measured too. A value of 98.7% was obtained, which is about 2% higher than for a conventional state-of-the-art machine.

The cooling system is based on the successful thermosyphon design from the 400 kW machine. The system consists of three Leybold RGS120T GM cryocoolers and the corresponding compressors. They are coupled via a manifold for the liquid neon in such a way that each cold-head can be exchanged without affecting the operation of the whole system. First results indicate that during steady-state operation one cold-head might be sufficient. However, for faulty situations more cooling power would be needed and therefore a second cold-head might be necessary. In order to implement redundancy a third cold-head was included to the system. Also during cool-down additional cooling power as supplied by the second and third cold-head is useful. Simultaneous operation of all three cold-heads enables cool-down from room temperature to operating temperature within 72 h, which is slightly faster than the value given by computational predictions.

5. Remarks on applications for superconducting machines

As outlined above superconducting machines show advantageous properties that make them superior to conventional ones. In this section possible fields of application for such machines will be outlined.

Generally each situation where one of the properties of a superconducting machine is beneficial gives a possible field of application. Here we want to focus especially on onboard (marine vessels) or offshore applications: since HTS rotating machines provide an increased power density they can save space, which is of general importance in such applications.

For the purposes of ship propulsion such machines can also be used in pods where they offer an improved hydraulic efficiency due to their smaller size, in addition to their increased electrical efficiency. Since a pod is mounted axially far away from the centre of mass of the ship, the light-weight HTS machines are better suited for this application than their conventional counterparts.

The electrical properties of HTS generators make them interesting for the electric power supply on a ship. Their enhanced stiffness (voltage stability) and the possible supply of reactive power are essential benefits in such an island grid.

Another option is to combine an HTS generator with a gas turbine and mount them in a standard container to form a 'power block'. These blocks can be placed onboard a freight vessel according to the needs of the actual freight. It is no longer necessary to implement the maximum power supply ever needed onboard the vessel, but to use such power blocks in a modular way.

The combination of a high-tech gas turbine and a superconducting generator has a weight which can be eight to ten times less than a conventional generator driven via gear box by a conventional diesel motor. This gives more degrees of freedom to the ship designer for where to put the power supply. Of course, such compact power units will also find good applications in fixed installations.

The increased efficiency reduces storage space for fuel. Together with reduced size of the machine itself, this offers more space to the ship owner for the payload. Another kind of value-added effect is the reduction of pollution due to increased efficiency, which not only provides ecological advantages but may also offer economic benefits to the owner due to reduced greenhouse emissions.

In order to make all these points effective there are some requirements that have to be met. First of all the performance of HTS wires has to be increased further. It is also necessary that reliable cooling units suitable for onboard applications with long maintenance times are developed. When these requirements are met, within 5–10 years a complete new generation of all-electric ships will govern the seas.

Acknowledgments

The authors wish to thank the Bundesministerium für Forschung und Technologie (BMBF) for financial support under contracts 13N7621/8 and 03SX143. Also the help and continued effort of all colleagues encountered in the projects is gratefully acknowledged.

References

[1] Kalsi S S, Madura D and Ingram M 2005 Superconductor synchronous condenser for reactive power support in an electric grid *IEEE Trans. Appl. Supercond.* **15** (2)

[2] Frank M, Frauenhofer J, Gromoll B, van Haßelt P, Nick W, Nerowski G, Neumüller H-W, Häfner H-U and Thummes G 2004 Thermosyphon cooling system for the SIEMENS 400 kW HTS synchronous machine *CEC/ICMC 2003: Cryogenic Engineering Conf. (Anchorage, Alaska, Sept. 2003)*; *Adv. Cryog. Eng.* A **49** 859–66