Superconducting Rotating Machines

T A Coombs
27/09/2019
Outline

• Ancient History
• Recent History
• Future ?
Industrial promise of the ‘super-motor’

The world’s largest superconducting motor—a 3250 horsepower dc machine—has just completed its test programme driving a water pump at Fawley power station. The lessons learned are helping to provide new propulsion systems for the navy and ac generating sets in the 2000 megawatt class.

Anthony Appleton is head of the electrical engineering department at International Research and Development at Newcastle upon Tyne. The success of this contract, for the Ministry of Defence (Navy), led the National Research Development Corporation to back further work to construct and test a full scale prototype machine. The objective in this case was to build a motor of sufficiently large rating to bring out the major development problems, and to test it in an industrial environment. The suggested rating was about 5000 hp at a few hundred rpm. Given the ability to pass heavy electrical currents through superconducting coils, the design engineer will then be able to take advantage of the zero power loss and be free of the limited fields achievable with conventional iron magnets.

After examination of a number of possible alternatives, the most convenient application for the big motor was found to be at Fawley power station near Southampton. This station has four 500 megawatt turbine-generator sets served by four large cooling water pumps, each with a rating of 3250 hp at 260 rpm. With the close co-operation and assistance of the Central Electricity Generating Board it was arranged that the superconducting motor would be installed to drive one of these pumps for a limited period before the station became fully operational. The design of the motor subsequently began in May 1967 and the working tests were completed in the IRD laboratories by the end of 1969. The motor is a homopolar machine with a superconducting field winding which provides nearly three million ampere turns to give a maximum flux density of 3-7 Tesla. The winding is maintained at the very low temperature of 4-4K by means of liquid helium supplied by a closed cycle refrigerator. The armature of the machine is at ambient temperature and is segmented Faraday disc. An idealised diagram of the motor is shown left (Figure 2) and the principle of operation is demonstrated in the diagram over page (Figure 3).

The Fawley motor was first operated in...
Figure 6. The 2.4 MW, 200 rev/min superconducting d.c. Fawley motor with the 37 kW model motor in the foreground.

Figure 7. Superconducting d.c. generator field coils being fitted into coil support structure.
CONCLUSIONS

1. The industrial application of superconductivity in the United Kingdom will be realized in the near future with the superconducting dc motors and generator developed at I.D.
2. The continuing development towards practical superconducting ac transmission cables is assisted through the large team engaged on this work at C.E.R.L.
3. Further work on superconducting transformers at any significant level is unlikely in the foreseeable future.
4. The development of superconducting ac generators is expected to increase, although the many formidable problems which must be overcome will necessitate a very substantial financial investment.
5. The development of superconductors will continue, but as far as rotating machines are concerned, the order of priority is lower costs, improved techniques for fabricating windings, and improved performance.
6. Improvements are required in the operating field, particularly in the size and efficiency of the refrigeration components and in the cost of the refrigeration plant.

ACKNOWLEDGMENTS

The author acknowledges discussions on superconducting cables with Dr. N. Ono, Dr. Rayns, and Mr. MacPherson of C.E.R.L., and with Mr. Edwards of R.R.C., and discussions on the engineering aspects with Mr. Ransford of I.D.

The author thanks the Ministry of Defence (U.K.), the National Research Development Corp., and the International Research and Development Co. for permission to present this paper.

REFERENCES


DISCUSSION

Question: By P. H. Morton, Imperial Metals Industries: Would you comment on the merits and future potential of superconductor? Will they be used generally or only in particular applications, and so on?

Answer: By the author. The introduction of superconductors has led to marked improvements in superconductors because it materials and systems are designed with a much lower operating temperature, it is no longer considered that the mechanical issues issues. However, as far as rotating electrical machines are concerned, there are more significant benefits to be derived from the use of the inherently stable superconductors. Since the superconductors do not require intimate contact between the turns and the superconductor, an even smaller amount of loading can be employed and the manufacturing problems are simplified.

7. There is no longer any doubt that superconductors will be employed increasingly in electrical power plants, and we may look forward hopefully to the not-too-distant future when every large rotating machine, ac or dc, will be superconducting.
1. **Electrical propulsion gives better control.**
Conventional DC machines cannot be manufactured in the ratings required.

2. **Gas turbine may be located away from propeller shaft to effect improvement in layout.** The problem which is solved is the space taken by large air inlet and exhaust ducts to gas turbines.

3. **One turbine can drive both propellers during cruising to improve running costs and life of turbines.** It also allows easier maintenance.

**Fig. 5. Advantages of superconducting propulsion systems.**
A. D. APPLETON

growth of conventional generators

possible breakeven position on capital cost between conventional and superconducting machinery

1000 MW significantly lower than conventional generators.

3. On reasonable estimates they appear to be more efficient than conventional generators.

Of course, there is the overriding requirement that, on reasonable engineering judgement, the development problems of the superconducting generators are not insuperable; it is the consensus of informed opinion that this is the case.
Drax 660 MW-300 tonne
https://www.drax.com/technology/refurbishing-300-tonne-generator-core-within-heart-power-station/
Early motors – Tended to Be Homopolar
36.5 MW HTS Propulsion Motor Development
ONR Program

- **Objective**: Develop a Full Scale, High Power Density, Lightweight, Advanced 36.5 MW Propulsion Motor and Drive System compatible with naval applications
- Contract Awarded to AMSC February 2003
- **Design Drivers**: Low Weight, High Power Density, Improved Efficiency and Low Noise
- Detail Design Completed October 2004 – Design meets MIL-S-901D Shock and DD(X) Acoustics
- Factory Acceptance Testing (Marine Systems) completed in 4th Quarter 2006

Design leverages features successfully tested on 5 MW HTS motor
36.5 MW HTS Propulsion Motor Development
Summary and Power Density Comparison

- HTS Motors are multi-phase synchronous machines with active field control, large airgap, and the flexibility to utilize a variety of drives.
- HTS wire used in the actively cooled rotor is presently 1G; starting migration to 2G wire
- The 36.5 MW motor is based on experience from multiple HTS electric machines.
- The ONR 5 MW motor provided the basis for the components used in the 36.5 MW motor.
- The program is on track to deliver a high power density 75 metric ton motor to the Navy in September of this year.
- The rotor has been tested and the stator assembly is almost complete.
- No load testing at the NGC Philadelphia facility this summer.
- HTS is also applicable to generators.

*HTS motors offer the next generation in power density for naval propulsion*
Recent History – Focus Shifts to Synchronous Generators
GE proposed this machine which uses LTS.
Optimization parameters
- Width of the coil
- Height of the coil
- End radius of the coil
- Operating current in the coil
- Short sample percentage for coils
- Current sharing temperature for the conductor

A sufficient margin is required for the stable operation of the coils. Current sharing temperature depends on the maximum field in the coil, critical current at maximum field, ratio of operating current to critical current at maximum field and ratio of maximum field in the coil to critical field of the conductor.
Technology Readiness Level Analysis

**Technology Readiness Levels for Key Generator Components**
*(Project Phase 1 and predicted Phase 2)*

<table>
<thead>
<tr>
<th>Sub-System</th>
<th>PHASE 1</th>
<th>PHASE 2 projected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armature</td>
<td>10 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Superconducting Field</td>
<td>28 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Cryogenic Cooling</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Mechanical</td>
<td>43%</td>
<td>28 %</td>
</tr>
</tbody>
</table>
Various Recent Projects – variety of conductors used.
Dates to Around 2010 and uses BSCCO as this was the most mature conductor of the time.

Hydrogenie, First Superconductor Hydro Generator

- Partners: Converteam, E.On
  - Technology platform
  - 1789 kVA, 1700 kW, 5250 V, 28 poles, 0.95 pf, 214 rpm
- The generator tested successfully and exceeded expectations
  - Tested to 2500 kVA under nominal and under short-circuit load.
Clive Lewis in his book identifies a clear motivation
Horizontal shaft machine driven by a Francis double turbine with integral thrust bearing. Back-of-core diameter = 3m. Axial length = 1m.
Innwind Picks up on the need for direct drive but MgB2 has now taken over as the conductor of choice
Direct drive trains

Pseudo direct drive (Magnomatics)

INNWIND LEAFLET  www.innwind.eu
Suprapower SUPerconducting, Reliable, lightweight, And more POWERful offshore wind turbine – 10MW Mgb2 -
Another Paper study again using MgB2

**Basic Design Windspeed - Rotor**

- Various rotor designs were constructed in Windspeed (see report for details)
- Rotor option 5a (cold rotor yoke) is shown here
- Vacuum enclosure, thermal shield and MLI are omitted for clarity
MgB2 Wires – Critical Currents

- Engineering current densities improve over time
- Actual current densities are high enough for DD wind generators
- Higher current densities lead to more compact & lighter generator design, with lower first costs
EcoSwing

(Re)BCO has arrived!
Fig. 1: EcoSwing generator (right) next to the original permanent magnet generator (left) in a CAD generated image. Note the considerably smaller diameter of the EcoSwing.
Fig. 3: First power production from EcoSwing on December 6, 2018 at 14:00. The plot shows from the top: wind speed, rotor speed, pitch angle of the blade, measured power to the grid.
10 Mvar HTS synchronous condenser (2018-2021) Funded by China Southern Power Grid

Designed by Tsinghua University

Phase 1 (2018-2019): 300 kvar prototype
Under construction

- 10 Mvar, 1500 rpm
- REBCO rotor magnets
- Gap field > 1.4 T
- Non-ferro teeth
- Cooled by 20 K gas helium

Cryogenic rotary joint

HTS rotor magnet for test

HTS rotor coils
Focus Swings to Motors – Driven by initiatives such as Flightpath 2050

EADS E-Thrust
Focus Swings to Motors – Driven by initiatives such as Flightpath 2050
Rolls-Royce Turbo-Electric Distributed Propulsion (TeDP) System Architecture Concept.
A: Launchpoint Hallbach array motor
B: Masson et al. aerospace HTS machines
C: Westinghouse LTS generator (1977)
D: AMSC 36.5 MW HTS marine motor

Data supplied and presented at EUCAS 2015 by F. Berg of Airbus Group
Summary of recent large superconducting motors
Cryocooler power density (1 - 5 kg/kW)

Machine power density (kW/kg)

Tank gravimetric efficiency (50% - 90%)

Machine inefficiency

0.2 %  0.1 %  0.07 %  0.05 %  0.03 %

Courtesy: F. Berg - EADS
Early mock-up of a Superconducting motor using bulk YBCO
The PSAM – all HTS motor
ASuMED - Advanced Superconducting Motor Experimental Demonstrator

• ASuMED is building the first fully superconducting motor prototype tests evaluate the technology’s benefits and allow its integration into designs for future aircraft.

• Target 1MW machine having specific power density of 20kW/kg
Sutor – Precursor to ASumed
Schematic diagram of the prototype super motor/generator (SUTOR) which is a synchronous four-pole machine and is topologically the same as Asumed
Purpose

• Demonstrate benefits of a new fully superconducting motor with a power density of 20kW/kg. In particular:
  • design an appropriate motor topology
  • develop a high-temperature superconducting (HTS) stator with an electric loading of $>450\text{kA/m}$
  • develop a rotor using HTS stacks operating like permanent magnets providing an average magnetic loading of $>2.5\ T$
  • integrate a magnetization system into the stator area
  • implement a highly efficient cryostat for motor combined with integrated cryogenic cooling system and associated power converter

• Demonstrate above technologies in a prototype with approximately 1 MW power at 10,000rpm and a thermal loss $<0.1\%$

• Design innovative modular inverter topology with enhanced failure protection, to realize highly dynamic and robust control of superconducting machines.
A trapped field of 17.7 T in a stack of high temperature superconducting tape
Anup Patel\textsuperscript{1}, Algirdas Baskys\textsuperscript{1}, Tom Mitchell-Williams\textsuperscript{1}, Aoife McCaul\textsuperscript{1}, William Coniglio\textsuperscript{2}, Jens Hänisch\textsuperscript{3}, Mayraluna Lao\textsuperscript{3} and Bartek A Glowacki\textsuperscript{1,4}
Non-linear eddy currents and AC loss

more than 1000 tapes
Machine Efficiency

- Highest power Densities only achievable with all superconducting machine ... Stator will see alternating field and current
- AC conditions lead to loss in superconductors

Mitigations
- Flux Divertors
- Roebel Cables
- CORC
- Striation

- 600 μm stripe / 200 μm trench (5 stripes)

Striation of Superpower’s tape led to 5x reduction on loss
Roebel Cables

Image Courtesy of: The Robinson Institute Wellington University
Conductor on Round Core (CORC®) cable

- Graphic image courtesy of Advanced Conductor Technologies
Narrower tapes decrease AC loss.

4 mm tape width

2 mm tape width

Narrower tapes with the same $J_c$ are very interesting!
## Superconducting machines: stator

<table>
<thead>
<tr>
<th></th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2.67 MW</td>
<td>2.67 MW</td>
<td>2.67 MW</td>
</tr>
<tr>
<td>Operational temperature</td>
<td>25/65 K</td>
<td>25/65 K</td>
<td>25/65 K</td>
</tr>
<tr>
<td>Stator HTS width</td>
<td>1 mm</td>
<td>0.5 mm</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>AC loss of stator @50Hz</td>
<td>107 kW</td>
<td>29.9 kW</td>
<td>13.1 kW</td>
</tr>
<tr>
<td>Stator efficiency</td>
<td>95.9%</td>
<td>98.8%</td>
<td>99.5%</td>
</tr>
</tbody>
</table>

Narrow multi-filament HTS cables are essential for fully HTS machine applications.

- Soldering stack of narrow HTS strip *
- Diffusion stack of HTS (SuNam)
- Striated HTS without copper/Ag coupling
- Bi2212
Superconducting machines: cooling

<table>
<thead>
<tr>
<th></th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator HTS width</td>
<td>1 mm</td>
<td>0.5 mm</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>AC loss of stator</td>
<td>107 kW</td>
<td>29.9 kW</td>
<td>13.1 kW</td>
</tr>
<tr>
<td>Stator efficiency</td>
<td>95.9%</td>
<td>98.8 %</td>
<td>99.5%</td>
</tr>
<tr>
<td>Machine efficiency @ 100 kW cooling station</td>
<td>59.9%</td>
<td>88.8%</td>
<td>95%</td>
</tr>
</tbody>
</table>

Conclusion:

1. A 2.67 MW fully HTS propulsion machine was designed as a baseline case.
2. The upper limit of this machine is 54 kW/kg using current 2G HTS technology.
3. HTS multi-filament cables <= 0.5 mm are essential for stator winding to maximum machine efficiency.
4. Active magnetic shielding will help to improve power density.
Summary

Early Seventies optimism dampened by failure to realise ever larger generators removing original driver for innovation

Development of Generators mirrors the development of conductors

EcoSwing is a significant step forward and indicates that the technology is essentially mature

All superconducting machines need to be developed if the next big market (air travel) is to be realised. This is leading to developments in the conductor geometry rather than the material itself in an effort to bring AC losses down to an acceptable value