High Temperature Superconducting Rotating Electrical Machines: An Overview (Highlights)

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March 2023 (HP152). Superconductors have a promising potential to be used in electrical machines to reduce the machines' mass, volume, and improve their efficiency. Whilst low temperature superconducting (LTS) materials have been used in various superconducting machine projects in 1960s-1980s, high temperature superconducting (HTS) materials have received sustained interest throughout the 21st century after their discovery in the 1980s. While the dominant machine design has been the synchronous machine, in the last decade, superconductors have also been applied to the designs of many other types of electrical machines – particularly those that allow superconducting windings to remain stationary. Furthermore, there have been successful, major EU projects recently that have seen prototypes of HTS machines at the MW-level for wind turbine generator [1] and aircraft propulsion [2] applications. Thus, with the aim of providing a timely overview of the field of superconducting machines, we have recently published a review article in *Energy Reports* (available at https://www.sciencedirect.com/science/article/pii/S2352484722025628), and here we highlight the areas covered.

In terms of some background, HTS materials of practical use in machines are Bi2233 and REBCO. In addition, MgB_2, which has a relatively high critical temperature of 39 K, is also used, but less often. The most promising applications in which HTS machines can be used effectively are those where low mass/volume offer significant advantages, such as aircraft propulsion (where weight is critical), ship propulsion (where small pods can reduce hydraulic drag) and wind turbine generators (where lowering the mass can reduce the complexity and cost of tower support). However, HTS machines have also been applied to utility generators, industrial motors, and electric vehicles.

Over 100 rotating superconducting machines that have been prototyped in the 21st century are tabulated in the article and summarized in Fig. 1; some significant projects are described in more detail.

A classification of superconducting machines is also given based on the form of superconductors found in the machines: wires/tapes, bulks and/or stacked tapes.

Amongst machines that use superconducting wires/tapes, synchronous machines are the most popular. Partially superconducting machines have either the field winding or the armature as superconducting, so it is possible to avoid transfer of cryogenic fluid across a rotary joint; and fully superconducting machines have both field and armature windings as superconducting, and achieve higher power density at the expense of the armature generating an ac loss, which is loss in the superconductors when subject to external time-varying magnetic field and/or transporting time-varying current.

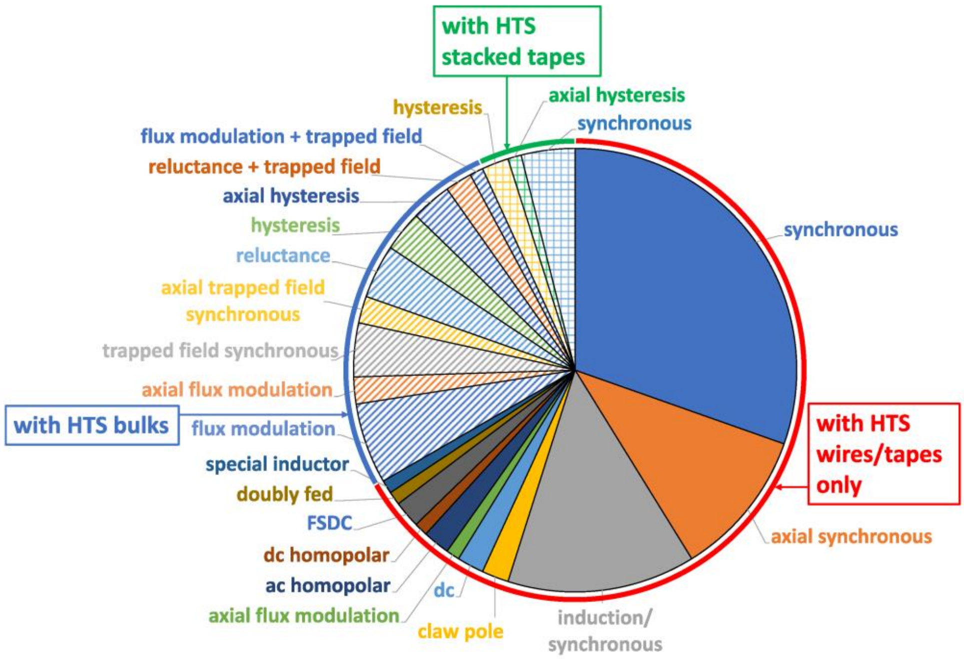

Fig. 1. Summary of the 102 superconducting machine prototypes surveyed in the review article. Figure taken from the article.

However, other machine types have also been proposed and built. Induction motors with their squirrel cage replaced by superconductors were found to have a synchronous mode due to the zero dc resistance of superconductors [3]. Claw pole machines work like synchronous machines but use rotating magnetic claws to direct flux generated by stationary superconducting windings to appropriate positions along the air gap. DC homopolar machines also have stationary superconducting windings to generate a stationary magnetic field, and a large dc current travels perpendicularly to the field in a copper disk. AC homopolar machines feature a stationary superconducting winding, which generates flux that is directed to desired locations in the air gap by a robust rotor made of iron with offset poles. Flux switching dc machines also have all windings on the stator, but the recent trend is to separate the armature and field windings onto two stators to reduce harmonics seen by the dc field winding to reduce ac loss.

Amongst machines that use superconducting bulks or stacked tapes, the synchronous machine is again a popular type, which makes use of the bulks'/tapes' ability to trap flux and act as permanent magnet analogues, so-called trapped field magnets. In contrast, flux modulation machines make use of the bulks' shielding property to achieve a variation of magnetic field in the air gap within an otherwise uniform field generated by the field coil. Reluctance machines make use of the bulks' shielding property to achieve a variation of reluctance along difference axes of the rotor. Finally, hysteresis machines rely on the flux pinning property of the bulks and the torque generated is proportional to the area of the hysteresis loop (references in [4] [5]). Although no prototypes have been built, some designs have also used superconducting bulks in vernier machines and magnetic gears, either as trapped field magnets or to shield magnetic flux.

Finally, in terms of outstanding challenges and trends in machine designs, fully superconducting machines are gaining significant interest – if the ac loss can be constrained to an acceptable level – but the desire to have no moving cryogenic superconducting windings has influenced recent designs. In terms of excitation methods, flux pumps have been designed and implemented to remove the need to connect current leads to rotating superconducting coils; for bulks, the in-situ magnetization of bulks and the retention of magnetic flux during machine operation continue to be studied. Overall, we anticipate superconducting machines can be a solution when lightweight, low-volume machines are required, and search for methods to reduce ac loss, e.g., flux diverters, novel wire architectures and winding designs, as well as further development of numerical modeling techniques, will thrive.

References

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The review article, High temperature superconducting rotating machines: An overview, is available open access in the latest issue of *Energy Reports*:
https://www.sciencedirect.com/science/article/pii/S2352484722025628