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High temperature superconducting rotating electrical machines: an overview

Calvin C. T. Chow\textsuperscript{a}, Mark D. Ainslie\textsuperscript{b}, K. T. Chau\textsuperscript{a} *

\textsuperscript{a} Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong SAR, China
\textsuperscript{b} Department of Engineering, King’s College London, London WC2R 2LS, U.K.

Abstract
Superconducting rotating machines are more efficient, smaller and lighter than conventional ones. Thus, they can reduce energy consumption and can be an enabling technology in applications that require light-weight machines. Using high temperature superconducting (HTS) materials in machines simplifies cooling designs compared to using low temperature superconductors. This review presents a summary of all major HTS machines worldwide built and tested in the 21\textsuperscript{st} century, covering several different types of machines, e.g., synchronous, induction, dc homopolar, ac homopolar, reluctance, hysteresis and flux modulation machines. Classification of the machines is also described based on the form of superconductor used: wires/tapes, bulks and stacked tapes. The working principles of the more unusual HTS machine types are qualitatively explained, such as machines with claw poles, dc and ac homopolar machines, magnetic gears, vernier permanent magnet machines and flux switching dc machines. Finally, the targeted, practical applications of HTS machines are explored and the significant trends and challenges in HTS machine design in recent years – and in the future – are described.

Highlights
- Summarises all major HTS machine prototypes of the 21\textsuperscript{st} century
- Reviews HTS machines that use HTS wires/tapes, bulks and/or stacked tapes
- Reviews the main applications of HTS machines
- Reviews all major HTS topologies and explains unconventional topologies
- Summarises future trends and challenges in superconducting machine design

Keywords
High temperature superconductivity, HTS machines, electric machines, transport electrification, wind turbine generator

Abbreviations
\begin{tabular}{|l|l|}
\hline
ac & alternating current \\
AMSC & American Superconductor \\
Bi-2223 & Bi\textsubscript{2}Sr\textsubscript{2}CaCu\textsubscript{2}O\textsubscript{x} \\
BSCCO & bismuth strontium calcium copper oxide \\
dc & direct current \\
EM & electromagnetic \\
ENEA & European Nuclear Energy Agency \\
EV & electric vehicle \\
FSPM & flux switching permanent magnet \\
FSDC & flux switching direct current \\
GE & General Electric \\
HTS & high temperature superconducting \\
IMD & internal Mg diffusion \\
\hline
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* Corresponding author.
Email addresses of authors: ctcchow@eee.hku.hk, mark.ainslie@kcl.ac.uk, ktchau@eee.hku.hk.
Introduction

Electric motors and the systems they drive account for more than 40% of global electricity consumption [1]. The desire for electrification of transport to meet environmental targets presents a huge, additional demand for both electricity and electrical machines (generators and motors). An increase in distributed electricity generation, e.g., by wind turbines and other renewable sources, and a shift towards microgrids and local power balance also require more locally-installed, electrical machines. Superconducting machines promise higher efficiency, smaller mass and smaller size compared to conventional machines by exploiting the ability of superconductors to carry large current with little or no resistance when cooled below a certain critical temperature $T_c$. Machines using low temperature superconducting (LTS) materials were investigated intensely from the 1960s-1990s, and the discovery of high temperature superconducting (HTS) materials late in the 1980s led to significant renewed interest, since cooling HTS materials is easier and, in some cases, does not require helium, whose supply has been volatile, and HTS materials offer significant performance advantages.

There have been many good overview papers written on superconducting machines, but they are limited to specific geographical areas, applications, or types of machines. For example, Kalsi et al. [2] published a review in 2004 that covered synchronous machines according to the companies that made them, and bridged the gap between LTS and HTS machines by covering both as the world transitioned from the former to the latter. Barnes et al. [3] published a review in 2005 that provided a chronological account of LTS and HTS synchronous generators starting from 1960s. Qu et al. [4] reviewed superconducting synchronous generator topologies for wind turbines. Tsukamoto [5] covered various Japanese HTS machines for various applications, including ship propulsion, wind turbines and electric vehicles (EVs). Kirtley et al. [6] covered superconducting and non-superconducting machine types for ship propulsion. Yanamoto et al. [7] covered the development of superconducting machines for ship propulsion by three main groups in Japan. Biasion et al. [8] introduced the main superconductors for electrical machines and covered superconducting synchronous, dc, and induction machines. Haran et al. [9] collected articles that covered different applications and topologies of superconducting machines, and their cooling and structural aspects; a list of superconducting machine prototypes that used superconducting wires up to 2013 was presented. Review papers covering bulk superconductor machines are fewer, but [10] reviewed the different topologies that used bulk superconductors.

The aims of this paper are to provide a timely update on the above reviews, and to provide a unified and broad coverage of HTS machines developed around the world, across a comprehensive variety of machine types, different forms of superconductors (wires/tapes, bulks and stacks of tapes) and applications. We explain how different topologies are useful for different applications, while
acknowledging that the same aims and trade-offs may be encountered in different applications, e.g., both ship propulsion and wind turbine generators require low-speed, high-torque machines. In addition, this paper provides unique features: a comprehensive list of HTS superconducting machines, including those using HTS bulks and stacked tapes, developed since 2000 (an expanded version of the one given in our previous conference paper [11]), and a classification of HTS machines based first on types of superconductors (wires/tapes, bulks and stacked tapes) and then on operating principle (synchronous, induction, dc machines and so on).

The paper is organised as follows. Section 2 gives an overview of the basics of superconductor properties relevant to electrical machines. Section 3 introduces the use of superconductors in machines for different applications. Section 4 classifies HTS machines, and describes the different types of machines that exploit HTS materials in the form of HTS wires/tapes only. Section 5 described the different types of machines that exploit HTS bulks or stacked tapes. Section 6 provides a future outlook and outstanding challenges. A summary of all major HTS prototypes manufactured since the year 2000 is provided in Appendix A.

2 Background of superconducting materials

2.1 The phenomenon of superconductivity

Superconductivity is characterised by zero resistance (but up to a limited dc current only) and perfect diamagnetism, i.e., complete expulsion of magnetic field from the superconductor’s interior, an effect known as the Meissner effect [12]. A superconductor is in its superconducting state if it is below a critical surface defined by three parameters: temperature, external magnetic field, and current density. The critical temperature \(T_c\) is the temperature below which a superconductor enters its superconducting state. The critical field \(H_c\) and critical current density \(J_c\) are the magnetic field strength and current density limits, respectively, below which the superconductor is in the superconducting state.

There are two types of superconductors. Type I superconductors exhibit both zero resistance and perfect diamagnetism when they are below their critical field, \(H_c\). However, type I superconductors tend to have low critical fields and low critical temperatures and thus are not of much practical use [13]. Type II superconductors have two critical fields: a lower critical field, \(H_{c1}\), and an upper critical field, \(H_{c2}\). Below \(H_{c1}\), both zero resistance and perfect diamagnetism are observed. Between \(H_{c1}\) and \(H_{c2}\), zero resistance is observed but magnetic flux penetrates the material in the form of quantised vortices, resulting in partial diamagnetism [14]. Above \(H_{c2}\), the material is in its normal state and no longer superconducting. Since \(H_{c2}\) can be high (can exceed 100 T), type II superconductors can carry large current even under significant magnetic fields and thus are of interest for rotating machines, and indeed many other applications that rely on high magnetic fields. In type II superconductors, as current through a sample increases and approaches the critical current density \(J_c\), a resistance begins to appear, and the criterion for defining \(J_c\) is an electric field strength \(E = 1 \mu \text{V/cm}\) (or a resistivity \(\rho\) of \(10^{-11} \text{\Omega m}\)) (see p.18 of [15]).

Superconductors generate a so-called ‘ac loss’ when experiencing an ac magnetic field or when carrying ac current. Both the superconducting and the non-superconducting parts of the tape/wire can contribute to these losses [16]. The loss the superconductors generate is a hysteretic loss and the origin can be traced back to how vortices move in type II superconductors under the influence of ac magnetic field or current.

2.2 Practical superconducting materials for machines & their important properties

There are three type II superconductors that are commonly found in modern superconducting machine designs, as detailed in Table 1.

The first class of material is bismuth strontium calcium copper oxide (or BSCCO for short), also known as first generation (1G) HTS. Both Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_x\) (Bi-2212) and Bi\(_2\)Sr\(_2\)Ca\(_2\)Cu\(_3\)O\(_x\) (Bi-2223) went into industrial production, but the former could only operate effectively at lower temperatures (<
20 K) and did not find any commercial applications [17]. However, there is ongoing research to improve the $J_c$ of round Bi-2122 wires for use in future high-field accelerator magnets and other applications [18, 19]. Bi-2223 has a critical temperature of around 110 K and can carry large currents, even at 30-50 K [17], but most machine designs have used 20-35 K as the operating temperature [3]. Bi-2223 is usually produced via the powder-in-tube (PIT) technique, during which the constituent powders are placed in Ag or Ag-alloy tubes, which are in turn bundled into a larger metallic tube [15]. The composite wire is then drawn, rolled and heat-treated (see p. 218 of [15], for example). Only tapes, and not (round) wires, are manufactured because Bi-2223 only has large critical current if the Bi-2223 grains are aligned appropriately, and alignment is achieved via mechanical deformation during rolling and heat treatment [17].

A second class of material, called second generation (2G) HTS, is the rare-earth barium copper oxides (or REBCO for short), where the rare-earth (RE) element is usually Y (i.e., YBCO) and Gd (i.e., GdBBO). YBCO has a critical temperature of around 90 K. A biaxial texture is needed to attain a large current density [17] and this is achieved by depositing REBCO on a biaxial substrate (see p. 221 of [15], for example). Therefore, commercial REBCO tapes are available in the form of coated conductors, in which REBCO only occupies a thin layer of about 1 μm in a tape that is made up of many layers, including a substrate (e.g., Hastelloy or stainless steel) that can be up to 100 μm thick, a silver protective layer, and typically copper as the top and bottom layers [17], [15]. The cross-section of a typical REBCO tape is shown in Figure 1. These additional layers provide protective benefits in terms of mechanical strength and thermal stability. The critical current is highly anisotropic and varies widely with respect to the direction of the applied magnetic field to the tape: it is greatest when the magnetic field is parallel to the wide face of the tape [17]. Compared to Bi-2223, REBCO coated conductors have larger critical stress and strain [17].

The third class is MgB$_2$, whose superconducting property was discovered in 2001 [20]. It has a critical temperature of 39 K [21] and is typically operated at 20-30 K in a machine design [3]. MgB$_2$ cannot be drawn into wires like copper due to its brittle mechanical properties so MgB$_2$ wires/tapes are produced by PIT or internal Mg diffusion (IMD) methods. For ex-situ PIT (used by Columbus), Mg and B powders are reacted, and the MgB$_2$ powder is put into Nb tubes, which are then put into a larger Monel or Ni tube [21]. For in-situ PIT (used by Hypertech), Mg and B powders are reacted in the Nb tube [21]. For IMD, a pure Mg rod is inserted into a Ta or Nb tube with B powders, and the tubes are placed into a Cu-Ni tube; then during heat treatment, Mg diffuses into B and form MgB$_2$ layers on the inner wall of the Ta tube [21].

Though not classified as an HTS material, MgB$_2$ behaves like a type II superconductor and can be used as a low cost and lightweight alternative to HTS, despite having poorer superconducting
performance [21]. A 10 MW superconducting design study [22] compared a rotor field winding made of REBCO and MgB₂, both operating at 20-30 K. It found that the former was lighter (54.6 t vs 59.1 t), more efficient (92% vs 85%), and required a shorter wire length (640 km vs 1500 km), since REBCO is able to carry higher current and generate a higher airgap field. A similar study [23] for a 4 MW generator found that the mass of the YBCO version was lighter (50.0 t vs 75.6 t), but the MgB₂ design actually required a shorter wire length. In terms of ac loss in a machine environment, [24] and [25] showed that the loss was much higher with YBCO than MgB₂.

<table>
<thead>
<tr>
<th>Table 1 Properties of MgB₂, BSCCO and REBCO</th>
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<tbody>
<tr>
<td>Commercial suppliers [17, 26]</td>
</tr>
<tr>
<td>Typical operating temperature [3] [K]</td>
</tr>
<tr>
<td>Critical temperature, $T_c$ (p.20 [15]) [K]</td>
</tr>
<tr>
<td>Dimensions for tape: width x thickness [mm]</td>
</tr>
<tr>
<td>Diameter for wire [mm]</td>
</tr>
<tr>
<td>Max. piece length [km]</td>
</tr>
<tr>
<td>Critical current, $I_c$ @ 20 K, (for tape) [A]</td>
</tr>
<tr>
<td>Engineering critical current density, $J_c$ @ 20 K (for wire) [A/mm²]</td>
</tr>
<tr>
<td>$I_c$ @ 77 K self-field (for tape) [A]</td>
</tr>
<tr>
<td>Critical tensile strength [MPa]</td>
</tr>
<tr>
<td>Critical tensile strain [%]</td>
</tr>
<tr>
<td>Critical bending / double bend diameter [mm]</td>
</tr>
<tr>
<td>Cost [$/kA-m]</td>
</tr>
</tbody>
</table>

n/a = (data) not available, AMSC = American Superconductors, SCSC = Shanghai Creative Superconductor Technologies, STI = Superconducting Technology Inc., SST = Shanghai Superconducting Technology, WST = Western Superconducting Technologies, [27] refers to p.15-18 [27].

2.3 Forms of superconductors

Superconducting materials appear in three typical forms in machines: wire/tape, bulks, and stacked tapes. Superconducting wires/tapes of different materials have been introduced above in Section 2.2. Using superconductors in the form of wire/tape offers flexibility in coil shape and size.

Superconducting materials in bulk form can trap large magnetic fields and function as permanent magnet (PM) analogues, as so-called ‘trapped field magnets,’ in electrical machines. Bulk HTS materials offer the advantage of not needing a continual current source, provided via current leads, like for HTS wire-wound coils. Furthermore, they can generate higher magnetic flux densities than can be produced by coils for the same volume. For example, to generate a 1.5 T magnetic field, a double pancake coil of diameter 160 mm at 30 K would be needed, compared to a GdB₇C₈ single-grain bulk of 30 mm at liquid nitrogen temperature (77 K) [10]. A record of 17.6 T at 26 K was trapped in a GdB₇C₈ bulk disc pair 25 mm in diameter in [29] and 3 T was trapped at 77 K in a GdB₇C₈ bulk 65 mm in diameter in [30]. However, bulks have limited mechanical strength [31], have size limitations and require magnetization, e.g., using the stator coils of the machine, before using them as PMs (see Section 2.4 for further discussion).
Stacks of HTS tapes, or simply ‘stacked tapes,’ can also trap a magnetic field like bulks and thus can be used as PM analogues [32]. Stacked tapes offer some advantages over bulks in terms of better thermal stability and mechanical strength, due to the presence of the other layers in the HTS tape, e.g., copper, silver and Hastelloy [31]. In addition, stacks can be manufactured to more complicated shapes, e.g., so as to follow the curvature of the rotor [33]. However, they can suffer the problem of demagnetization, like that of bulk HTS and conventional PMs (see Section 2.4). A record of 17.89 T was trapped in a stack of REBCO tape at 6.5 K [34].

For completion, superconducting sheets should also be mentioned, though they appear rarely in the literature. Sheets of BSCCO in an Ag sheath were produced by the All-Russian Scientific Research Institute of Inorganic Materials (VNIINM) and have superconducting properties similar to those of YBCO at 20-40 K [35]. Such sheets have been used to create hysteresis, reluctance and trapped field synchronous machines [35], [36].

2.4 Advantages & disadvantages of superconductors in electrical machines
The use of superconducting materials offers several advantages compared to conventional machines:

- The zero (dc) resistance in the superconducting state results in no ohmic loss when acting as a magnet carrying dc (e.g., as the rotor field winding), thus improving efficiency;
- Whether carrying ac or dc current, superconductors have a much higher current density compared to copper, thus less conductor volume (and mass) is required;
- Since superconductors can generate much larger fields than copper or PMs, iron may not have to be used (or at least reduced) in the machine, reducing the machine mass and eliminating iron losses;
- As PM analogues, bulks and stacked tapes can provide magnetic fields an order of magnitude higher than conventional PMs;
- Friction and windage losses can be reduced due to the smaller machine size [37];
- HTS synchronous machines have been observed to have high efficiency at partial load not observed in copper machines [38], low synchronous reactance [39], and high overload capacity [40].

However, there are also disadvantages with superconductors. Firstly, they experience ac loss when carrying ac current or experiencing time-varying magnetic fields (see Section 2.1). This problem has limited their use in the armature of many machines. Historically, for LTS machines back in the 1960s, it was concluded fairly quickly that LTS conductors subjected to ac currents produced significantly high thermal losses and an unacceptable heat load at the very low cryogenic temperature required (e.g., using liquid helium at 4.2 K). This led to an optimum configuration of LTS machines with an isolated, superconducting rotating dc field winding and a normally-conducting, stationary armature winding, which has continued to influence the design of a typical HTS machine. This complicates the machine design in comparison to conventional machines, but such technical challenges were solved long ago. The cryogenic cooling power required to remove the heat generated is much larger than the raw loss, reducing the overall efficiency of the machine. For example, removing 1 W of heat generated at 77 K requires 12-20 W of cooling power, and 100-200 W at 20 K [41]. Secondly, superconducting wires/tapes also have limited mechanical strength and bending radii, adding an additional constraint with respect to conventional machines. Finally, superconducting wires/tapes can suffer from a quench (a sudden loss of superconductivity due to a thermal disturbance), and this can be a concern for machine reliability and safety.

Using bulks or stacked tapes also present challenges for a superconducting machine design. Firstly, in order to act as PM analogues, they must be magnetised, which requires the application and removal – ideally in-situ – of a large external magnetic field. This has been demonstrated successfully using pulsed field magnetisation via conventional (copper) stator coils [10], which are then used for machine operation, but the trapped magnetic fields using this technique to date have been significantly
lower than the actual material capabilities [42]. There are also concerns with machine operation in terms of a reduced field due to demagnetisation from any time-varying magnetic field or thermal disturbance seen by the bulks, which requires further investigation [42].

3 Superconducting machine applications

Superconducting machines can be used in a variety of applications which require lightweight and compact machines with high power density, particularly where size and weight is a very significant cost driver. The requirements of different applications are presented in Table 2. Having low mass translates to having high (gravimetric) power or torque density, and having low volume translates to having high volumetric power or torque density.

<table>
<thead>
<tr>
<th>Application</th>
<th>Power level (W)</th>
<th>Speed (rpm)</th>
<th>Importance (5 = most important, 1 = least important)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne generator</td>
<td>10M-50M [11]</td>
<td>7k-50k (p.11 [9])</td>
<td>5 2 5 2 5 4</td>
</tr>
<tr>
<td>Ship generator</td>
<td>1M-50M</td>
<td>1.5k-7k</td>
<td>3 4 4 3 4 3</td>
</tr>
<tr>
<td>EV (incl. buses) proliferation</td>
<td>20k-3M</td>
<td>1k-20k</td>
<td>4 5 4 4 4 4</td>
</tr>
<tr>
<td>Wind turbine (offshore)</td>
<td>1M-20M</td>
<td>5-20</td>
<td>3 5 5 4 4 4</td>
</tr>
<tr>
<td>Utility generator</td>
<td>100M-2G</td>
<td>1.5k-3.6k [43]</td>
<td>4 4 5 4 1 1</td>
</tr>
<tr>
<td>Industrial motor</td>
<td>Up to ~100M</td>
<td>Up to ~10k</td>
<td>3 4 4 4 2 2</td>
</tr>
</tbody>
</table>

Table 2 Requirements of different applications.

In aircraft, distributed propulsion with a few central generators driving multiple motors has been proposed to increase propulsion efficiency in comparison to current central propulsion by turbofans [45, 46]. One reason is that the turbines and the fans are now decoupled mechanically, allowing each to run at their most efficient speeds [47]. Distributed propulsion also allows convenient placement of motors at desired locations of the aircraft to realise boundary layer ingestion [48]. The requirements for aircraft superconducting motors and generators are being lightweight and efficient [47, 48]. [48] suggested a target power density of 25 kW/kg. Efficiency is important because the more inefficient a machine is, the larger the cryocooler or volume of cryogenic fluid needed to cool the machines; thus, more fuel/battery capacity is needed for each flight, leading to a heavier system overall. Reliability is also important due to stringent air safety requirements.

Electric ship propulsion brings advantages such as the removal of gear boxes [6], flexibility over steam turbines for ships that require frequent starts-stops (e.g., cruise ships) [6], and reduced fuel consumption [7], because generators can be switched on or off depending on the required propulsive output whilst each generator operates at its most efficient speed [49]. In particular, in podded propulsion system, the electric motors are housed in pods suspended from the ship hulls, and this brings the advantages of high maneuverability [50], elimination of the rudder (since the pods can be rotated) and heavy propeller shafts and gears [51], and opportunity to optimize the hull shape hydro-dynamically without compromises due to propeller position [51] [50]. The requirements for such podded motors include a small volume, in order to reduce hydro-dynamical drag [7].

Though not common, superconducting motors for electric vehicles have been prototyped by Sumitomo and Kyoto University (see Table A1). Sumitomo has installed prototypes in actual vehicles for testing [52, 53]. The advantages of superconducting motors cited in [52] include high efficiency
over a wide torque range, compared to ordinary motors which have poor efficiency when outputting high-torque; and high torque output allowing direct drive and elimination of gears. However, due to the time needed to cool the motors, superconducting motors may be more suitable for vehicles that run for a long time to prevent the need of frequent cool-downs and warm-ups [52]. For high output vehicles, one can look at the Liebherr T284 mining truck, which is equipped with a 3 MW generator-motor drivetrain [54]. However, to compete with conventional machines, superconducting machines must have their costs lowered, and have low volume and mass including the cryogenic system.

Wind turbines require low-speed, high-torque generators. Such generators must be of low mass to reduce the tower mass. The tower cost is the most expensive component in a wind turbine generator system [9]; thus, reducing the mass of the generator can reduce the structural complexity of the tower. Reliability and low maintenance requirements are important in offshore turbines due lowered accessibility. Again, lowering the cost is important in order to allow superconducting generators to replace the current traditional generators.

Superconducting utility generators can bring advantages such as increased efficiency, high efficiency even at partial loads [9], and a small synchronous reactance [9] due to a large magnetic airgap [55]. A small synchronous reactance brings a number of benefits with respect to grid stability, such as ‘stiff’ electrical behaviour, meaning that changes in load results in small changes in voltage [39] [40]; a large overload ability [39]; an ability to be over-excited to provide power factor correction without using capacitors [3]; and an ability to operate anywhere on the real/reactive power diagram [39], allowing for operation as a synchronous condenser to absorb or supply reactive power, which was demonstrated in [56] and used by the Tennessee Valley Authority [57, 58]. General Electric (GE) closed a program [59] to develop a 100 MVA superconducting generator without eventually building the machine. It was pointed out that small generators offered no advantage in the power utility industry since the generator itself occupied a small portion of the overall power plant footprint [59]. The efficiency improvement was not enough to cover the increased cost, e.g., the cost of HTS wire, wire support and cryogenic system [59]. GE believed an HTS utility generator would be economically viable at power levels above 500 MW and when the cost of superconducting wire decreased to $5/kA-m [59].

Industrial motors serve various heavy industries, including oil and gas, petroleum and chemicals, pulp and paper, mining and minerals, and water and wastewater [60]. There were initial attempts by AMSC and Rockwell to develop commercial HTS motors, aiming to achieve 50% reduction in loss compared to conventional induction motors, as well as reduction by 50% in volume and mass [61].

4 Machines with HTS wires/ tapes
A list of major HTS machines that have been manufactured and tested is given in the Appendix in Table A1. A summary by machine type is provided in Figure 2 and the various classifications of superconducting machines are given in Figure 3. The machines are classified according to the form of superconductors used: wires/tapes, bulks and stacked tapes. This classification is employed here because the form of superconductor used has a major impact on the methods used for analysis, numerical simulation, mechanical support, excitation/magnetization method, cooling system, and machine performance parameters, such as power density and AC loss.

From Figure 2, we can see that most machines built with HTS only in the form of wound wires/tapes were either synchronous or induction/synchronous machines. However, there were also prototypes of machine types that allow both armature and field windings to remain stationary, so no cryogenic rotary coupling or slip rings are needed. Such topologies include claw pole, homopolar, flux switching dc (FSDC) and doubly-fed machines. These machines will be explained in this section.

The two other types – dc and flux modulation machines – also allow all-stationary windings. Sumitomo reported two dc superconducting motors for use in EVs in 2008 [52] and 2012 [53],
respectively. A four-pole dc field was provided by stationary Bi-2223 coils and stationary iron claw poles, which directed the flux provided by the field coils to generate a four-pole field in the airgap between the claw poles and the inner rotating armature. IH! reported the world’s first liquid nitrogen-cooled motor in 2005 [51, 62-64]. This was a flux modulation machine with Bi-2223 field coils and a Bi-2223 armature. The motor had two rotors, one armature layer and two field layers [51]. On the rotors, sandwiched between the field and armature layers, was iron that modulated the magnetic field seen by the armature winding as the rotor rotated, so that the armature coils experienced a time-varying flux and a back-emf could be induced.

Figure 2 Summary of the types of superconducting machine prototypes listed in Table A1 (see Appendix A). All types are radial flux unless specified otherwise. A total of 102 prototypes are represented in the chart.

4.1 Synchronous machines
HTS synchronous machines offer a variety of advantages. They have high power density compared to HTS induction machines, since when the latter eventually operates as a synchronous machine (due to
the zero dc-resistance and effective magnetization of the HTS rotor), the rotor excitation field generated by the stator is weaker than the rotor field that can be generated with HTS coils or HTS bulks in an HTS synchronous machine [65]. Compared to many other machines with stationary field windings, synchronous machines can adopt an ironless design, whereas other designs, e.g., machines that rely on the magnetic gearing principle (see Section 4.5), have iron as a necessity; thus synchronous machines can be lighter.

4.1.1 Synchronous machine prototypes

Synchronous machines typically have a single outer stator housing the armature winding and a single inner rotor providing the dc magnetic field. HTS synchronous machines can either be fully or partially superconducting, but the latter are more common, influenced by the lessons learnt from LTS machines (see Section 2.4) and concerns about the losses (and cryogenic heat load) of ac windings. Hence, these partially superconducting HTS synchronous machines generally have an isolated, superconducting rotating dc field winding and a normally-conducting, stationary armature winding.

4.1.1.1 Field-superconducting

In a partially superconducting synchronous machine with HTS rotor field windings (‘field-superconducting’ hereafter), the superconductors experience little ac loss compared to an armature winding, since the field winding carries a dc current and ideally sees a stationary magnetic field as the armature field rotates in synchronism with the rotor. In practice, some ac loss will exist in the field winding due to armature winding harmonics, e.g., due to presence of iron teeth and/or dynamic load conditions.

The field-superconducting synchronous machine can adopt either a radial or axial flux topology. For the radial flux topology, a typical machine cross-section is shown in Figure 4(a). Design decisions that have to be made include whether iron is used: in the rotor core, in stator iron teeth, and whether there will be iron back yoke. Using iron gives magnetic flux paths with lower reluctance and thus the magnetomotive force (mmf) needed to be generated by HTS wires is lower, so less HTS wire material or current is needed. Lowering the current in the HTS also reduces the ac loss. However, using iron limits the airgap flux density, due to the saturation of iron and similar ferromagnetic materials, to around 2 T, and increases the mass of the machine. In addition, using iron in the stator leads to radial attraction between the rotor and stator and thus complicates the coil support structure [66]. A decision also has to be made on whether there will be insulation between HTS wires/tapes in the winding. No-insulation coils can lead to lower transport ac loss [67] and better quench protection [68], but a higher ramping loss [69].

A typical longitudinal structure of a radial flux field-superconducting synchronous machine is shown in Figure 4(b), adapted from [37]. The major components include HTS coils; a support structure to affix the HTS coils to the rotor; an excitation system to supply current from a stationary external power supply to the rotor field winding or to induce current in the field winding using contactless means (e.g., flux pumping [70] to induce a dc current, as implemented in a machine in [71], or harmonic excitation [72]); torque transmission tubes, typically glass fibre reinforced plastic, that minimize heat transfer to the rotor whilst transferring torque to the shaft; an electromagnetic (EM) shield, usually a copper mesh or sheet, to prevent the HTS rotor field winding from experiencing the aforementioned ac disturbances from the stator and minimize ac loss; a vacuum system, which is optional, for enhanced thermal insulation; a cooling system, which typically does not rotate with the rotor, and thus requires a rotary cryogenic coupling to transfer cooling fluid to the rotor. A warm rotor requires a complex support structure to transmit torque between the cold HTS coils and the warm rotor while providing thermal insulation [37]; a warm rotor is typically used for large machines, e.g., wind turbine generators [37].

Many significant projects adopted the radial field-superconducting topology, as follows. The series of three Siemens machines [39, 40, 73-77] (a demonstration machine, a ship generator and a ship motor, respectively) all had Bi-2223 field windings on iron-cored rotors and copper armatures on
nonmagnetic stator cores without iron teeth (but with an outer iron yoke for shielding), and were shown to be more efficient than conventional counterparts [74, 75, 77]. The two AMSC ship motors, rated at 5 MW [78, 79] and 36.5 MW [80] respectively (the latter machine having the highest rated power amongst the prototypes surveyed in Table A1), employed air-cored Bi-2223 rotors, and copper coreless armature windings. There have also been two major EU projects to develop HTS wind turbine generators. **Suprapower** was a €5 million project that designed a 10 MW generator with a copper armature winding on a toothless magnetic stator core and MgB2 wires on a warm iron rotor. A 500 kW prototype was manufactured and tested; the prototype had coils of the same size as those in the 10 MW design, but fewer poles [81]. **EcoSwing** was a €14 million project that saw the world’s first MW-level wind turbine generator successfully installed in a commercial wind turbine [82]. This 3.6 MW machine had GdBCO field coils and a copper armature, and both the rotor and stator had iron cores [83].

Whilst most field-superconducting machines to date have been radial flux, **IHI** [51, 62-64] and **Tokyo University of Marine Science and Technology (TUMSAT)** [84] developed axial flux field-superconducting synchronous machines. For the latter, to reduce the heat transferred to the rotor, GdBCO bulk was used for current leads to supply dc current to the Bi-2223 rotor field winding.

![Typical structure of a radial flux field-superconducting (partially superconducting) synchronous machine with a cold rotor: (a) cross-sectional view (b) longitudinal cross-section view (rotating parts are hatched).](image-url)


4.1.1.2 Armature-superconducting

There are also partially superconducting synchronous machine designs employing an HTS armature winding (‘armature-superconducting’ hereafter). The field winding is then either copper or PMs. These machines typically have a low rotation speed, otherwise the ac loss in the armature would be too high. One exception is [85], which used toroidal cores to eliminate the self-induction created by the armature coils, thereby reducing ac loss due to the self-field. Despite rotating at 3600 rpm, the efficiency (excluding input power to the refrigerator) was 98.3%. Whilst a group at Tsinghua University adopted a radial topology, IHI [86, 87] and the European Nuclear Energy Agency (ENEA) [88] adopted an axial topology.

When designing the stator, decisions to be made include whether there will be teeth, whether there will be back iron and the winding configuration (concentrated or distributed, full pitch or fractional pitch, overlapping or non-overlapping). Magnetic materials placed judiciously around the superconductors in the stator can act as flux diverters to reduce the magnetic field seen by superconductors, and thus reduce ac loss [16, 89-91]. However, simply replacing nonmagnetic teeth with magnetic teeth in the stator actually increases the tangential filed in the slots and increases the ac loss of the superconductors [92]. In addition, magnetic teeth lead to harmonics and so the rotor sees a time-varying magnetic field too; thus, in fully superconducting machines, the teeth can lead to ac loss in the rotor field winding [93].

4.1.1.3 Fully superconducting

Moscow Aviation Institution (MAI) reported a fully superconducting synchronous machine [94] in 2020, and the load test results agreed well with prediction [95]. In 2021, researchers from Kyushu University and other institutions published test results for a 1 kW fully superconducting synchronous motor with REBCO windings on both the stator and rotor [96]. Whilst the ac loss of HTS windings was estimated to be 38 W (excluding refrigeration power needed to remove that loss), the eddy current loss in the nonmagnetic castings was estimated to be 607 W [96].

4.1.2 Selected synchronous machine designs

For aircraft motors, [97] showed that for a 3 MW, 4500 rpm motor, power densities of 10.2 kW/kg and 36.6 kW/kg could be achieved with partially and fully HTS synchronous machines, respectively, by developing analytical models of the machines and then optimizing their designs. Recently, there have been design studies reported for fully superconducting synchronous machines [98] [99] [25, 100]. A schematic of a fully superconducting machine is given in Figure 5, adapted from [98]. [91] investigated the mass and efficiency of various stator designs in a fully superconducting synchronous motor rated at 1 MW, 12000 rpm. Stator designs included 4- and 8-pole variations, air-cored and magnetic core designs, and flux diverters of different thicknesses. A new machine design was added in [101] to compare with the air-cored design; the new design had a magnetic-cored stator sandwiched between two magnetic-cored rotors, and the external rotor eliminated the need for the stator yoke to guide flux. [25, 102, 103] studied the ac loss of HTS armature windings in synchronous machines. A design for NASA’s high-efficiency megawatt motor (HEMM) [104] adopted a partially superconducting synchronous configuration, with a rotating cryocooler integrated in the rotor [105].

For aircraft generator, [106] proposed several 10 MW fully superconducting synchronous generator designs with different rotational speeds, operating temperature and structural materials. The best designs achieved a power density of 25.6 kW/kg with over 99% efficiency. [65] investigated designs of synchronous machines with copper armature for a 10 MW, 7000 rpm generator with a limitation on stray magnetic field. The authors showed that an inner rotor and an outer rotor synchronous machine (both with rotors with Halbach-array HTS bulks trapping 5 T) had active mass power densities of 77.5 kW/kg and 104.6 kW/kg, respectively. An inner rotor synchronous machine with wound HTS coils carrying 300 A mm$^2$ achieved 64.8 kW/kg, and an ensuing detailed design had a power density of 20 kW/kg (including inactive mass). For comparison, a 4 MW, 15000 rpm PM synchronous generator was built in [107] with a power density of 17.3 kW/kg, including passive mass, without the need of superconductors.
Superconducting wind turbine generators designs are periodically reviewed: for example, p.25-26 of [27] in 2018 lists the designs available in the literature and so these are not repeated here. Most of the designs were synchronous machines. Since then, partially superconducting machines have remained popular, with extensive optimisation [108-110]. However, fully superconducting designs are also found in [111, 112].

In order to reduce or eliminate iron yoke to reduce overall mass, active shielding has been suggested by adding superconducting wires at the periphery of the machine to reduce stray field. This was proposed in [113], and applied in an aircraft motor design in [100] and wind turbine generator designs in [108, 111].

**Figure 5** Typical structure of a radial flux fully superconducting synchronous machine: (a) cross-sectional view (b) longitudinal cross-section view (rotating parts are hatched).

4.2 Induction machines

In 2003, researchers at Soonchunhyang University [114, 115] built an induction motor with Bi-2223 tapes as squirrel cage bars and rings on the rotor. It was found that compared to a conventional rotor, the HTS rotor had a larger starting torque, higher efficiency at all loads, and maintained synchronous speeds for higher loads. [115] suggested that at starting, the HTS would quench due to large ac current induced in the rotor by the stator field, and the resultant, large resistance generates a large starting torque; as the rotor speeds up, it was suggested the low resistance of the HTS material, as it returns to its superconducting state, results in high efficiency and very little slip for a wide range of load. Instead
of replacing the rotor bars with HTS materials, researchers at Seikei University [116] added Bi-2223 tapes to the slots cut in aluminium bars. The torque-speed characteristic was slightly different to [114, 115]. The synchronous mode was not observed in [116], but the results suggested the HTS material trapped magnetic flux. This was confirmed and theoretically analysed more thoroughly in [117].

Researchers at Kyoto University have developed a series of squirrel-cage rotors in which the bars and end rings of conventional squirrel-cage rotors were replaced with HTS coated bars and end rings. Most of the prototypes had stators with copper windings. Such motors were found to generate asynchronous torque when operating in slip mode, and generate synchronous torque when operating in synchronous mode [117]. The induction machine eventually works as a synchronous machine because of the zero dc resistance of the superconductors [65]. Most of the machines operated at around 77 K (liquid nitrogen), except for [118], which operated between 4.2-20 K as it used an MgB2 rotor cage and was intended as a liquid hydrogen fuel pump. Almost all of the prototypes were partially superconducting, except [119], [120, 121] and [122], in which the rotor all had Bi-2223 in all three cases, the armature of the first two used Bi-2223 and the armature of the last used REBCO. In [123], there were two sets of rotor bars and end rings: one made of Bi-2223 and one made of normal copper. This was so that the machine could operate at cryogenic temperatures as well as normal temperatures. Other induction motor prototypes are detailed in Table A1.

4.3 Claw pole machines
Claw pole machines have a similar operating principle to synchronous machines, except that the field poles are now realised by claw poles for which magnetic flux is generated from stationary field coils or PMs. This makes them suitable for high speed generators, since superconducting field windings in high speed synchronous machines could suffer from quench due to strong electromagnetic and centrifugal forces [124].

The machine built by the Central Japan Railway Company (JR) is shown in Figure 6, adapted from [125]. It had a copper armature and two superconducting Bi-2223 field coils. In Figure 6(a), flux crosses two airgaps. For the claw poles on the left-hand half of the machine, the flux crosses the airgap near the field coil from the stator to the rotor, then travels along the claw poles towards the tips of the poles, then crosses the airgap at the armature from the poles to the armature and the back iron. Thus, these claw poles are like PMs with a north pole facing the armature. In contrast, for claw poles on the right side of the machine, flux crosses the armature airgap from the back iron and armature to the claw poles, thus the claw poles are like PMs with a south pole facing the armature. The left-side claw poles and the right-side claw poles are arranged alternately at the armature airgap, thus as the claw poles rotate, the armature winding sees a time-varying flux and thus a back-emf is induced. MAI published results of a claw pole machined in 2016 intended for airborne generator [124]. Its novelty was adding PMs to the claw pole rotor to provide additional flux for redundancy in case field windings failed.
A series of claw pole machines were designed at the University of Edinburgh. The first design [126, 127] (see Figure 7(a), adapted from [126]) was like the machine made by JR [125] except that the two field windings were merged together and relocated to the centre. The machine was also a radial flux machine, and the rotor consisted of one set of claw poles on the left and a set of claw poles on the right, which linked to the shaft on the left and right (not shown in Figure 7(a)), respectively. The left claw poles and right claw poles were arranged alternately. In the second design [128] (see Figure 7(b), adapted from [128]), a double-sided claw pole design and an axial flux topology were adopted; the third set of armature windings at the centre was added as a later design [129, 130].

In addition to the advantage of having a stationary superconductor, the claw pole machine designed in [128] also used less HTS materials compared to other machines of the same 10 MW power level [128]. The reasons for this included: the airgaps are shorter than the airgap in synchronous machines, since the airgap in synchronous machines needs to accommodate the vacuum separation between the armature and field windings [128]; the use of loop-shaped superconducting coils uses the superconducting material more efficiently [128] than the racetrack coils typically used in radial synchronous machines, since the end windings of the racetrack coils do not contribute to useful mmf. However, the claw pole machine designed is heavier than other superconducting machines of the same 10 MW power level [128].

### 4.4 Homopolar machines
Homopolar machines also have stationary field coils. Homopolar machines can be divided into dc homopolar machines and ac homopolar machines. As the name suggests, in dc homopolar machines, the whole machine is run by dc. A schematic is shown in Figure 8, adapted from [131]. The field windings (which can be superconducting) produce a magnetic field perpendicular to the surface of the rotor disk. Current is fed from the rim of the disk and travels towards the centre and along the shaft, and collected at the end of the shaft and travels along an external circuit. Force is exerted on the disk in the direction mutually perpendicular to the applied field and current directions. DC homopolar machines are characterised by high current, low voltage and sliding contacts that transfer large current [131]. In 2016, Guina reported a 200 kW dc homopolar machine [131] whose dc magnetic field was provided by a Bi-2223 winding, and a single billet copper rotor rotated in the magnetic field, carrying current up to 20 kA. The voltage was 10 V and sliding contacts were realised by liquid metal current collectors.
In ac homopolar machines, ac current flows in the armature windings whilst dc current flows in the field windings. In 2009, General Electric reported an ac homopolar machine as an airborne generator [132]. The armature winding was made of copper and the stationary field coil was made of Bi-2223. A schematic of an ac homopolar machine is shown in Figure 9, adapted from [133]. The rotor is divided into two halves connected via a shaft. There are four salient poles on each half but poles on each half are offset by 180 electrical degrees [134] (which is 45 mechanical degrees for the 8-pole machine shown). The field winding at the centre is stationary and can be superconducting. The main flux leaves from the salient poles on the left half of the rotor and travels along the back yoke and into the salient poles on the right half of the rotor. All salient poles on each half of the rotor are magnetised in the same direction [133]: poles on the left half act like magnets with a north pole facing the armature, and poles on the right half act like magnets with a south pole facing the armature. The armature coils run axially along the stator and they see a time-varying flux as the rotor rotates. There is also a reluctance torque in ac homopolar machines, as described in the detailed analysis in [134]. The impact of ripple fields on superconducting field windings is quantified in [135].

A bearingless ac homopolar machine has its rotor suspended by magnetic means without mechanical bearings. This is useful for high-speed operations to reduce mechanical wear and frictional loss. Rotor suspension can be realized by simply adding two sets of two-pole dc windings in the stator, as done in [133, 134, 136].

Superconducting ac homopolar machines offer several advantages. The superconducting field winding increases the mmf of the field and thus reduces the mass of the field windings. The robust rotor structure, stationary field coils and simple bearingless system make ac homopolar machines suitable for high-speed applications. So far, the main applications proposed for superconducting ac homopolar machines are airborne generators [132] and flywheel energy storage [136, 137].

### 4.5 Magnetic gears

The magnetic gear was first proposed in [138] to transfer torque between two bodies rotating at different speeds. It is an alternative to a mechanical gear, which can suffer from wear and frictional losses. The magnetic gear proposed in [138] is shown in Figure 10. It consists of an inner rotor with PMs, an outer rotor with PMs, a stationary layer of iron pieces \( n_s \) of them) arranged as a ring between the rotors, and two airgaps, between the iron pieces and each rotor.

Consider a rotor (inner or outer) with \( p \) pole pairs rotating at \( \Omega_r \). Due to the modulation effect of the \( n_s \) iron pieces, the rotor’s magnetic field is modulated to become a number of magnetic flux density harmonics that are of different pole pairs and rotating at different speeds compared to \( p \) and \( \Omega_r \).
respectively [138]. The flux density harmonics have a number of pole pairs \( p_{m,k} = |mp + kn_s| \), with corresponding rotational speeds \( \frac{mp}{mp+kn_s} \Omega_r \), where \( m = 1, 3, 5, \ldots, \infty \); \( k = 0, \pm 1, \pm 2, \ldots, \pm \infty \) [138]. Torque is produced when harmonics of the same number of pole pairs rotate at the same speed. Therefore, even though the two rotors rotate at different speeds, they can transmit torque to each other because the flux density harmonics that one rotor produces can have the same number of pole pairs and rotational speed as the pole pair number and rotational speed of the other rotor.

The possibility of replacing the PMs with superconducting tapes in a magnetic gear was investigated [139], which showed that higher torque density could be achieved, but the mechanism of operation changed slightly because the superconducting magnets would saturate and magnetise the iron pieces, which would then act like a Halbach array; whereas PMs in a normal magnetic gear are not strong enough to saturate the iron pieces, which would operate in their linear region in the B-H curve. [140] proposed an axial magnetic gear in which excitation was provide solely by HTS coils on the stator and the two rotors contained only salient iron poles. [141] replaced the PMs in conventional magnetic gears with trapped field HTS bulks.

In other papers [142-145], superconducting bulks (exploiting their shielding property) replaced the iron pieces (with very high permeability) in the modulation layer to achieve the flux modulation effect, since variation in permeability is still present. Such a proposed machine is shown in Figure 11. The advantage is that a thinner modulation layer could be used, leading to a lighter design [142]. [143] calculated the magnetic field distribution in such a machine analytically and showed how the torque changes due to changes in the height of the HTS pieces and PMs. [144] and [145] used both iron and HTS bulks in the modulation layers.

![Figure 10](image1.png) **Figure 10** A magnetic gear with 4 and 22 pole pairs on its two rotors, respectively, and 26 iron pieces. Note that the red and blue PM pieces are magnetised in opposite directions.

![Figure 11](image2.png) **Figure 11** Magnetic gear using HTS bulks to replace iron pieces, based on [142].

### 4.6 Vernier machines

Vernier PM (VPM) machines, shown in Figure 12 [Error! Reference source not found.], work in a similar way to a magnetic gear, except that one of the (rotating) rotors with PMs is now replaced by a stator with an armature, which is also able to provide a rotating field. In addition, the number of iron pieces (of a corresponding magnetic gear) is the same as the number of stator slots in the armature (of the VPM machine), and thus the iron pieces are incorporated into the stator. Vernier machines are known for their low-speed, high-torque characteristic, which is needed in wind turbine and ship propulsion applications.

A superconducting VPM machine was designed in [146], in which the armature winding was replaced with HTS. Low temperature superconductors replaced PMs in a double stator design in [147]. An advanced vernier PM machine was designed in [148] that combined a VPM with the ac homopolar machine, as shown in Figure 13. The machine had an outer PM rotor and inner stator housing the copper armature. Two sets of field flux were present: the first produced by the PMs, and the second
produced by an HTS field winding located on the stator. By controlling the current in the HTS coil, a controllable field flux, not available in a regular VPM machine, is possible. The PMs on the rotor were dispensed with in the design in [149].

![Diagram of a verier PM with 18 stator slots, 17 rotor pole pairs and 3-phase, 1-pole-pair stator winding (3 slots per pole per phase).](image1)

Figure 12

HTS bulks have also been used as insets on the pole faces of a VPM [150] [151]. The flux shielding property of the bulks was used effectively to divide a pole face into smaller flux modulation poles (which perform the same function as the iron pieces in the magnetic gear) and to reduce flux leakage. A double-stator version was proposed in [152] and quantitatively compared with a regular, double-stator VPM with the same geometry other than the pole faces. It was shown that the vernier machine with HTS bulks had a higher torque, lower iron core loss, but higher torque rippler than the conventional version.

![Diagram of the vernier machine proposed in [148] (figures from [148]).](image2)

Figure 13

4.7 FSDC and stator-excited machines
Consider a partitioned-stator flux switching PM (FSPM) machine, as shown in Figure 14(a), in which the inner stator contains PMs, the outer stator contains the armature, and the rotor consists of iron pole pieces. This can be interpreted as a magnetic gear with stationary inner PMs, rotating iron pieces, and faster-rotating outer PMs (the armature produces a rotating mmf wave). The airgap open-circuit PM mmf is modulated by the rotor iron pieces to form field harmonics of different pole pair numbers in the outer airgap, which interact with the armature mmf wave to produce torque. This is quantitatively analysed in [153]. A conventional FSPM machine is shown in Figure 14(b). The PMs and armature winding are now in one outer stator, and the rotor is simply iron with salient poles. The airgap flux distribution generated by the PMs and armature are quantitatively analysed in [154]: the open circuit PM mmf wave, taking into account stator saliency, is modulated by the rotor saliency in the form of an airgap permeance function to give the airgap open-circuit flux density distribution; whereas the armature reaction mmf, taking into account stator saliency, is also modulated by the rotor saliency in the form of an airgap permeance function to give the airgap flux density distribution generated by
armature. The airgap flux density distributions generated by the PMs and armature interact and there are many harmonics with the same pole pair number and speed, thus producing torque.

Field PMs in FSPM machines may be replaced by a dc winding, giving rise to FSDC machines. Superconducting FSDC machines offer the advantage of a simple and robust rotor structure, and the stationary superconducting field winding does not require rotary cryogenic coupling or brushes/slip rings to transfer current. The China University of Petroleum reported an FSDC machine with Bi-2223 racetrack coils as dc coils [155]. The machine had 12 modular stator poles and 7 rotor poles, and the armature coils and field coils were wound on alternate teeth. There are also other FSDC designs such as [156] and [157], both with 12 stator poles (10 and 11 rotor poles, respectively) and have a slot at the tip of each stator pole to house HTS field coils; a double rotor structure to essentially combine two FSDC motors together but using only one set of field excitation [158]; and an axial design [159]. Four different field winding topologies were described in [160], as shown in Figure 15, and their performance parameters such as torque, cogging torque and flux leakage were compared. [161, 162] used claw poles to direct the flux generated by a single HTS (Bi-2223) field ring. Using claw poles gives the advantage that the excitation field does not have to be provided by many separately-cooled HTS coils, but by a single HTS ring. [163] combined a FSPM with a homopolar structure, such that excitation was provided by both PMs and an HTS ring-shaped coil.

Figure 14(a) A partitioned-stator flux switching PM (FSPM) machine, and (b) a conventional FSPM (both of 12 stator poles, 10 rotor poles).
Due to the large-amplitude harmonics of various frequencies found in the FSDC machine, they are often used for low-speed applications, e.g., as wind turbine generators [164], to avoid excessive ac loss. Recently, more designs have focused on the partitioned-stator FSDC topology [164-166] to reduce the ac loss experienced by the superconducting dc field winding, since the field windings are then located further away from the armature. Methods to reduce the armature harmonics seen by field windings are detailed in [167], including a copper or aluminium shield outside the superconductor, and an iron layer (magnetic ring) and damper coils above the superconducting coils in the inner stator.

Finally, a doubly-fed machine is also a stator-excited machine, but with two sets of coils both carrying ac in the stator. The Harbin Institute of Technology published results on a 2 kW, 12000 rpm doubly-fed machine in [168]: in this machine, a four-pole copper winding carried higher frequency ac current with a small magnitude, and a two-pole YBCO winding carried lower frequency ac current with a large magnitude. The rotor in a doubly-fed machine can be a salient iron rotor, but saliency was achieved by a magnetic barrier rotor in this prototype. The working principle of a doubly-fed machine, as laid out in [168], is that the rotor saliency, expressed as an airgap permeance function, modulates the mmf waves produced by the two sets of windings, and torque is produced when the modulated waves have harmonics of the same speed and pole number.

5 Machines with HTS bulks/stacked tapes

Bulk HTS materials can be used in various ways in a superconducting machine design depending on the particular property being exploited [169, 170]. Firstly, HTS bulks have the ability to trap flux so that after being magnetised, they act like a PM as so-called trapped field magnets (TFMs), and can be used as magnets in PM synchronous machines. ‘Trapped’ magnetic flux densities have been demonstrated of an order of magnitude higher than conventional PMs (as high as 17 T; see Section 2.3) and the most useful gains in machine performance come from their use as TFMs. The flux shielding ability of HTS bulks has been exploited in reluctance machines and flux modulation (also
called flux concentration) machines, as explained below. Finally, the flux pinning property of HTS bulks allows them to be used in hysteresis machines. Stacked tapes can function as bulks, so machines with stacked tapes are discussed in this section as well.

### 5.1 Trapped field synchronous machines

Researchers at TUMSAT [171] in 2005 published the test results of an axial flux trapped field synchronous machine. The machine had GdBCO bulks on the rotor, which was sandwiched between two stators. The stators had copper armatures in the form of concentrated windings, which also served as coils to magnetize the bulk using pulsed field magnetisation in-situ. The maximum trapped field 1.5 mm away from the bulks was about 0.4-0.6 T. The measured output power was 3 kW, which was later increased to 10 kW [172, 173]. Further, a twin-rotor, triple-stator configuration was also developed in [172, 173] to further increase the measured output power to 16 kW. The maximum trapped field was 0.7 T when operating at 720 rpm [174]. A schematic of the type of axial flux motors developed by TUMSAT is shown in Figure 16.

![An axial flux, trapped field synchronous machine developed by TUMSAT utilising HTS bulks as the field poles. Three rotor plates housing the bulks are shown in the figure (adapted from [174]).](image)

Researchers at University of Cambridge published results of the world’s first bulk-type fully-superconducting machine in 2014 [175], and a schematic of the machine is shown in Figure 17. The rotor of the radial flux machine contained 75 YBCO bulks, which trapped a field of around 250-350 mT. The bulks were magnetized using pulsed field magnetization ex-situ above the stator by copper coils before being lowered inside the superconducting stator for the motor to operate, with the entire setup immersed in liquid nitrogen.

![Schematic of the fully superconducting synchronous motor developed at the University of Cambridge.](image)

ASUMED was a €5 million project funded mainly by the EU to design and assemble a fully superconducting 1 MW synchronous motor for aircraft propulsion, with a target power density of 20...
kg/kW. The motor design had a GdBCO armature winding on the stator and stacked HTS tapes on the rotor, acting as TFMs [33, 176].

5.2 Hysteresis machines
A hysteresis machine has the simplest structure amongst HTS machines with the rotor simply being a cylinder/shell of HTS bulk, as shown in Figure 18. The (copper) armature winding generates a rotating magnetic field and the rotor HTS bulk sees a time-varying magnetic field. Instead of using the flux shielding property of HTS bulks, hysteresis machines rely on the flux pinning property of type II superconductors and the penetration of flux into the rotor material. Thus, the HTS bulk undergoes hysteresis (evident in applied field, H, vs magnetisation, M, loops of these materials [177]). It was found experimentally [178] and theoretically [36] that the torque produced is proportional to the area of the hysteresis loop (i.e., the hysteresis loss). Since hysteresis loss is independent of the frequency of the applied field, a hysteresis machine has a constant torque-speed characteristic [179]. The torque producing mechanism is introduced in [170] as follows: the applied field induces current in the bulk, and the magnetization caused by the induced current is hysteretic in nature and opposes changes imposed by the external magnetic field; thus, the instantaneous directions of magnetisations of the armature field and the rotor field are not the same and torque is produced. As the rotor speeds up to synchronous speed, though it is expected the torque to decrease [179], it is found experimentally that synchronous torque exists [178-180]. A hysteresis motor is like an induction motor in the sense that there is a lag between the field generated by the stator and rotor, but the lag is independent of rotor speed and thus constant torque-speed characteristic results [181].

![Figure 18 Schematic of a hysteresis machine with HTS bulk.](image1)

Researchers from the Federal University of Rio de Janeiro (UFRJ) wound stacks of HTS tapes spirally around the rotor core to build small prototypes of around 200 W [182]. The stacks were magnetized (using a technique called field cooling magnetization) before experiments [183]. It was found that the machine had two operating modes, one being synchronous mode and the other being asynchronous mode [183]. In the latter mode, which is entered when load torque is above the pinning torque, the HTS material enters a hysteresis cycle [183].

5.3 Reluctance machines
Reluctance machines work by the principle that the rotor will tend to align itself in the direction of minimum reluctance. Traditional reluctance machines have iron rotors with salient poles or rotors made of magnetic materials interleaved with non-magnetic materials, such that flux travels along a particular axis. The larger the difference in reluctance between the direct (low reluctance) and quadrature (high reluctance) axes of the rotor, the larger the torque. Using superconductors in the rotor can further enhance the ratio of this difference because the shielding property of superconductors prevents flux from travelling along the quadrature axis and encourages flux to travel along the direct axis [169, 170]. However, the use of iron limits the flux density due to the saturation of iron, and using superconductors in reluctance machines can only increase torque by approximately one-third [181].
MAI reported three types of rotors for radial reluctance machines in [184], which are shown in Figure 19: the first had alternate layers of HTS bulks and steel; the second was a solid steel cylinder with two opposite slots for HTS bulks; and the third was similar to the second, but with an additional HTS bulk plate at the centre between the two original HTS bulks. In [36], two modifications were proposed to the traditional reluctance rotor (with alternate layers of HTS bulks and iron). The first added a cylindrical HTS shell around the rotor and the shell trapped magnetic field. The second replaced part of the shell with conventional PMs. Oswald also reported testing of a reluctance motor with rotor made of alternate layers of iron and HTS bulks [185].

![Figure 19 Three types of rotors for reluctance machines introduced in [184].](image)

5.4 Flux modulation machines
Exploiting the shielding property of HTS bulks, Masson et al. [186] reported a magnetic field concentration device that focused magnetic field in the space between two blocks of HTS bulks. This principle was later used by the same authors to design, manufacture and test an inductor consisting of two circular coils carrying current in opposite directions, separated by HTS bulks and an air space, as shown in Figure 20(a)(b) (adapted from [187]). The magnetic field generated by the two coils carrying opposing currents without being modulated by the HTS bulks, as obtained from finite element modelling, is shown in Figure 20(c), which shows a radial field between the two coils. Due to the shielding property of the HTS bulk, the flux density is largest at B and smallest at A in Figure 20(b) [187], thus the inductor produces an eight-pole field and can be used as a rotor in a synchronous machine [187][188].

An axial flux modulation machine manufactured and tested by Safran is shown in Figure 21. A Bi-2223 coil generates axial flux and the rotor containing the YBCO bulks modulates the field seen by the copper armature, shielding the armature in areas behind the bulks and concentrating the flux between the bulks. Thus, as the rotor rotates, the copper coils experience a time-varying magnetic field and a back emf is generated. Safran has a program to build more flux modulation machines in the future at higher power levels and with higher power density, aiming at an eventual target of a 3 MW motor for aircraft propulsion [189]. A 500 kW machine has been designed with the same mass and size as a previous 50 kW machine [190] by using single-seeded bulks and REBCO field coils.
6 Future trends and challenges in machine designs
There are several trends that we can identify in the superconducting machines surveyed in this paper. First, there is a trend towards fully superconducting machines where both armature and field windings are superconducting, e.g., an HTS flux modulation machine reported in 2005 [51, 62, 64]; three induction machines reported in 2012 [119], 2019 [120, 121, 192] and 2022 [122]; and two synchronous machines reported in 2020 [94] and 2021 [96]. A fully superconducting machine with bulks was reported in 2013 [175, 193], and one with stacked tapes in 2020 [33, 176]. Compared to partially superconducting machines, fully superconducting machines can provide higher magnetic and electrical loadings, leading to an even higher power density, reduced design complexity [3] – particularly for the cryogenic system – and a reduced airgap since there is no need for cryogenic walls between the stator and rotor [12].

What has not been definitively answered yet, however, for an ac superconducting stator using HTS materials, is whether the ac loss – when including the energy required to extract the associated heat – is acceptable without compromising the machine benefits. As described in Section 2.4, the ac loss in LTS machines operating at 4.2 K was completely unacceptable and designs moved very quickly to a conventional ac stator with a cryogenic superconducting dc rotor design. Operating at a much higher temperature with HTS materials alleviates this issue somewhat, but the question still remains. Various methods have been proposed to reduce ac loss in machines, for example, flux diverters [16, 89-91], magnetic shield [167] or pole shoes [194], and using partitioned stators in FSDC designs [164-166]. Numerical methods have been used to evaluate different low ac loss architectures [194, 195] in the
recent literature, but these are yet to be proven in terms of their feasibility for real world machines. Numerical modelling, in particular the T-A formulation, has advanced to a stage where superconducting machines can be readily modelled, even with 100s of turns [196, 197]. The T-A formulation allows the superconducting parts and the non-superconducting parts of the machine to be coupled and modelled in one model rather than separately [198]. Numerical modelling of low ac loss machines is expected to flourish over the next few years.

Second, the axial flux topology (see Sections 4.1.1.1 and 4.1.1.2) has been used for lower power ratings (up to 400 kW by IHI [87, 199] amongst prototypes surveyed) and the use of this topology for higher ratings is still unproven [37]. Whilst it is often claimed in the literature that axial flux machines offer higher power density, this advantage may diminish at higher power levels, with a transition occurring when the radius (of the axial flux machine) equals twice the length of the radial flux topology [200]. Furthermore, at high power levels, the mechanical limitation on the rotor-shaft joint for an axial flux machine is also difficult to mitigate [201]. A solution would be to stack smaller axial flux machines together to give the required power output, as adopted in the design study for a 1 MW aerospace motor in [202], but this leads to a complicated assembly. More studies on the merits of the axial flux topology at high power levels (> 1 MW) are needed.

Third, many design efforts have focused on topologies that eliminate the need for placing HTS materials on the rotor and thus eliminate the need for rotary cryogenic and current couplings, and reduce vibrational and rotational forces on the superconductors [128]. Topologies pursuing this aim include claw pole, FSDC, and dc and ac homopolar machines. An interesting alternative, which avoids the need for current leads directly connected to an HTS rotor, has been proposed by Bumby et al. [70]. A brushless HTS exciter, based on a superconducting flux pump in the form of an HTS dynamo, can be used to energise the rotor windings, and this can be done even across a cryostat wall. Recently, in 2020, researchers at Jeju University [71] demonstrated this form of brushless HTS exciter practically in a 1 kW-class prototype HTS synchronous generator with good success.

In terms of HTS machine applications, the wind turbine sector has attracted major EU projects (EcoSwing and Suprapower, see Section 4.1.1.1) and the ship propulsion sector – particularly in Japan – has seen major programs run by companies (AMSC, IHI, Kawasaki, DOOSAN). However, to compete with conventional machines, it was estimated that HTS wires have to be reduced to $20/kA-m or lower [203]. A recent surge in interest for superconducting machines has been seen in aerospace, for which the ASUMED project and MAI have developed the latest prototypes, and ASCEND is a live project by Airbus that intends to test a 500 kW superconducting motor and the associated cryogenic and superconducting electricity distribution systems [204]. It has been argued that only superconducting machines will be able to provide the high power densities required for electric aircraft [205].

Finally, for bulk HTS machines, as outlined in [42], future areas of studies include further optimizing magnetisation methods, particularly pulsed field magnetization, to trap higher field in bulks. While over 17 T has been demonstrated as the record trapped field to date in these materials (see Section 2.3) using quasi-static magnetisation, only up to around 5 T has been trapped using the more practical pulsed field magnetization technique. In actual machine prototypes (see Section 5.1), the trapped fields have generally been less than 1 T, although 1.3 T [206] has been demonstrated using a controlled magnetic flux density distribution coil (CMDC) designed specifically for a bulk HTS machine. Understanding and developing methods to prevent demagnetization of bulks when bulks operate under dynamic machine conditions also requires further investigation [42], as well as improving the mechanical properties of the ceramic bulks to withstand large forces when they trap high fields and interact within a machine environment [42].
7 Conclusions

HTS machines offer distinct advantages of increased efficiency, and reduced mass and volume. Many prototypes have been built to demonstrate their use in various applications, such as aircraft and ship propulsion, EVs, wind turbine generators, utility generators and industrial motors. In particular, the light-weight advantage of HTS machines may render them the only candidate for powering large electric aircraft, and can deliver significant cost-saving when used in large (>10 MW) offshore wind turbines due to reduced tower construction costs. We have provided an up-to-date list of HTS machines built worldwide in the 21st century, and we observe that the pace of investigating the feasibility of HTS machines in wind turbines and aircraft has accelerated in recent years.

Various machine topologies have been designed that focus on meeting various objectives. Synchronous ac machines have been the most popular, but to eliminate rotating superconductors (and thus the need for current and cryogenic couplings), other topologies have been proposed, such as claw poles machines, dc and ac homopolar machines, and FSDC machines. In addition to using HTS wires/tapes, there have also been a number of machines that exploit HTS bulks, and more recently, HTS stacked tapes. Whilst bulks and stacked tapes are mainly used as PMs in trapped field synchronous machines, they can also be used in hysteresis, reluctance, and flux modulation machines.

In terms of future HTS machine topologies, we expect power density would continue to be a driver, thus an increased interest in fully superconducting machines, active shielding, and verification of the axial flux topology for higher power ratings (>1 MW). Reducing ac loss is another driver, thus novel coil architectures and shielding methods will be developed, and it is expected that the partitioned stator FSPM will gain more interest. For advanced superconducting machine design, a number of numerical modelling tools have been developed in recent years, especially the T-A formulation. These tools have focused predominately on quantifying ac loss in machine environments, leading to improvements in overall efficiency, but further developments will provide comprehensive machine design and analysis tools. Although the challenge of rotary cryogenic coupling was solved when developing past LTS generators decades ago, there is still continued interest in developing machines with stationary HTS windings. For machines with HTS bulks, research on practical magnetisation techniques and the retention of their magnetisation during machine operation continues to attract attention.
## Appendix A List of HTS machines

Table A1 List of major HTS machines that have been manufactured and tested since the year 2000.

*design only, ^preliminary test only, d= year designed/built, r = radial, a = axial, syn = synchronous, ind = induction, hom = homopolar, rel = reluctance, flux mod = flux modulation, tf = trapped field, PSDL = flux switching dc; 2R, 2S, 3S = double rotor, double stator, triple stator; Demo = demonstrator, M = motor, G = generator, Wind G = wind turbine generator; LSHT = low speed high torque; cdsr = condenser; n/a = data not available; LHe = liquid helium, LN2 = liquid nitrogen, LH2 = liquid hydrogen.

Efficiency: regular font means tested value including or excluding cooling, **bold means the value explicitly includes power needed for cooling**, italics means the value explicitly excludes cooling, dotted underline means design value.

<table>
<thead>
<tr>
<th>Group, year published</th>
<th>Referenees</th>
<th>Type</th>
<th>Applicati on</th>
<th>Stator</th>
<th>Rotor</th>
<th>HTS wire/ tapes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMSC, 97</td>
<td>[207]</td>
<td>r, syn</td>
<td>M</td>
<td>Cu</td>
<td>Br-2223 in Ag matrix</td>
<td>27</td>
</tr>
<tr>
<td>Reliance Electric, 02</td>
<td>[61, 208, 209]</td>
<td>r, syn</td>
<td>M</td>
<td>Cu Litz, air core, magnetic yoke</td>
<td>Bi2223, nonmagnetic core</td>
<td>33</td>
</tr>
<tr>
<td>AMSC, 02</td>
<td>[56]</td>
<td>r, syn</td>
<td>M</td>
<td>Cu, air core, back iron</td>
<td>HTS (assume Bi2223) multifilamentary composite wire, assume air core</td>
<td>~35</td>
</tr>
<tr>
<td>AMSC, 04</td>
<td>[57, 210-212]</td>
<td>r, syn</td>
<td>Syn cdsr</td>
<td>Cu, back iron</td>
<td>Br-2223</td>
<td>35-40</td>
</tr>
<tr>
<td>AMSC, 05</td>
<td>[78, 79]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu Litz, air core, back iron</td>
<td>Br-2223, air core</td>
<td>32</td>
</tr>
<tr>
<td>AMSC, 11</td>
<td>[80]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu Litz winding, no iron teeth</td>
<td>HTS, air core</td>
<td>~30</td>
</tr>
<tr>
<td>Siemens, 02</td>
<td>[40, 74]</td>
<td>r, syn</td>
<td>Demo M + G</td>
<td>Cu Litz winding, no iron teeth, iron yoke</td>
<td>Br-2223 in 48 flat pancake coils, iron core</td>
<td>25</td>
</tr>
<tr>
<td>Siemens, 07</td>
<td>[39, 75]</td>
<td>r, syn</td>
<td>Ship G</td>
<td>Cu Litz winding, no iron teeth, iron yoke</td>
<td>Br-2223, magnetic core</td>
<td>25</td>
</tr>
<tr>
<td>Siemens, 12</td>
<td>[76, 77]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu Litz winding, no iron teeth, iron yoke</td>
<td>Br-2223, iron core</td>
<td>30</td>
</tr>
<tr>
<td>Soonchunh yang, 03</td>
<td>[114, 115]</td>
<td>r, ind</td>
<td>M</td>
<td>Cu</td>
<td>Br-2223 as short bars and short rings</td>
<td>n/a</td>
</tr>
<tr>
<td>DOOSAN/ KERI, 05</td>
<td>[213, 214]</td>
<td>r, syn</td>
<td>M</td>
<td>Cu, air core, magnetic yoke</td>
<td>Br-2223, aluminium core, double pancake coils</td>
<td>~30</td>
</tr>
<tr>
<td>DOOSAN, 08</td>
<td>[38]</td>
<td>r, syn</td>
<td>Industrial M</td>
<td>Cu Litz, distributed winding, air core, conduit wire [215]</td>
<td>Br-2223, non-magnetic core</td>
<td>&lt;30</td>
</tr>
<tr>
<td>DOOSAN, 16^</td>
<td>[215]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu wire, distributed winding, modular air cored</td>
<td>REBCO</td>
<td>27</td>
</tr>
<tr>
<td>IHI, 05^</td>
<td>[51, 62, 64]</td>
<td>a, syn, 2S1R</td>
<td>Ship M</td>
<td>Field coils made of Br-2223, iron core</td>
<td>Cu armature, coreless</td>
<td>66</td>
</tr>
<tr>
<td>IHI, 05</td>
<td>[51, 62, 64]</td>
<td>a, flux mod</td>
<td>Ship M</td>
<td>Field coils and armature both made of Bi-2223, iron core</td>
<td>Inductor made of iron</td>
<td>66-70</td>
</tr>
<tr>
<td>IHI, 06d</td>
<td>[199]</td>
<td>a, syn, 2R</td>
<td>Ship M</td>
<td>Bi-2223, iron core</td>
<td>Nd PM, iron yoke</td>
<td>66-70</td>
</tr>
<tr>
<td>IHI, 08</td>
<td>[87, 199]</td>
<td>a, syn, 2R</td>
<td>Ship M</td>
<td>Bi-2223, iron core</td>
<td>Nd PM, iron yoke</td>
<td>66-70</td>
</tr>
<tr>
<td>IHI, 08</td>
<td>[216]</td>
<td>a, syn, 2R</td>
<td>M</td>
<td>HoBCO field winding, iron core</td>
<td>Cu armature, iron core</td>
<td>69-77</td>
</tr>
<tr>
<td>Southampto n, 11</td>
<td>[217, 218]</td>
<td>r, syn</td>
<td>G</td>
<td>Cu (BiPb)-2223, pancake coils, magnetic core</td>
<td>67-77</td>
<td>100k</td>
</tr>
<tr>
<td>Southampto n, 11</td>
<td>[219, 220]</td>
<td>r, syn</td>
<td>G</td>
<td>Cu (BiPb)-2223, coreless, with flux diverters</td>
<td>61.6-77.4</td>
<td>100k</td>
</tr>
<tr>
<td>GE, 06</td>
<td>[59]</td>
<td>r, syn</td>
<td>Demo utility G</td>
<td>Conventional stator of an induction motor</td>
<td>Single coil, 605 turns, BiSCCO wire, magnetic core</td>
<td>30</td>
</tr>
<tr>
<td>GE, 06*</td>
<td>[59]</td>
<td>r, syn</td>
<td>Utility G</td>
<td>Cu, stator of GE Frame 7E gas turbine</td>
<td>2740 turns of Bi-2223 wire, warm salient magnetic steel pole</td>
<td>n/a</td>
</tr>
<tr>
<td>GE, 09</td>
<td>[132]</td>
<td>r, ac hom</td>
<td>Aircraft G</td>
<td>Cu armature, BiSCCO stationary field coil</td>
<td>Iron rotor with offset poles</td>
<td>~30</td>
</tr>
<tr>
<td>Kyoto, 06</td>
<td>[222]</td>
<td>r, ind/</td>
<td>M</td>
<td>Cu Bi-2223 for bars (2mm tapes) and end rings (4.3mm tapes)</td>
<td>65-77</td>
<td>~1.5k</td>
</tr>
<tr>
<td>Kyoto, 08</td>
<td>[223]</td>
<td>r, ind/</td>
<td>M</td>
<td>Cu Bi-2223 for bars (2.6mm tapes) and end rings (4.1mm tapes)</td>
<td>77</td>
<td>~3.3k</td>
</tr>
<tr>
<td>Kyoto, 08</td>
<td>[117, 224]</td>
<td>r, ind/</td>
<td>M</td>
<td>Cu YBCO film conductor as bars and Bi-2223 as end rings</td>
<td>77</td>
<td>1035</td>
</tr>
<tr>
<td>Kyoto, 09</td>
<td>[123]</td>
<td>r, ind/</td>
<td>M</td>
<td>Cu Hybrid excitation: Bi-2223/Ag + Cu as bars, Bi-2223/Ag + Cu end rings</td>
<td>77</td>
<td>~1.1k</td>
</tr>
<tr>
<td>Kyoto, 12*</td>
<td>[119]</td>
<td>r, ind/</td>
<td>EV M</td>
<td>Cu, iron core</td>
<td>Bi-2223-type H, iron core</td>
<td>77</td>
</tr>
<tr>
<td>Kyoto, 12*</td>
<td>[119]</td>
<td>r, ind/</td>
<td>EV M</td>
<td>Racetrack double pancake Bi-2223-type ACT coils, iron core</td>
<td>Bi-2223-type H, iron core</td>
<td>77</td>
</tr>
<tr>
<td>Kyoto, 12</td>
<td>[118]</td>
<td>r, ind/</td>
<td>LH2 fuel pump</td>
<td>Cu Mono-core MgB, wires for bars and end rings, iron core</td>
<td>LHe</td>
<td>1.5k</td>
</tr>
<tr>
<td>Kyoto, 14</td>
<td>[226]</td>
<td>r, ind/</td>
<td>EV M</td>
<td>Cu Bi-2223 as bars and end rings, GdBBCO bulks, iron core</td>
<td>~2.5k</td>
<td>1800</td>
</tr>
<tr>
<td>Kyoto, 15</td>
<td>[225]</td>
<td>r, ind/</td>
<td>EV M</td>
<td>Cu, iron core</td>
<td>Bi-2223 bars and end rings, iron core</td>
<td>77</td>
</tr>
<tr>
<td>Kyoto, 19*</td>
<td>[120, 121]</td>
<td>r, ind/</td>
<td>EV M</td>
<td>Cu Bi-2223, ring winding, iron core (laminated silicon steel)</td>
<td>Bi-2223 bars and end rings, iron core (laminated silicon steel)</td>
<td>77</td>
</tr>
<tr>
<td>Kyoto, 22</td>
<td>[122]</td>
<td>r, ind/</td>
<td>G</td>
<td>REBCO, 20 mm bending diameter</td>
<td>Bi-2223 bars and end rings</td>
<td>77</td>
</tr>
<tr>
<td>Seikei, 07</td>
<td>[116]</td>
<td>r, ind/</td>
<td>M</td>
<td>Cu Bi-2223/Ag</td>
<td>77</td>
<td>~50</td>
</tr>
<tr>
<td>Kyushu, 07</td>
<td>[227]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu, iron core</td>
<td>YBCO tape, iron core</td>
<td>20-30</td>
</tr>
<tr>
<td>Kyushu, 08</td>
<td>[228]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu, iron core</td>
<td>YBCO and GdBBCO tape, no iron core</td>
<td>40</td>
</tr>
<tr>
<td>Kyushu, 13</td>
<td>[229]</td>
<td>r, ind/</td>
<td>LH2 fuel pump</td>
<td>MgB2, iron core, single-layer, short-pitch winding</td>
<td>Same MgB2, rotor as [118]</td>
<td>LHe</td>
</tr>
<tr>
<td>Date, ref</td>
<td>no.</td>
<td>Coaching party</td>
<td>Driver</td>
<td>Inductor and field</td>
<td>Armature and Field coils</td>
<td>Output Parameters</td>
</tr>
<tr>
<td>----------</td>
<td>-----</td>
<td>----------------</td>
<td>--------</td>
<td>-------------------</td>
<td>--------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>JR, 08</td>
<td>[125]</td>
<td>r, claw pole</td>
<td>Demo M</td>
<td>Cu armature, 2 Br-2223 circular field coils</td>
<td>8 claw poles</td>
<td>40</td>
</tr>
<tr>
<td>Sumitomo, 08</td>
<td>[52]</td>
<td>r, dc</td>
<td>EV M</td>
<td>Br-2223 type H, claw poles</td>
<td>Cu armature</td>
<td>LN2</td>
</tr>
<tr>
<td>Sumitomo, 12</td>
<td>[53]</td>
<td>r, dc</td>
<td>EV M</td>
<td>Br-2223 type H, claw poles</td>
<td>Cu armature</td>
<td>LN2</td>
</tr>
<tr>
<td>TUMSAT, 09</td>
<td>[84]</td>
<td>a, syn, 2S</td>
<td>Ship M</td>
<td>Cu, back iron yoke</td>
<td>Br-2223 winding, ironless core</td>
<td>30</td>
</tr>
<tr>
<td>Convertea m, 10</td>
<td>[55]</td>
<td>r, syn</td>
<td>Hydroelectric G</td>
<td>Copper, iron stator with iron teeth</td>
<td>Br-2223, warm rotor, iron core</td>
<td>30-40</td>
</tr>
<tr>
<td>Kawasaki, 10</td>
<td>[230]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu, nonmagnetic teeth</td>
<td>Br-2223, coreless [7]</td>
<td>30</td>
</tr>
<tr>
<td>Kawasaki, 17</td>
<td>[231]</td>
<td>r, syn</td>
<td>Ship M</td>
<td>Cu, nonmagnetic teeth</td>
<td>Br-2223, nonmagnetic core</td>
<td>30</td>
</tr>
<tr>
<td>WIMEP, 12</td>
<td>[232]</td>
<td>r, syn</td>
<td>M</td>
<td>Cu Litz, back iron, air core</td>
<td>Br-2223, nonmagnetic core, double pancake coils</td>
<td>30</td>
</tr>
<tr>
<td>Tsinghua, 14</td>
<td>[233],[234]</td>
<td>r, syn</td>
<td>G</td>
<td>Bi-2223, iron core, double layer concentrated winding</td>
<td>PM</td>
<td>82</td>
</tr>
<tr>
<td>MAL, 14</td>
<td>[235]</td>
<td>r, syn</td>
<td>Transportaation M</td>
<td>Cu</td>
<td>YCBO, iron core</td>
<td>LN2</td>
</tr>
<tr>
<td>MAL, 16</td>
<td>[124]</td>
<td>r, claw pole</td>
<td>Demo G</td>
<td>Cu armature, REBCO field coil</td>
<td>Claw poles + PM</td>
<td>77</td>
</tr>
<tr>
<td>MAL, 17</td>
<td>[236]</td>
<td>r, syn</td>
<td>EV M</td>
<td>Cu, magnetic core</td>
<td>2G HTS</td>
<td>65-77</td>
</tr>
<tr>
<td>MAL, 20</td>
<td>[94],[95]</td>
<td>r, syn</td>
<td>Aircraft M</td>
<td>REBCO racetrack coils</td>
<td>REBCO racetrack coils</td>
<td>77</td>
</tr>
<tr>
<td>MAL, 22</td>
<td>[237],[238]</td>
<td>r, special inductor</td>
<td>Aircraft G</td>
<td>HTS field coils, HTS armature coils, Cu backup field coils and armature coils</td>
<td>Salient pole rotor with PM</td>
<td>LN2 and LH2</td>
</tr>
<tr>
<td>POSCO, 15</td>
<td>[240]</td>
<td>r, syn</td>
<td>G</td>
<td>24 slot Cu winding</td>
<td>GdBCO</td>
<td>30</td>
</tr>
<tr>
<td>Suprapower, 16*</td>
<td>[241]</td>
<td>r, syn</td>
<td>Wind G</td>
<td>Cu, magnetic core, no magnetic teeth</td>
<td>MgB₂, warm rotor iron</td>
<td>20</td>
</tr>
<tr>
<td>Guina, 16*</td>
<td>[131]</td>
<td>dc hom</td>
<td>M</td>
<td>Bi-2223 wires to provide magnetic field</td>
<td>Cu rotor</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Kawasaki, 17</td>
<td>[85]</td>
<td>a, syn, 2R</td>
<td>M/G</td>
<td>YCBO wound on toroidal cores (wound from silicon iron tape) mounted on stator plate</td>
<td>Nd PM</td>
<td>77</td>
</tr>
<tr>
<td>Lorraine, 17</td>
<td>[242]</td>
<td>a, syn</td>
<td>Demo G</td>
<td>Cu on slotless iron core</td>
<td>Insulated DI-Bi-2223/Ag multifilamentary tape</td>
<td>77</td>
</tr>
<tr>
<td>Lorraine, 22*</td>
<td>[243]</td>
<td>a, syn</td>
<td>G</td>
<td>BSCCO</td>
<td>NdFeB PM</td>
<td>77</td>
</tr>
<tr>
<td>Location</td>
<td>Year</td>
<td>Type</td>
<td>Description</td>
<td>Segmentation</td>
<td>Speed</td>
<td>Torque</td>
</tr>
<tr>
<td>----------</td>
<td>------</td>
<td>------</td>
<td>-------------</td>
<td>--------------</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>CUP, 18</td>
<td>2018</td>
<td>r, FSDC</td>
<td>Wind G</td>
<td>Cu armature, Bi-2223 field winding, iron core</td>
<td>Segmented iron salient rotor</td>
<td>77</td>
</tr>
<tr>
<td>CUP, 22</td>
<td>2022</td>
<td>r, 2S FSDC</td>
<td>G</td>
<td>Cu armature in outer stator, Bi-2223 field winding in inner stator</td>
<td>Iron and non-iron blocks</td>
<td>LN2</td>
</tr>
<tr>
<td>EcoSwing, 19</td>
<td>2019</td>
<td>r, syn</td>
<td>Wind G</td>
<td>Cu, iron core</td>
<td>GdBBCO winding, cold back iron</td>
<td>30</td>
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<tr>
<td>ENEA, 19</td>
<td>2021</td>
<td>a, syn</td>
<td>Wind G/LSHT M</td>
<td>REBCO armature (6 coils, concentrated), ironless</td>
<td>NdFeB PM (10-pole), ironless</td>
<td>77</td>
</tr>
<tr>
<td>Jeju, 20</td>
<td>2020</td>
<td>r, syn</td>
<td>Demo G</td>
<td>Cu, iron core</td>
<td>2G HTS (SCS 12S05, SuperPower), iron core</td>
<td>77</td>
</tr>
<tr>
<td>Harbin, 20^a</td>
<td>2018</td>
<td>r, doubly-fed</td>
<td>Flywheel</td>
<td>Cu @600Hz 4-pole, YBCO @50Hz 2-pole, iron teeth</td>
<td>Magnetic barrier rotor, 6-pole</td>
<td>77</td>
</tr>
<tr>
<td>Strathclyde, 2020</td>
<td>2017</td>
<td>a, syn</td>
<td>Demo G</td>
<td>6 coils (2 per phase), 1 phase HTS (1 coil YBCO, 1 coil GdBBCO), other coils Cu; air core</td>
<td>PM, on laminated silicon steel plate</td>
<td>77</td>
</tr>
<tr>
<td>Beihang, 2021^a</td>
<td>2018</td>
<td>r, ac hom</td>
<td>G</td>
<td>YBCO field coil, Cu armature</td>
<td>Salient pole rotor, with and without PM (two rotors tested)</td>
<td>LN2</td>
</tr>
<tr>
<td>Kyushu, 21^a</td>
<td>2019</td>
<td>r, syn</td>
<td>M</td>
<td>EuBCO+BHO (65K)</td>
<td>EuBCO (~70K)</td>
<td>65, ~70</td>
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### HTS bulks

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Type</th>
<th>Description</th>
<th>Segmentation</th>
<th>Speed</th>
<th>Torque</th>
<th>Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAL 99</td>
<td>2019</td>
<td>r, hys</td>
<td>n/a</td>
<td>Assume Cu</td>
<td>YBCO</td>
<td>77</td>
<td>4k</td>
<td>24k syn spd</td>
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<tr>
<td>MAL 99</td>
<td>2019</td>
<td>r, rel</td>
<td>n/a</td>
<td>Assume Cu</td>
<td>Fe + YBCO bulk</td>
<td>77</td>
<td>10k</td>
<td>n/a</td>
</tr>
<tr>
<td>MAL 01</td>
<td>2019</td>
<td>r, rel</td>
<td>n/a</td>
<td>Assume Cu</td>
<td>Compound layers of Fe and single domain YBCO (YBCO replaced by foliate Ag-BSCCO in other prototypes)</td>
<td>65</td>
<td>5k</td>
<td>N/a</td>
</tr>
<tr>
<td>MAL 01</td>
<td>2019</td>
<td>r, rel+ tf</td>
<td>n/a</td>
<td>Assume Cu</td>
<td>(Layers of YBCO and Fe) plus a YBCO surrounding shell</td>
<td>n/a</td>
<td>~1.6k</td>
<td>n/a</td>
</tr>
<tr>
<td>MAL 01</td>
<td>2019</td>
<td>r, tf + PM</td>
<td>n/a</td>
<td>Assume Cu</td>
<td>(Layers of HTS and Fe) plus a surrounding shell of PM and HTS</td>
<td>n/a</td>
<td>~6k</td>
<td>n/a</td>
</tr>
<tr>
<td>MAL 10</td>
<td>2019</td>
<td>r, flux mod</td>
<td>M</td>
<td>Assume Cu</td>
<td>YBCO bulks &amp; PM, magnetic core</td>
<td>LN2</td>
<td>500k</td>
<td>n/a</td>
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<tr>
<td>MAL 10</td>
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<td>r, flux mod</td>
<td>M</td>
<td>Assume Cu</td>
<td>YBCO bulks &amp; PM, magnetic core</td>
<td>LN2</td>
<td>150k</td>
<td>n/a</td>
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<tr>
<td>Tokyo, 01</td>
<td>2020</td>
<td>r, hys</td>
<td>M</td>
<td>Cu</td>
<td>YBCO ring-shaped bulk</td>
<td>LN2</td>
<td>16 k</td>
<td>900 syn spd</td>
</tr>
<tr>
<td>Tokyo, 03</td>
<td>2020</td>
<td>r, hys</td>
<td>M</td>
<td>Cu</td>
<td>HTS ring-shaped bulk</td>
<td>LN2</td>
<td>n/a</td>
<td>900</td>
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<tr>
<td>Kyoto, 02</td>
<td>2021</td>
<td>a, hys</td>
<td>M</td>
<td>Cu</td>
<td>Bi-2223 ring-shaped bulk</td>
<td>LN2</td>
<td>~6</td>
<td>600</td>
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<tr>
<td>Kyoto, 06</td>
<td>2021</td>
<td>a, hys</td>
<td>M</td>
<td>Cu</td>
<td>Sm-123 ring-shaped bulk</td>
<td>77.3</td>
<td>~60</td>
<td>1800 syn spd</td>
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<tr>
<td>JR, 03</td>
<td>2021</td>
<td>r, tf syn</td>
<td>M</td>
<td>YBCO field</td>
<td>Cu armature</td>
<td>27</td>
<td>1.5k</td>
<td>600</td>
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<td>Location</td>
<td>Year</td>
<td>Type</td>
<td>Material</td>
<td>Configuration</td>
<td>Inductor Size</td>
<td>Applied Field</td>
<td>Max Field</td>
<td>Comments</td>
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<tr>
<td>Cambridge, 03</td>
<td>2014</td>
<td>r, flux mod</td>
<td>only inductor is designed and tested</td>
<td>NbTi as two coils, YBCO bulk for flux concentration</td>
<td>4.2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>Cambridge, 07</td>
<td>2014</td>
<td>r, flux mod</td>
<td>Two NbTi coils for excitation and 4 YBCO bulks for flux mod</td>
<td>Cu armature, magnetic core</td>
<td>4.2</td>
<td>n/a</td>
<td>190</td>
<td>n/a</td>
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<tr>
<td>Cambridge, 10</td>
<td>2014</td>
<td>r, flux mod</td>
<td>Inductor made of NbTi coil</td>
<td>Cu armature</td>
<td>4.2</td>
<td>15k</td>
<td>750</td>
<td>n/a</td>
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<td>Lorraine, 05</td>
<td>2014</td>
<td>r, flux mod</td>
<td>Demo M</td>
<td>Cu armature</td>
<td>4.2</td>
<td>n/a</td>
<td>500</td>
<td>n/a</td>
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<tr>
<td>FAMU-NOVA, 09</td>
<td>2014</td>
<td>r, flux mod + tf</td>
<td>Aircraft M</td>
<td>Outer Cu armature</td>
<td>30</td>
<td>160k</td>
<td>2700</td>
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<tr>
<td>Musashi, 05</td>
<td>2014</td>
<td>r, rel</td>
<td>M</td>
<td>DyBCO bulks + iron</td>
<td>LN2</td>
<td>-30</td>
<td>750, 1500</td>
<td>-8</td>
</tr>
<tr>
<td>TUMSAT, 05</td>
<td>2014</td>
<td>a, tf syn, 2S</td>
<td>Ship M</td>
<td>GdBCO bulk</td>
<td>LN2</td>
<td>10k, 30k</td>
<td>720</td>
<td>n/a</td>
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<tr>
<td>TUMSAT, 06</td>
<td>2014</td>
<td>a, tf syn, 2R3S</td>
<td>Ship M</td>
<td>GdBCO bulk</td>
<td>LN2</td>
<td>16k, 60k</td>
<td>720</td>
<td>n/a</td>
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<tr>
<td>Oswald, 05</td>
<td>2014</td>
<td>r, rel</td>
<td>Industrial M</td>
<td>Cu</td>
<td>YBCO bulk and stack of iron</td>
<td>77</td>
<td>200k, 188k</td>
<td>3000</td>
</tr>
<tr>
<td>Tecno-Westphinghaus, 09</td>
<td>2014</td>
<td>r, tf syn</td>
<td>Demo M</td>
<td>Cu</td>
<td>YBCO bulk</td>
<td>LN2</td>
<td>-2.2k max</td>
<td>450-1800</td>
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<tr>
<td>NOVA, 10</td>
<td>2014</td>
<td>r, rel+tf syn</td>
<td>M</td>
<td>Cu</td>
<td>Iron rotor with YBCO bulks, 3 configurations tested</td>
<td>LN2</td>
<td>-2k</td>
<td>3000</td>
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<tr>
<td>NOVA, 2014</td>
<td>2014</td>
<td>a, hys, 2S</td>
<td>Demo M</td>
<td>YBCO multi-seeded bulk</td>
<td>Cu</td>
<td>-240</td>
<td>3k (4-pole)</td>
<td>n/a</td>
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<tr>
<td>Cambridge, 14</td>
<td>2014</td>
<td>r, tf syn</td>
<td>Demo M</td>
<td>2G HTS, air core</td>
<td>Y123 bulk</td>
<td>77</td>
<td>540</td>
<td>150</td>
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<tr>
<td>Safran, 20</td>
<td>2014</td>
<td>a, flux mod</td>
<td>Aircraft M</td>
<td>Cu Litz armature + Bi-2223 coil</td>
<td>YBCO bulk as magnetic shield</td>
<td>30</td>
<td>50k</td>
<td>5000</td>
</tr>
<tr>
<td>Douma, 21</td>
<td>2014</td>
<td>a, flux mod</td>
<td>M</td>
<td>Cu armature + NbTi coil (but Cu coil tested)</td>
<td>YBCO bulk as magnetic shield</td>
<td>77</td>
<td>890</td>
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### HTS stacked tapes

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Type</th>
<th>Material</th>
<th>Configuration</th>
<th>Inductor Size</th>
<th>Applied Field</th>
<th>Max Field</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>UFRJ/UFF, 19</td>
<td>2014</td>
<td>r, hys</td>
<td>Demo M</td>
<td>Cu</td>
<td>Stacks of 2G HTS tape spirally wound, 2 versions: iron and noniron cores</td>
<td>77</td>
<td>~200</td>
<td>1200</td>
</tr>
<tr>
<td>UFRJ/UFF, 22</td>
<td>2014</td>
<td>r, hys</td>
<td>Demo M</td>
<td>Cu</td>
<td>SuperPower 2G tape stacked spirally around core with soft iron outer layer and fiberglass inner layer</td>
<td>77</td>
<td>1788</td>
<td>465, (973 max)</td>
</tr>
<tr>
<td>Cambridge, 19</td>
<td>2014</td>
<td>r, syn</td>
<td>Demo G</td>
<td>Cu, stator teeth, iron core</td>
<td>Iron core, one stack of AMSC REBCO tape</td>
<td>77</td>
<td>n/a</td>
<td>650</td>
</tr>
<tr>
<td>Cambridge, 20</td>
<td>2014</td>
<td>r, syn</td>
<td>Demo G</td>
<td>Cu, stator teeth, iron core, plus a set of magnetizing coil</td>
<td>8 stacks of AMSC REBCO tapes</td>
<td>77</td>
<td>n/a</td>
<td>600-2130</td>
</tr>
<tr>
<td>Cambridge, 20</td>
<td>2014</td>
<td>r, syn</td>
<td>Demo G</td>
<td>Cu, distributed (LN2 temp)</td>
<td>4 stacks of tape: a standard stack made of impregnated superconducting tapes, an interlayered stack with ferromagnetic layers, a shielded stack and a sectioned stack</td>
<td>16</td>
<td>n/a</td>
<td>~600</td>
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[173]
<table>
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<tr>
<th>ASUMED, 20 [33, 176]</th>
<th>r, syn</th>
<th>Aircraft M</th>
<th>$\text{GdB}_2\text{Cu}_3\text{O}_7$, distributed winding, warm iron yoke, toothless</th>
<th>Stacks of HTS tape, tape from Deutsche Nanoschicht</th>
<th>30 for rotor</th>
<th>1M</th>
<th>6000</th>
<th>Target thermal loss &lt;0.1%</th>
<th>8-pole, target 20 kW/kg.</th>
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</thead>
<tbody>
<tr>
<td>NOVA, 22 [263]</td>
<td>a, hys, 2S Demo M</td>
<td>Cu, iron core, stator teeth</td>
<td>YBCO sliced tapes (tapes 12 mm wide, SuperOx) on both sides of a carbon plate</td>
<td>77</td>
<td>~2.2k</td>
<td>~675 (4-pole)</td>
<td>Pole number can be varied during operation (3-phase, 2,4,8 poles tested)</td>
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</tbody>
</table>
Acknowledgements
The work of Mark D. Ainslie was supported in part by an Engineering and Physical Sciences Research Council (EPSRC) Early Career Fellowship, EP/P020313/1. Calvin C. T. Chow and K. T. Chau would like to acknowledge that this work was supported in part by two grants (Project Nos. 17204021 and T23-701/20-R) from the Hong Kong Research Grants Council, Hong Kong Special Administrative Region, China.

Data availability
No new data were created during the study.

References


