Superconductivity and its Application in the Field of Electrical Machines

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Abstract— **This paper provides a review on the most recent applications of superconductors in rotating electrical machines. The main types of superconductors for the present-day electrical applications are shown to highlight their main features. The main characteristics of superconducting synchronous machines, DC machines and induction machines for marine and vehicle propulsion, future electric aircraft, wind energy and industrial applications are discussed by presenting data of prototypes and demonstrators. The paper aims to raise awareness among researchers and engineers on the importance of superconductivity to enhance the performance of conventional electrical machines.**

Keywords— Electric machines, electric propulsion, aerospace applications, superconductivity, superconductor topologies, DC machines, induction machines, synchronous machines.

I. INTRODUCTION

Superconductivity arises in some elements and alloys, namely superconductors (SCs), which exhibit a near-zero DC resistivity when operated in their superconducting state. The exceptional characteristics of today's SCs are due to both their intrinsic near-zero DC resistivity and their ability to carry high currents at high magnetic field levels.

The use of SCs enables to achieve almost zero Joule losses in DC-operated windings for electrical machines. Moreover, the use of SCs in some machine topologies can lead to a significant increase of the magnetic loading. Consequently, electrical machines featuring a decreased volume, decreased mass and increased efficiency can be designed. However, SCs exhibit non-negligible losses under AC regime. Despite this, many studies have been carried out towards loss reduction.

Superconductivity was discovered for the first time by Kamerlingh Onnes in 1911. It was found out that mercury (Hg) samples exhibited zero DC resistivity when cooled down to temperatures close to 4 K.

The development of electrical equipment employing Low Temperature Superconducting (LTS) materials began in the 1960s when superconductivity at high magnetic field levels was possible [1]. LTS materials such as NbTi and Nb$_3$Sn wires are still used nowadays in low-temperature superconducting magnets, high-energy physics accelerators, magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) [2].

The early application of superconductivity to electrical machines included the use of the Nb-25-percent Zr LTS wires in the manufacturing of field windings in alternators [3]. However, the widespread of LTS technology in this field was interrupted soon due to the challenges related to the cooling system, especially from the cost and efficiency point of view [4]. Indeed, LTS technology required the use of liquid helium cooling at 4.2 K.

A renewed interest in superconductivity for electrical applications such as motors, generators, transformers, fault current limiters and power cables started from 1986 with the discovery of High Temperature Superconducting (HTS) materials operating above 35 K [5]. Indeed, the use of HTS materials allowed to overcome the challenges related to LTS technology. The breakthrough occurred in 1987 when YBa$_2$Cu$_3$O$_7$ (YBCO), a new HTS compound operating above the boiling point of liquid nitrogen at 77 K, was announced [6]. The discovery of SCs operating well above 77 K brought superconductivity to a new era for electric power applications. To date, many demonstrators employ (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (BSCCO-2223) silver-sheathed HTS conductors exhibiting superconductivity up to ~ 110 K.
In 2001 the MgB$_2$ binary compound was found to superconduct at 39 K. A strong interest has grown on its use in electric applications and much research is ongoing to make it application-ready [7].

The present paper illustrates the use of SCs in rotating electrical machines. The aim of the paper is twofold. First, the authors briefly induct the reader into superconductivity and present the main features of HTS materials for electrical applications. The challenges related to their use in electrical machines are mentioned as well. Second, the authors target to raise awareness among machine designers about the characteristics of superconducting electrical machines. To do so, the main features of synchronous, DC and induction machine prototypes and demonstrators for marine and vehicle propulsion, future electric aircraft, wind energy and industrial applications are presented.

II. SUPERCONDUCTORS FOR ELECTRICAL APPLICATIONS

A. Macroscopic properties of Superconductors

Three interdependent parameters characterize any superconductor: the critical current density J_c, the critical magnetic field H_c and the critical temperature T_c. They describe a region which defines the limits of the superconducting state. Whenever any of these parameters is exceeded, the material leaves superconductivity entering the normal (dissipative) state. It is important to remark that the magnetic field strength inside the superconductor can reach H_c by virtue of the current flowing

through it as well as an external applied magnetic field. SCs can be divided in two types on the basis of their transition from the superconducting to the normal state when subjected to an external applied magnetic field H_a [8], [9].

Type I SCs behave as perfect diamagnets in their superconducting state at $H_a < H_c$. They enter the dissipative state at $H_a \geq H_c$. Type I SCs at ambient pressure are mainly metallic elements such as Hg (T_c of 4.2 K), Al (T_c of 1.2 K) and Pb (T_c of 7.2 K). Type I SCs do not find useful applications because of the very low values of H_c. For the three elements above, H_c at absolute zero does not exceed tens of kA/m.

Type II SCs present a perfect diamagnetic behavior up to a critical field H_{c1} and enter a vortex state for $H_{c1} \leq H_a < H_{c2}$. In this condition, the external magnetic field partially penetrates the material. Superconductivity is lost at $H_a \geq H_{c2}$. Type II SCs are very useful in applications. Examples are compounds like YBCO and BSCCO-2223. They present a vortex state between 10-20 mT and 100 T [10]. Thus, type II SCs can withstand large currents at very high magnetic field levels.

From a macroscopic point of view, SCs show a nonlinear electric field-current density behavior that can be modeled through a power law where $E = f(J^n)$ [2].

B. HTS materials for Electrical Applications

In early day SCs relatively small magnetic fields and small currents caused the material to abandon their superconducting state [1]. During the 1960s LTS materials such as NbTi and Nb$_3$Sn in the form of wires opened several possibilities to the use of SCs in electrical applications. However, those LTS conductors are not used in electrical machines anymore. Two complete reviews on their features can be found in [2] and [11].

HTS materials exhibiting a superconducting behavior above 35 K represent nowadays the most common choice for electrical applications. The following presents the SCs which are considered good candidates for electrical machines.

(Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (BSCCO-2223) compounds, enabled the use of HTS materials in electrical applications by virtue of their electrical, mechanical and thermal performances [5], [12]. The cross-section of a BSCCO-2223 multifilamentary composite tape is shown in Fig. 1a [12]. Superconducting filaments are embedded in a silver alloy matrix which acts as a stabilizer [5]. A critical temperature T_c of about 110 K allows their cooling using liquid nitrogen at 77 K. Tapes featuring a critical current density between 10 and 15 kA/cm^2 at 77 K, self-field can be fabricated easily nowadays [5]. BSCCO-2223 wires have been identified as the first-generation (1G) HTS wires.

YBa$_2$Cu$_3$O$_7$ (YBCO) layered conductors have been identified as second-generation (2G) HTS conductors. The representation of a YBCO tape is shown in Fig. 1b [10]. As can be seen, the coated conductor features multiple layers, applied using thin-film technology on a metallic (Ni) substrate [5]. On top of it is a multifunctional oxide barrier with CeO$_2$, YSZ and Y$_2$O$_3$ layers. On top of that is the YBCO superconducting layer. The conductor is completed with a protective Ag layer and a Cu protection and stabilization layer [2], which are not displayed in Fig. 1b. Overall thickness is less than 0.1 mm [5]. Critical temperature T_c is 92 K. YBCO tapes allow current densities between 30 and 37.5 kA/cm^2 at 77 K, self-field [13].

The MgB$_2$ binary compound features a critical temperature T_c of 39 K. An advantage of MgB$_2$ SCs is that both Mg and B

raw materials have an inherent low cost [7]. Fig. 1c depicts the cross-section of a low-loss MgB$_2$ wire [14]. MgB$_2$ filaments, in black, are surrounded by an outer sheath and a central core made with non-magnetic, resistive alloys. The performance of undoped monofilament strands at 10 T, 4.2 K reached a current density of 16.7 kA/cm^2. Multifilamentary strands having similar properties were already produced as well [11].

Bulk SCs can be used to store high values of magnetic flux density. They find applications in superconducting magnets, levitation systems and magnetic bearings [15]. Moreover, they can be used as shields. Fig. 1d and Fig. 1e show samples of YBCO and GdBCO HTS bulk superconductors [16]. Their critical temperature T_c is equal to 93 K. Their use in the magnetic circuit of an electrical machine was investigated in [16]. The common techniques used to magnetize superconducting bulks are Field-Cooling and Pulse-Field-Magnetization techniques [16]. SCs for shielding applications must be cooled to their superconducting state without applying any external magnetic field. Such technique is called Zero-Field-Cooling and it is common in levitation systems [17], [18].

An extensive review of the challenges inherent in the application of HTS wires to rotating electrical machines was reported in [19]. From the electrical point of view, SCs used for AC machine windings are subjected to time-varying currents and magnetic fields. In such condition, non-negligible losses arise and cannot be eliminated [2]. A reduction in the filament size represents an effective way to reduce AC losses in SCs [11]. Another possibility consists of deviating the magnetic field from the SCs [20]. Tape-shaped SCs present a limited deformation capability which limits their use in arbitrary shaped machine windings. Reference [21] proposed the use of a ring winding configuration for the superconducting stator of an induction machine. Some of the limitations due to the bending strain characteristics and the mechanical strength of the tapes were solved and their critical current density was improved.
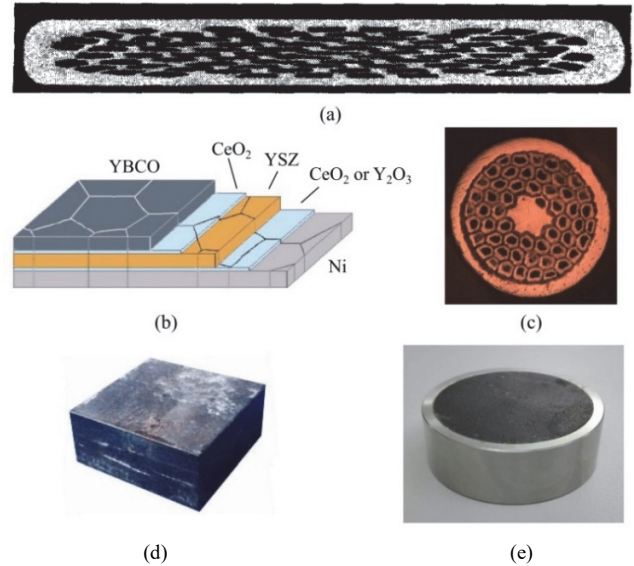

Fig. 1. HTS materials for electrical applications. (a) 85 filament BSCCO-2223 tape-shaped wire [12], (b) YBCO coated conductor [10], (c) 54 filament MgB$_2$ wire [14], (d) YBCO bulk superconductor [16], (e) GdBCO bulk superconductor [16]. Electric current path lies perpendicular to the plane of the paper in both (a) and (c) and from right to left in (b).

III. SUPERCONDUCTING ROTATING ELECTRICAL MACHINES

As a first categorization, it is possible to divide superconducting electrical machines in two main categories:

- partially superconducting machines manufactured using both SCs and conventional conductors or permanent magnets. A cryostat is normally employed to maintain the temperature of the superconducting parts well below T_c;
- fully superconducting machines employing SCs for all their electric circuits. Such machines are normally completely submerged in a cryogenic environment. The use of separate cryostats for each winding complicates the construction of the machine and increases the air gap length.

A. Superconducting Synchronous Machines

A comprehensive analysis of synchronous machines manufactured with LTS materials can be found in [4]. To date, wound field synchronous machines equipped with a superconducting field winding are the main machine topology investigated in literature and industry [22]. Fig. 2 shows the common structure of a HTS wound field synchronous machine for ship propulsion [23]. By using DC-excited superconducting rotor coils, near-zero excitation losses are observed. In addition to this, a significant increase of the air gap flux density can be obtained by using an air-core structure [5]. This is crucial for the torque density improvement. The limitation of the magnitude of the air gap flux density is mainly related to the amount of superconductor required for the field winding [15]. A cryogenic refrigeration system on the rotor maintains the SCs at a fixed operating temperature well below T_c. A vacuum chamber thermally insulates the rotor cryostat. A warm electromagnetic shield in the air gap prevents the SCs on the rotor to experience strong AC fields under transient operation. The use of an air-core structure, that is, the teeth part on the stator and the rotor core manufactured using a non-magnetic material, is necessary since the air gap flux density is typically twice that of a conventional machine [5]. A conventional liquid-cooled armature winding is employed on the stator. Specifically, Litz wire technology is normally employed to reduce eddy current losses in the conductors [24]. The stator back iron is used to close the magnetic circuit [25].

When compared to a conventional design, HTS wound field synchronous machines display the following advantages:

- higher power density [15];
- reduced mass, size and losses [26];
- superior performance in terms of efficiency in the whole operating range [26], [27];
- lower synchronous reactance (air-core structure), smaller load angle, enhanced system stability [28];
- lower harmonic content of back-EMF due to the non-magnetic teeth part and a larger air gap [23];
- lower life-cycle cost and reduced capital cost [15];
- less maintenance: no re-winding or re-insulation required [15].

Wound field synchronous machines were identified as ideal candidates for ship propulsion applications. The main system advantages are improved naval architecture and increased ship's mission capability. Experimental results of two motor prototypes
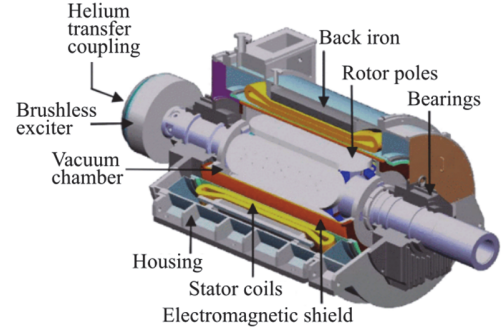

Fig. 2. Illustration of a wound field synchronous machine with a superconducting field winding for ship propulsion applications [23].
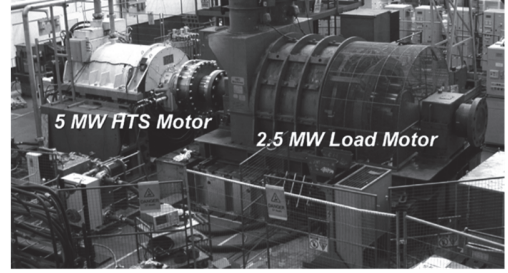

Fig. 3. Load test of a 5 MW HTS ship propulsion motor coupled to a 2.5 MW conventional motor [26].
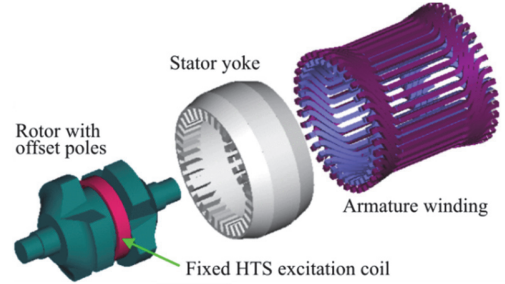

Fig. 4. Illustration of a superconducting homopolar AC synchronous machine for airborne applications [30].

rated 5 MW and 36.5 MW were presented in [26] and [27], respectively. Both the prototypes employed BSCCO-2223 HTS wires for the field winding. The operating temperature was set to 32 K. The machines had roughly half the size and weight compared to that of a conventional design of similar power and torque rating. High efficiency down to 20% of the rated load was achieved for the 5 MW design. Both the machines exhibited a measured efficiency equal or greater than 96% at full load. Fig. 3 shows the 5 MW motor under test [26]. Its dimensions were roughly the same as a conventional 2.5 MW load motor. The design and test of a partially superconducting MW-class ship propulsion motor was presented recently in [29]. The field coils were operated at 27 K and manufactured using 2G HTS wires. The authors claimed that the use of 2G instead of 1G HTS wires allowed a potential cost reduction and higher current densities.

Superconducting synchronous machines also include the AC homopolar configuration. Such machines are manufactured in the partially superconducting configuration. The HTS excitation coil is fixed and encircles a single-pieced ferromagnetic rotor [30]. This layout simplifies the design of the cryostat since it has fixed parts only. The general structure of the machine is depicted in Fig. 4 [30]. The superconducting excitation coil

provides a higher magnetic flux density in the air gap compared to that of a conventional design. The copper armature is wounded on an air-core teeth structure. A laminated stator yoke sustains the excitation coil, closes the magnetic circuit and acts as a shield. The use of a single-pieced rotor allows the machine to rotate at very high speed with simplified mechanical support and electrical interfaces [5]. A particular design of the rotor ensures that the stator winding experiences an alternating magnetic field, since the excitation field is fixed in space and constant in time. Nevertheless, such machines have a larger size compared to an equivalent wound field machine concept [15]. The main applications of AC homopolar machines can be found in electric generators coupled with high-speed gas turbines for future electric aircrafts and high-speed flywheels for energy storage [31]. The demonstrator of a 1.3 MW, 10 000 rpm machine for airborne applications, see Fig. 4, was presented in [30]. An efficiency of 97% was measured, including the power requirement of the refrigeration system.

Other prototypes of partially superconducting synchronous machines included a 3.1 kW, 720 rpm axial gap-type machine featuring a vortex-type copper armature and superconducting bulks to act as magnets on the rotor [32]. Its potential application concerns ship propulsion. A 50 kW, 5000 rpm axial gap-type machine with a copper armature, a fixed HTS field winding and rotating HTS bulks acting as shields to modulate the flux density in the air gap was discussed in [33]. It aims at future electric aircraft applications. Their configuration is shown in Fig. 5. A novel synchronous machine prototype was presented in [34]. It was a 2.5 kW low-speed synchronous generator equipped with a Bi-2223 HTS armature winding on the stator and permanent magnets on the rotor. The experimental tests showed an efficiency up to 85.5% at 290 rpm. The machine was intended for wind power applications in which SCs have a major potential. The preliminary testing proved the feasibility of a HTS armature winding in a low frequency (10 Hz) and low power application. The configuration of the machine is shown in Fig. 6.

Remarkable efforts in analyzing fully superconducting synchronous machines have been carried out recently. A small-scale prototype was used in [25] to validate the analytical calculations for the design of MW class motors and generators for future electric aircrafts. In [35] it was highlighted the importance of the manufacturing and testing of HTS machines to carefully evaluate the AC losses in HTS armature windings.

B. Superconducting DC Machines

Superconducting DC machines in both the homopolar and conventional configurations were discussed in [36]. The use of SCs for the armature winding in conventional DC machines was discouraged by the commutation and the presence of time-varying magnetic fields and electric currents. The armature and torque reaction and the mechanical forces between the coils discouraged the use of SCs for the field winding too, even if operated with DC currents.

The operating principle of homopolar DC machines relies on Lorentz force. The rotation of a movable disk is caused by the interaction between a constant magnetic field and currents circulating in the disk itself. Superconducting homopolar DC machines exist in disk and drum configurations. They are manufactured using a fixed superconducting field coil and a movable copper disk or drum. The illustration of a disk-type machine is shown in Fig. 7 [37]. Drum-type machines have been
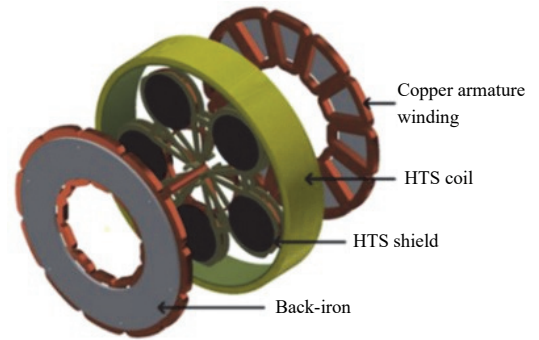

Fig. 5. The axial gap-type synchronous machine for future electric aircraft applications presented in [33].
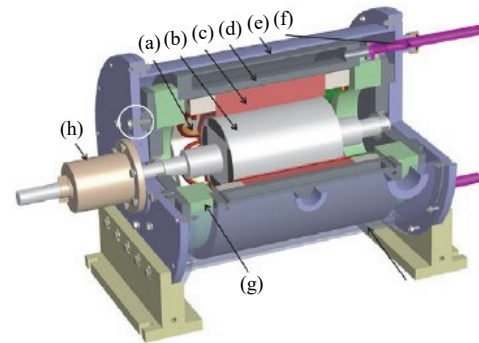

Fig. 6. Configuration of the 2.5 kW generator for wind power applications presented in [34]. (a) HTS armature coils, (b) permanent magnet rotor, (c) stator iron, (d) stainless steel Dewar, (e) vacuum chamber, (f) liquid nitrogen pipe, (g) fiberglass torque flange, and (h) magnetic fluid sealing device.
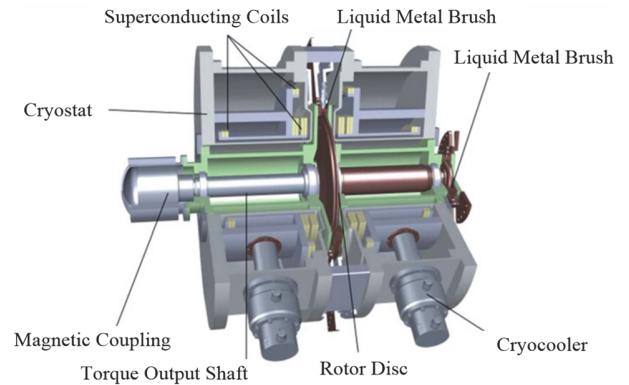

Fig. 7. Configuration of the disk-type homopolar DC machine presented in [37].
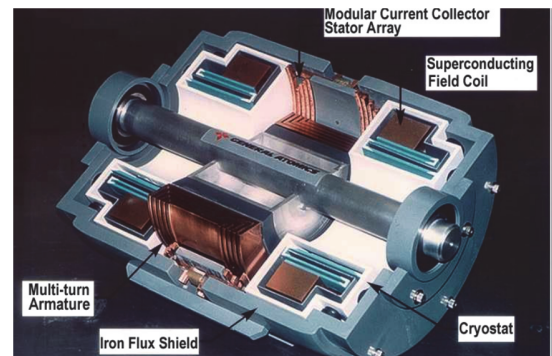

Fig. 8. The drum-type homopolar motor model presented in [38].

developed to increase the operating voltage of disk-type machines which is in general very low. Fig. 8 shows the configuration of a drum-type machine concept rated 3.7 MW [38]. From the operating principle point of view, the excitation field must be always oriented perpendicular to the current flow. In disk-type machines the electric current is directed radially in the disk, while in drum-type machines it is directed along the longitudinal axis. The use of a superconducting field coil allows to create a high excitation field with high DC currents and almost no Joule losses. The main features of homopolar DC machines concern [39]:

- high current and relatively low voltage rating;
- pure DC operation: no AC losses in the superconducting field coil;
- no mechanical torque exerted on the field coil in reaction to the armature torque;
- absence of torque oscillations if constant current and excitation field are considered;
- slip contacts are needed to convey current to the rotor.

The first prototypes and demonstrators of homopolar DC machines were built using LTS wires [40]. Uses were found in propulsion motors for electric ships and trains as well as high current sources in smelting applications. A 50 kW drum-type DC homopolar motor for industrial and ship propulsion applications was presented in [41]. The LTS field coil was cooled with liquid helium at 4 K. Liquid metal collectors were employed for the slip contacts. The experimental tests at 75 kW power demonstrated a measured efficiency of 96%. However, when considering the cooling power requirements, the overall measured efficiency dropped down to about 80%. This highlights the drawback of LTS technology from the cooling performance point of view. A homopolar DC machine for ship propulsion applications employing a 1G BSCCO-2223 HTS field coil was described in [39]. The machine was operated as a motor and delivered 91 kW at 11 700 rpm. The armature current was 30 kA. The cooling temperature was 28 K, well below the T_c of the superconducting wires. A measured efficiency of 86% was reached. A novel arrangement for the field coil in a disk-type homopolar DC machine, see Fig. 7, was presented in [37]. The authors discussed a strategy to overcome the problems of stray fields and brush shielding in high power and high torque machines. The field coil was fabricated with BSCCO HTS wires. Their operating temperature was 30 K. The maximum operating current was 160 A and the maximum excitation field was 2.4 T. A 200 kW prototype was built and tested. A maximum torque of about 532 Nm and a maximum speed of 3100 rpm were reached. During a 1.5-hour test at constant current and load, the machine delivered 38.5 kW at 1540 rpm. A measured efficiency of 93% was reached.

C. Superconducting Induction Machines

The first studies on the utilization of LTS materials in induction machines considered the possibility to replace the rotor bars and end-rings with SCs. A preliminary study on a 1.5 MW LTS induction machine was carried out in [42]. The authors illustrated that the machine could start as an induction motor and, after a transient state, it could rotate at synchronous speed. Therefore, it was possible to combine the principle of operation of an induction machine and a synchronous machine in a unique device. A superconducting induction machine can operate in both asynchronous and synchronous modes by virtue of the nonlinear relationship between the electric field and the current density in SCs. In detail, during the startup phase, high currents at almost the stator frequency are induced in the superconducting rotor cage. Therefore, the SCs enter the dissipative state exhibiting a high resistivity and AC losses. The machine provides a high starting torque. During the acceleration, the induced currents on the rotor along with their frequency decrease. When approaching the synchronous speed, the SCs on the rotor cage operate again in their superconducting state. In this condition the superconducting rotor cage can trap their linked magnetic flux acting as a permanent magnet rotor which eventually makes the machine rotating at synchronous speed. Detailed investigations on HTS induction machines started to be published in the early 2000s by Korean [43], [44] and Japanese [45] research groups. The manufacturing and test results of a 0.75 kW induction motor fabricated with Bi-2223 tapes on the rotor was presented in [43]. A fully cryogenic setup with the motor completely submerged into liquid nitrogen at 77 K was considered. No-load, locked rotor and load tests were carried out and results were compared to a conventional air-cooled machine having the same volume. During the load test the motor rotated at synchronous speed up to ~ 60% of the rated torque. Rated slip was equal to 0.5%. Efficiency calculation showed an average increase of about 10% over the whole torque range. However, the power requirement of the cooling system was not considered. Analytical calculations and test results of the torque versus speed characteristics of the same machine were discussed in [44]. It was shown that the starting torque was more than twice that of a conventional machine. Reference [45] described a similar machine and considered a different manufacturing of the rotor cage.

A relevant number of studies on induction/synchronous machines for electric vehicle applications has been published starting from 2006 as part of an industry-academia cooperation in Japan. A considerable torque enhancement compared to a conventional air-cooled design was reported in [46]. Two machine prototypes rated 20 kW were fabricated employing a conventional copper winding on the stator and superconducting BSCCO tapes for the rotor cage. The superconducting rotor and a BSCCO rotor bar are shown in Fig. 9.
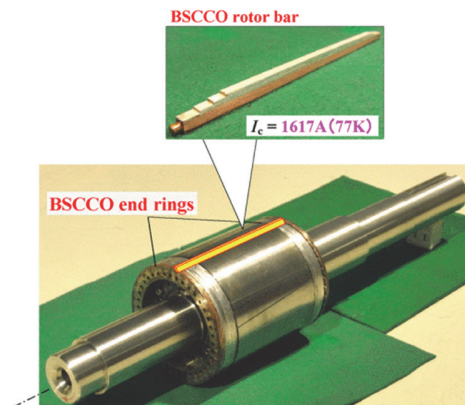

Fig. 9. The superconducting rotor of the machine prototype presented in [46]. A superconducting rotor bar is also shown along with the critical current of the BSCCO tape at 77 K.
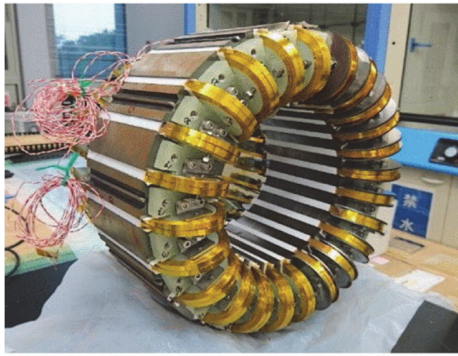
Fig. 10. Ring winding configuration of the superconducting stator of the machine presented in [50].

The second design was an optimized one and allowed to obtain the same rated in torque with a 70% reduction in the volume of the magnetic core. This means that a 70% improvement in torque density was obtained. Experimental tests shown that the machine successfully rotated at synchronous speed at full load.

A more detailed analysis of overload capabilities as well as efficiency of the previous design was presented in [47]. During a high-speed test with an output power ranging from 20 kW to 41.3 kW the machine showed an efficiency greater than 90%. Experimental studies on the variable speed control of a 20 kW partially superconducting induction/synchronous machine were carried out in [48]. The machine was controlled successfully using conventional V/f strategy under the JC08 test cycle for light vehicles. However, it was reported that an optimal control strategy was necessary because of the nonlinear behavior of SCs. As a result, a novel control strategy was discussed in [49].

A recent study on a fully superconducting machine rated 50 kW was presented in [50]. A ring winding configuration on the stator, see Fig. 10, allowed to increase the critical current of the BSCCO tapes. The operating frequency was 40 Hz.

After all the considerations above, it is possible to conclude that, compared to a conventional design, a superconducting induction/synchronous machine features [46]:

- operation in both induction and synchronous modes;
- higher torque density/reduced size;
- robustness against overload operation;
- superior efficiency over the whole operating range.

IV. CONCLUSION

Superconductors and their application in rotating electrical machines have been presented. Superconducting electrical machines are a reality since the introduction of LTS materials and experienced a renewed interest after the discovery of HTS materials. Prototypes and demonstrators of superconducting wound field synchronous machines, DC homopolar machines and induction machines have shown the advantages of superconducting technology in terms of size and weight reduction and a potential increase in efficiency. Much research is ongoing towards the effective reduction of AC losses in SCs and different solutions have been investigated to overcome the limited deformation capability of superconducting tapes.

The overall performance of a superconducting electrical machine must be evaluated carefully and thus, it is necessary to have more detailed information on the power consumption needed to maintain the SCs at a suitable operating temperature. The continuous research and development in superconducting technology applied to electrical machines is an important step towards their large-scale commercialization and their further widespread use. Indeed, superconductivity represents a suitable technology which can meet the challenging requirements associated to applications where conventional designs present important limitations.

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