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Superconducting AC Machines and Cryogenic Power Electronics for Reliable and Power-Dense Energy Conversion

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Abstract—**Implementing superconductivity in rotating electrical machines has many advantages such as increased efficiency, smaller size, and lighter weight if compared to conventional electrical machines. Due to the operative limitation of superconductors, they were mainly used in the DC excitation field windings. However, to target ever higher power density values, there are considerable efforts to use superconductors for the AC windings. This paper reviews the main significant prototypes that implement partially and fully AC synchronous and asynchronous superconducting machines. In the perspective of future cryogenic and superconducting integrated electric drives, the paper also reports research activities on the power electronics components under cryogenic temperature. Moreover, considering the safety critical applications or harsh environments where these drives are expected to be used, recent advancements on diagnostic techniques for electrical machines and drives for cryogenic environments are included.**

Keywords—Superconducting, cryogenic, electric machines, power electronics, power dense, diagnostic, AC losses.

I. INTRODUCTION

Since the discovery of superconductivity at the beginning of last century, superconductors (SCs) were considered worthy of being explored for their potential application in electrical machines. The transition from the normal state to superconductivity occurs when the material is cooled below a critical temperature T_C, and the external magnetic field and the current density are lower than the critical values H_C and J_C, respectively [1]. As a result, the material can carry large currents with almost zero resistance. Hence, substituting copper windings with superconductors can result in electrical machines with higher efficiency, reduced mass, and smaller size [2].

The application of superconductors to electrical machines dates back to the 1960s with the use of low temperature superconductors (LTS).

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However, their low critical field and their low critical temperature (typically < 20K) made the use of LTS unpractical for electrical machines. The interest renewed in late 80s with high temperature superconductors (HTS) that present critical temperatures higher than ~35K [3]. In particular, superconducting compounds with T_C > 77K made it possible using easier to handle cryogenic fluids, such as liquid nitrogen (LN2), as well as less challenging thermal insulation systems [4].

The application of SCs in rotating electrical machines has been mainly limited to excitation field windings supplied with a DC current. The reason is that variable magnetic fields as well as time varying currents generates non negligible AC losses that heavily impact the performance of the superconductor [5]. However, different research groups are nowadays working towards the potential application of SCs in the armature winding of AC electrical machines or as cage conductors in induction motors [6], [7]. The main reason driving all these efforts is the possibility of limiting the cryocooling system to the static part only, as well as the possibility of developing fully superconducting AC machines, i.e. realized using only SCs and without any conventional copper windings or permanent magnets, either on the stator or the rotor.

Furthermore, the ever-increasing integration required for the electrical drives, whatever is the application field, will most likely impose the adoption of power electronics converters integrated with the superconducting machines [8]. Thus, in perspective of possible future applications where the electric drive might be operated at cryogenic temperatures, research efforts are also towards the development and assessment of power electronics components suitable for cryogenic conditions [8]. Nonetheless, the overall dimensions, the system complexity as well as the critical environment where integrated cryogenic and superconducting electrical drives are expected to be used, will make out of order conditions and maintenance operations particularly undesired. Thus, reliable dedicated diagnostic techniques suitable for detecting possible failures in cryogenic and superconducting electrical drives are of primary importance to enhance the system reliability.

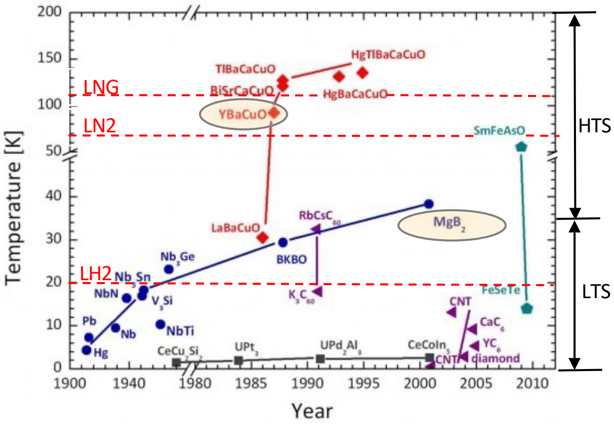

Fig. 1: Superconducting materials and their critical temperature (adapted from [12], [13]).

The goal of this paper is to provide an overview of different cutting-edge research contributions in the development of superconducting AC electrical machines and cryogenic power electronics, mainly focusing on experimental studies and prototyped solutions, as well as diagnostic techniques suitable for cryogenic applications.

II. Superconductors for Electrical Machines

Beside low and high temperature, superconductors are also categorized as in type I and type II. The former present perfect diamagnetism and zero resistance in superconducting state, but their low critical field and low critical temperature do not favor their application in rotating electrical machines. Type II superconductors present two critical fields: H_{C1} and H_{C2}. Below H_{C1} the material has zero resistance and perfect diamagnetism, between H_{C1} and H_{C2} superconductivity is preserved but the field penetrates the materials, over H_{C2} the superconducting state is lost, and the material operates in normal resistive conditions. Since above H_{C2} the magnetic field level can exceed 100 T, type II superconductors can potentially be applied in rotating electrical machines together with significant current density values [9].

Among type II superconductors, three alternative material compounds are mostly considered for electrical machines [6], [10], [11]:

- the bismuth strontium calcium copper oxide (BSCCO-2223), also known as first generation (1G) HTS, that presents a critical temperature of approximately 110K;
- the rare-earth barium copper oxides (REBCO) also known as second generation (2G) HTS, that with yttrium as rare-earth material (YBCO) has a critical temperature of approximately 90K;
- the magnesium diboride MgB_2 that has a critical temperature of 39K.

Figure 1 reports the different superconducting materials and their critical temperatures, as well as the boiling temperature for different cryogenics fluids (red dashed lines) that can be used to maintain the required cryogenic temperature [12]. The superconductors can be realized in the form of wires and tapes, that are particularly suitable for the realization of electrical machine windings. In particular, REBCO superconductors are normally produced as coated conductors made of several layers, where the superconducting one has a micrometer thickness, while BSCCO and MgB_2 are usually available in form of wires and tapes [10].

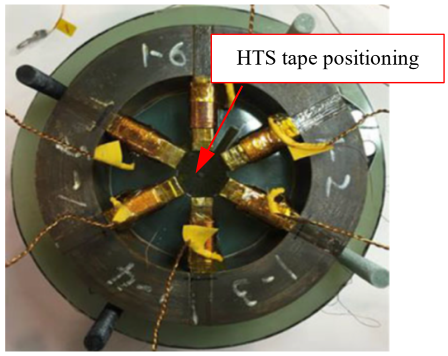

Fig. 2: Experimental setup used in [23] to inverstigate the impact of rotating magnetic field on HTS tapes.

Superconductors can also be realized in bulk shape or stacked tapes and used in substitution of permanent magnets in the electrical machines. Moreover, to limit the AC losses while preserving a high current-carrying capacity, superconducting cables realized using, for instance, Roebel HTS cables [14], [15], filamented tapes or striated tapes wound around a core have been investigated [16]-[19].

III. Superconducting Electric Machine Windings

Superconducting electrical machines can be partially or fully superconducting. The former type adopts SCs together with conventional copper windings or PMs, while in the latter SCs are the only excitation source on the machine. However, in AC regime a superconductor can present not negligible hysteretic losses and the consequent heat load must be dissipated by the cryogenic cooling, thus affecting the overall system efficiency. In particular, the penalty factors of cryocoolers for superconducting machines can be 15-20 at 77K, i.e. to extract 1W out of the cryostat 15-20W are consumed by the cryocooler. At lower temperatures, penalty factor drastically increases [20]. In [21] it is discussed that the losses in superconducting armature must be significantly lower than 0.1% of the machine rated power to be competitive with partially superconducting machines. In the literature, significant efforts are towards the accurate modeling and computation of AC losses in superconductors when subject to a time varying transport current and variable external magnetic field [5]. Therefore, partially superconducting machines have often been preferred, using SCs for rotating DC excitation field windings and conventional conductors for the machine armature [6]. In this way, the SCs are mainly subjected to constant magnetic fields and DC transport currents, thus limiting the AC losses. However, having superconducting windings on the rotating part of the machine increases the system complexity, both for maintaining their operating temperature at cryogenic conditions and for the necessity to supply the current to the rotor. Furthermore, SCs have limited mechanical strength and during the rotation they might experience mechanical solicitations and vibrations that could affect their mechanical performance [22].

To overcome these issues, electrical machines with both copper armature and superconducting DC excitation windings located on the stator side have been prototyped, such as homopolar, flux modulation, flux switching, claw pole and doubly fed machines [6]. Regarding conventional DC machine configurations, the use of SCs for the excitation field on the stator side was discouraged by the presence of armature and torque reaction and the mechanical forces between the coils, while in the armature the use of SCs was limited by the commutator [2].

Fully superconducting machines are expected to be superior in terms of power density because of the high values of current density in all the machine windings. Furthermore, AC synchronous machines can be realized ironless. This obviously reduces the machine weight and further enhances the achievable power density values [6]. Therefore, different research groups are working towards the potential application of superconductors to the AC windings of electrical machines.

The following overview includes selected prototypes and laboratory experiments on machine parts or mockups that focus on AC superconducting windings for electric machines. Bulks or superconducting stacked tapes in substitution of permanent magnets are not discussed in this paper.

A. Measurements on HTS tapes and coils in mockups

The studies that investigate the impact of AC losses in HTS tapes and coils surrounded by ferromagnetic cores and exposed to a variable or rotating magnetic field are often conducted using machine mockups or sample parts only. For instance, the experiment in [23] investigated the AC losses for an HTS tape carrying an AC transport current and exposed to a rotating magnetic field. Figure 2 shows the rotating magnetic field exposing system used for the experimental activity. The six-pole iron core was supplied with a three-phase AC source that generates a rotating magnetic field at the center space of the fixture where the HTS tape is positioned. The AC losses were measured through the calorimetric method, in which a thermocouple measures the temperature rise due to the dissipation of energy in the superconducting tape. By this experiment, the authors concluded that the rotating magnetic field generates losses comparable with those of a uniform AC magnetic field perpendicular to the tape face.

To limit the AC losses, different research groups investigate practical solutions to shield superconducting tapes and wires from leakage magnetic flux that occurs in the stator slots of electrical machines. For instance, in [24] the authors explore methods to suppress the magnetic field perpendicular to the superconducting tape when positioned into a slot of a laminated iron core. The experimental investigation is conducted on a stator core mockup and considering different coils wound with Bi2223 and YBCO tapes. The use of soft ferrite in the slot resulted effective to divert the magnetic flux path away from the tape, thus reducing the AC losses. However, the dimensions of these magnetic flux diverters must be optimized/minimized to limit their impact on the magnetic flux linkage between stator and rotor circuits, that might negatively affect the machine performance.

The same authors extended the study in [25] performing tests on YBCO tapes in three-phase configuration inserted in a complete stator of an electrical machine, confirming the previous achievements. Similar conclusions on the benefits of using magnetic flux diverters to shield HTS tapes positioned into stator slots have been drawn by the studies in [26] and [27].

B. AC superconducting stators

An interesting experimental study on AC superconducting stator windings is reported in [28], where edgewise or flatwise positioning of BSCCO tapes into the stator slot of an electrical machine are investigated.

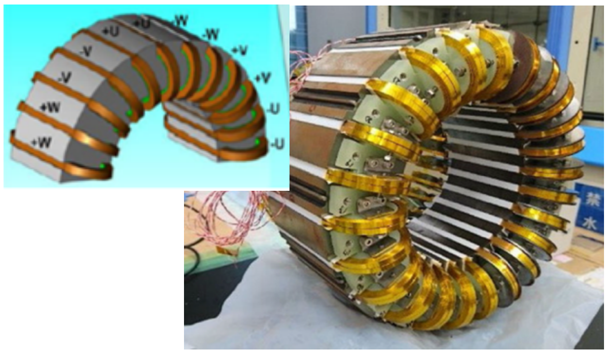

Fig. 3: HTS stator with three-phase ring winding [28], [36].

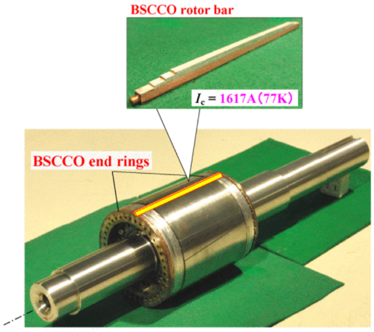

Fig. 4: Superconducting rotor of the machine prototype in [34].

The conducted tests revealed that the flatwise configuration improves the critical current; hence, to respect the bending strain characteristics and the mechanical strength of tape-shaped HTS the authors proposed the ring winding stator shown in Fig. 3. For a complete characterization of the stator, the entire test campaign was carried out without the rotor. The obtained results show that the AC losses in the stator are small at low frequency (few tens of Hz). Tests on superconducting armature windings were also conducted in [29], where a 2.5 kW, four-pole and six-slot permanent magnet synchronous generator was equipped with six double-pancake racetrack HTS coils disposed as tooth windings. Also in this case, the AC losses in the superconductors was found negligible at low rotational speed (300 rpm), as the armature frequency was 10 Hz. The study in [30] reports experiments on an axial flux HTS machine platform, where two stator phases were realized with conventional copper conductors, while the third one with REBCO tapes cooled in LN2. The tests, conducted also in this case at low frequency (10 Hz – 300 rpm), showed that the total AC losses in the superconductors also depend on the phase angle between the transport current and the external magnetic field.

C. Superconducting asynchronous rotors

Beside the application of SCs to the AC stator windings, researchers also investigated the use of superconducting tapes for the conductors on the rotor cage of asynchronous motors where, for normal operating conditions, the frequency of the induced AC currents is quite low. Since the early 2000s relevant studies have been conducted by Korean and Japanese researchers.

In [31] and [32] tests in LN2 on a 0.75 kW induction motor with Bi-2223 tapes on the rotor demonstrated that the motor was able to rotate at synchronous speed up to 60% of the rated torque, while at rated torque the slip was 0.5%. For the whole torque range the efficiency resulted approximately 10% higher than a conventional air-cooled machine.

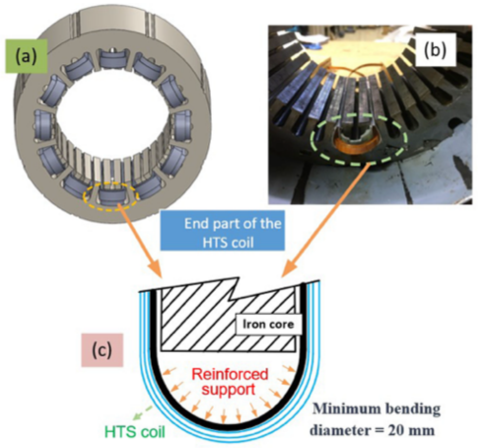

Fig. 5: Superconducting stator REBCO winding in [37].

Similar results are reported in [33] that considers a similar machine but with a different manufacturing of the rotor cage. Remarkable torque density improvements compared to a conventional air-cooled induction motor have also been achieved in [34] for two 20 kW prototypes with conventional stator copper windings and BSCCO tapes for the rotor cage (see Fig. 4). A further performance comparison between cryogenic-cooled and superconducting induction machines can also be found in [35]. In general, induction motors with superconducting cages are often referred to as induction/synchronous machine. In fact, at startup the high frequency of the rotor currents and the generated AC losses quench the SCs that operate in their dissipative state. At higher speed the rotor cage enters the superconducting state and traps the linked magnetic flux acting as a sort of permanent magnet, and the machine rotates at the synchronous speed [2].

D. Fully superconducting AC machines

Experimental tests and results have been achieved for fully superconducting synchronous and asynchronous electrical machines. For instance, the superconducting stator and rotor shown in Fig. 3 and Fig. 4, respectively, have been tested together in a 50 kW 4-pole fully superconducting induction/synchronous motor [36]. Despite load tests with the motor submersed in LN2 were conducted at reduced power only, the machine was successfully operated up to 1500 rpm.

In [37], with a 1 kW fully HTS induction/synchronous generator, the possibility of prototyping a small-size fully superconducting machine has been practically demonstrated. In detail, the rotor cage was realized with BSCCO tapes, while the stator winding was made by racetrack coils with a bending diameter of 20mm using REBCO tapes (see Fig. 5). The whole motor was tested submerged in LN2, succeeding in a power generation exceeding 500 W.

Another example of fully superconducting induction/synchronous machines can be found in [38], where a 20 kW prototype with BSCCO tapes achieved a synchronous speed of 1200 rpm and an efficiency higher than 92% at reduced load. Test results for a 3 kW and a 10 kW fully superconducting synchronous generators having a nominal speed of 2500 rpm are reported in [39] and [1], respectively. The no-load and load tests well agree with the predicted machine performance, thus providing at the authors confidence in the used design approach to move forward to the design of higher power HTS machines.

The authors in [3] designed a fully superconducting synchronous motor with REBCO tapes on both the stator and rotor for future electric aircraft propulsion systems. A 1 kW – 2-pole scaled size prototype has been constructed and successfully tested up to 500 rpm. To increase the SC critical current as well as to enhance the cooling capacity for removing the heat generated by the AC losses the armature was cooled by LN2 subcooled at 65K; instead, liquid helium was used for the rotor field winding.

The studies in [40] and [41] designed MW-class fully superconducting synchronous machines for 10 rpm wind turbine generators and 10,000 rpm future turbo electric propulsion systems, respectively. Although they do not report validation on prototypes, it is interesting to mention that in both cases MgB_2 wires have been considered for the stator armature windings since they are expected to reduce AC losses because of their multifilament structure [42]. Instead, for the rotors, HTS such as Bi-2223 and YBCO have been considered because of their better superconducting and mechanical characteristics. Nevertheless, the design study in [7] shows that filamentization of HTS does not warrant AC loss reduction and extra care is required if the magnetic field is not directly perpendicular to the tapes.

Fully superconducting AC machines also draw EU funding, such as the Advanced Superconducting Motor Experimental Demonstrator (ASuMED) project. The developed prototype uses REBCO tapes on the stator and HTS stack used as permanent magnets on the rotor [43].

IV. Power Electronics Under Cryogenic Temperatures

The integration of power electronic converters on-board SC electrical machines requires the electronics to be able to operate at cryogenic temperatures. Power electronic systems working at cryogenic temperatures can achieve lower power dissipation and smaller volume and weight, but they need to be designed carefully in order to withstand the unusual temperature range. Many studies have been conducted on the cryogenic behavior of various electronic components [44]. It has been found that semiconductor devices generally perform better at cryogenic temperatures, with higher efficiency and faster commutation speeds, with the exception of silicon carbide (SiC) MOSFETs, that perform worse, and silicon BJTs, that stop working at all. Passive components require attention as well. Ferrite-based magnetic components are not suitable for cryogenic applications due to a significant decrease in magnetic permeability, and while molypermalloy, nanocristalline, and amorphous magnetic cores perform better, all of them show a marked increase in power loss [44]. For capacitors, while NP0, polypropylene, polyphenylene sulfide (PPS), and mica perform well at cryogenic temperatures, for applications requiring high capacitance tantalum is preferable, although its dissipation factor increases, while electrolytic capacitors lose most of their capacitance.

Therefore, electronic power converters for cryogenic applications must use circuit topologies and control techniques which reduce the need for bulk capacitance [45]. Although heatsinks are not required in presence of LN2, a high efficiency of the overall converter architectures is required to minimize the power cost incurred in removing excess heat at very low temperatures.

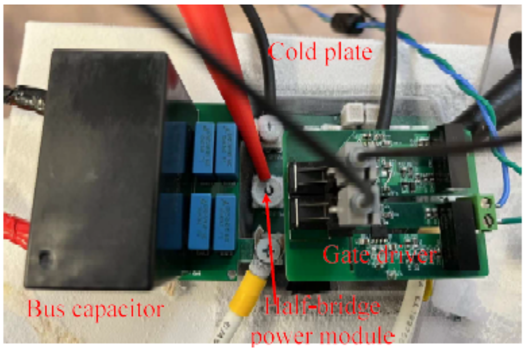

Fig. 6: Experimental setup for cryogenic characterization [53].

The operating temperature of cryogenic electronic devices can be monitored indirectly using so-called temperature-sensitive electric parameters (TSEPs), that can be used as proxies for junction temperature [46]. In turn, this requires models for the power electronic devices covering the target operating temperature range.

Using power electronics under cryogenic temperature generally yields better efficiency; nevertheless, tests for power electronics under cryogenic temperature must be developed and validated to achieve the required overall efficiency and performance of the complete system. Similar tests are used to extend the simulation models of power electronic devices to include very low and cryogenic temperature ranges. Extended temperature range models are necessary in order to be able to predict the behavior of power converters at cryogenic temperatures. Given the current interest in cryogenic operation, many recent papers deal with the characterization of electronic devices under extremely low temperatures, for applications as diverse as digital electronics [47], power electronics [48], [49], radio frequency [50], and quantum computing [51].

In this section, some of the most interesting results, which have been obtained from power electronics under cryogenic temperatures, will be investigated to identify their advantages and challenges. Furthermore, the advanced technologies that have been used to improve their efficiency and reliability are also mentioned.

A. Cryogenic Four-switch Buck-Boost Converter

The four-switch buck-boost converter tested in [52] was designed to improve electric aircraft efficiency performance by employing superconductor cables and machines. Due to the non-suitability of SiC devices for cryogenic applications as a result of carrier freeze out phenomenon, gallium nitride (GaN) was used in this design for its advantages as mentioned in [49]. Recently, specific designs such as a 1 kW GaN based flying capacitor multilevel inverter were evaluated down to 133K and an efficiency enhancement was observed [53]. Furthermore, a 40 kW cryogenically cooled three phase inverter has also been designed and tested [54]. A 650 V GaN HEMT (High Electron Mobility Transistor) cryogenic buck-boost converter was characterized in detail in [52]. The device current was 60 A, and the on-resistance reduction reached around 54% due to electron mobility increase. To obtain the optimal design of the converter, power loss models were developed. Designing the GaN HEMT based half-bridge power module, the current sharing operation was considered through identical parasitic circuits.

The half-bridge power modules, which were designed to build the buck converter, were thermally tested to validate the symmetric gate loop and power loop design. The experimental setup and test with LN2 and cold plates are shown in Fig. 6. It should be noted that only the half-bridge power module was tested under LN2, while the gate driver was working in non-cryogenic conditions.

B. SiC based Converter under Cryogenic Temperature

In [55] the feasibility of a SiC-based converter under cryogenic temperature was investigated. The experiments tested the performance of each component in the circuit. Then, a purposely designed 600 W resonant converter was tested. A symmetric half-bridge with a voltage doubler rectifier was chosen for the resonant converter. To achieve highly efficient power conversion and voltage isolation, resonant converters were used widely in this project.

The SiC MOSFET static characterization was performed under 93K. Due to the malfunction that may happen to the gate driver, the dynamic characterization was performed at 143K. It was observed that the on-state resistance increased around 2.5 times in lower temperatures due to increase of the channel resistance. In addition, it was observed that under the lower temperature, the turn-on speed was slightly improved. For the SiC Schottky Diode component in the system, the energy band gap increased, which led to an increase in forward voltage drop [56]. The selected gate driver showed improper operation when the temperature fell below 143K. At temperatures below 183K, the aluminum electrolytic capacitors started to face problems and failed. Additionally, the capacitance reduced by 5% if compared with the value at the room temperature. Moreover, the dissipation factor for this capacitor had a dramatic increase with the decrease of the temperature. Finally, it was noted that the film capacitor with polypropylene had stable capacitance over the temperature range.

V. Diagnostics and Fault-Tolerance in Superconducting Electrical Machines

In order to maximize the reliability of a superconducting electrical machine, a condition monitoring system and/or a fault-tolerant design should be adopted, by considering the solutions proposed in the literature that may be suitable in cryogenic environment.

In traditional AC motors, the most frequent faults occur in bearings and in stator and rotor windings insulation. Less frequent faults concern airgap eccentricity and lamination core. Diagnostic methods to detect these faults are based on the measurement and analysis of electromagnetic, mechanical and other quantities, e.g. vibration, current, stray flux, voltage, temperature, partial discharges and acoustic noise. Among these quantities, electromagnetic signals are preferred, since often they can be collected by means of sensors already existing in the electrical drive for machine control [57]. These signals are able to detect not only electric faults, but even mechanical faults, since most mechanical faults produce a radial displacement between rotor and stator and, in turn, this displacement brings an asymmetry in the magnetic flux at the airgap. This asymmetry affects the inductances of the machine which determine harmonics in the stator current and in the stray magnetic flux [58].

Compared to traditional applications, cryogenic AC motors are subject to different and more severe stresses, although they are manufactured with special materials suitable for this harsh environment, in particular for insulation [59], [60] and bearings [61], [62]. Therefore, these parts of the machine are expected to be more prone to failure even in cryogenic applications, and especially when the power supply is provided by an electronic converter, which causes greater dielectric stresses in terms of peak voltage and dv/dt at the motor terminals (due to the reflected wave phenomenon) and potentially dangerous bearing currents (due to the common mode voltage at high frequency). For these reasons, suitable diagnostic techniques should take into account two main issues: i) materials for insulating systems and bearings in superconducting machines are different from traditional ones; ii) sensors installed in standard applications may not work properly at cryogenic temperatures.

As for insulating materials, not only their dielectric properties, but also their thermal properties should be considered: in fact, polyimide and polyamide, which have high dielectric strength, cannot be used as pure polymers, due to their high coefficient of thermal expansion, which causes significant contraction in cryogenic environment. Introducing nanoparticles into these polymers can make the material suitable for HTS wires [59], [60].

As for bearings, superconducting magnetic bearings have been proposed [4], but the best solution seems a hybrid deep groove ball bearing with high nitrogen martensitic stainless steel rings, silicon nitride ceramic rolling elements and a glass fibre reinforced PEEK (polyether ether ketone) cage, where the lubricant is replaced by the liquefied gas; the ceramic rolling elements also protect the bearing from a damage that can rise from stray currents induced by the electronic converter.

In HTS electrical drives, sensors installed on the machine, like accelerometers, should be avoided, due to problems arising from the cryogenic environment. Therefore, condition monitoring could be based on the measurement and analysis of the stator current, known as Motor Current Signature Analysis (MCSA), which has proven effective in detecting both turn-to-turn short circuits and bearing faults in traditional AC drives. Nevertheless, its effectiveness has yet to be demonstrated in cryogenic environment.

Moreover, MCSA could be able to detect broken rotor bars in HTS induction motors. In fact, in cryogenic applications, a condition similar to bar breakage may occur in case of quench phenomenon, characterized by a current level, known as quench current, above which the cooling system cannot maintain the winding temperature. In fact, the HTS wires have a resistivity which grows as the wire temperature increases in a highly nonlinear fashion: when the wire approaches a critical temperature, the superconductor resistivity becomes extremely large and can reach a level at which the cooling system is no longer able to limit the winding temperature. In this condition, the winding temperature can climb rapidly to a value that will damage the superconducting winding [63]. Fortunately, this process is slowly progressive, therefore a diagnostic technique can effectively detect it in its early stage, to avoid the failure.

In the literature, coil voltages and acoustic sensors [64] have been used as indicators of the start of the quench process. In the authors' opinion, it is expected that a MCSA-based technique may be able to detect this phenomenon in rotor bars, since a bar in quench condition behaves similarly to a broken bar, due to the extremely large resistivity achieved. As for quench in stator winding, this could be interpreted as a variation of the impedance of one phase and so as an asymmetrical electrical condition, detectable by MCSA as well.

VI. Conclusion

The application of superconductors in electrical machines can potentially increase the achievable specific power to values that would pave the way for the electrification of high demanding applications, such as aircraft propulsion, or the production of lighter machines that have significant power ratings, such as large wind generators. To achieve these targets, researchers are working towards the application of superconductors to the armature windings of AC machines.

This paper reported an overview of selected experimental studies and prototyping activities on the application of superconductors to AC windings of synchronous and asynchronous machines. The reviewed tests on mockups, stator and rotor samples, as well as partially and fully superconducting machine prototypes reveals that the AC losses in superconductors still limits the maximum operating frequency. Different solutions are investigated to limit this loss component, both at superconductor and at the machine design levels. Examples are multifilament superconductors or wound superconducting cables, magnetic flux diverters. However, in this field the research is still working tight to make fully superconducting AC machines competitive.

In the perspective of highly integrated superconducting drives, the research on cryogenic power electronics also moves forward. Many studies have been performed to assess the behavior of the different electronic components that make up an inverter at cryogenic temperatures. Several types of power electronic devices have been found to perform worse, while other show improved efficiency and speed compared to room temperature conditions. Caution must also be used with passive components, which typically perform worse or, at most, the same as at room temperature.

Furthermore, for reliable operation of superconducting and cryogenic integrated drives, diagnostic techniques should be implemented, starting from the solutions proposed in the literature and adapting them to the cryogenic environment.

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