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Perspective

Perspectives on Electric Machines with Cryogenic Cooling

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Abstract: Cryogenic cooling is a well-established and expanding technology. In the field of electric machines, it allows the construction of more efficient machines with a high power density. This paper addresses the main cooling technologies and their impact on cryogenic machine construction, providing perspective for their use in future electrical machines. Although cost and safety issues of cryogenic systems are still holding back the uptake of cryogenic electric motors and generators, research in this field should provide significant improvements and promote their use at different levels.

Keywords: cryogenic cooling system; superconducting machine; temperature impact; electrical resistance measurement; performance

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1. Introduction

Electric machines with cryogenic cooling are still in the research and development phase. Cryogenic cooling has been shown to improve the performance and efficiency of electric machines by reducing winding resistance, eddy current losses [1], and core losses [2]. However, this technology is still not widely adopted in the industry due to its high cost and complexity. In addition, technological challenges still need to be overcome, such as the need for specialized insulation materials that can withstand the extreme temperatures of cryogenic cooling. Overall, research is underway in this area to develop more efficient and cost-effective ways to implement cryogenic cooling in electric generators, electric vehicles, and ships, and in other fields requiring small electric machine sizes with significant power. In general, cryogenic cooling systems used for electrical machines [3] usually use cryogenic fluids and particular cooling techniques. The paper has two main purposes:

- To provide a short review of superconducting machines (SCMs) with a description of different technologies used for cryogenic motors and generators. In particular, the cooling systems, cryogenic fluids, and materials used for cryogenic electrical machines will be treated;
- The second objective is to illustrate the perspective of electric machines with cryogenic cooling where possible research paths are suggested for the next few years.

Overall, the paper provides an aid to engineers and designers to build a clear picture of the techniques and materials used for cryogenic electric motors and evaluate this technology's prospects.

2. Superconducting Machines

In recent years, the world of research and industry has focused on researching the reduction of CO_2 emissions using all-electric solutions with ever-greater efficiencies [4]. Superconducting machines (SCMs) have the potential to offer higher power densities, higher efficiency, and reduced size and weight compared to traditional electric machines.

2.1. Applications of Superconducting Electric Machines

Superconducting electric machines have promising prospects for various applications. Some of these applications include:

- Electric propulsion: The development of superconducting machines for electric cars is still in the research and development phase, while for naval applications there were prototypes built in 2018 by General Atomics Electromagnetic Systems (GA-EMS) for the US Navy with 36.5 megawatts of power [5] and that of the companies Northrop Grumman and Rolls-Royce, which in 2019 announced that it had developed a prototype superconducting generator for use in naval propulsion systems [6]. Studies on electric ship propulsion [7] have shown that superconducting synchronous motors can achieve efficiency levels greater than 99% at full load, allowing traveling longer distances. The efficiency remains constant even at low loads, which is particularly important for ship propulsion, as ships employ around 30% of the maximum power at cruise speed. Additionally, the use of superconductors provides the potential to reduce the weight and volume of the motor, which can have a significant impact on the overall weight and size of the propulsion system;
- Wind turbines: Superconducting generators could increase the power output of wind turbines [8], especially offshore ones, by reducing the size and weight of the generator and increasing the efficiency [9]. In the year 2019, by the EU H2020 EcoSwing project [9], the world's first rotor for a 3.6 MW wind generator was successfully tested. The compatibility of the technology has been demonstrated with all the real impacts present in an operating environment such as variable speeds, network failures, electromagnetic harmonics, vibrations, etc., and with the volume of the active parts 50% lower, therefore lighter than the permanent magnet machines;
- Aeronautics: The development of superconducting aircraft motors is still in the research and development phase, and there are currently no commercial superconducting aircraft motors available on the market. However, there has been a growing interest in using superconducting technologies in aircraft propulsion systems due to their potential for high efficiency, power density, weight savings, and reduced emissions [10–12]. In 2020 the ASuMED project [13] was successfully closed and demonstrated on a prototype the advantages of a new fully superconducting motor with about 1 MW of power at 10,000 rpm a thermal loss $< 0.1\%$ with a power density of 20 kW/kg 99.9% motor efficiency. Currently, there is a major Airbus project named ASCEND (advanced superconducting and cryogenic experimental powertrain demonstrator) [14,15] aimed at developing a hybrid-electric demonstrator aircraft which is at an advanced stage;
- Industrial applications: Superconducting motors and generators could be used in various industrial applications, including compressors, pumps, and conveyors, where high power density, efficiency, and reliability are required. Several research activities are currently underway which aim to make this technology reliable. In this paper, the problems and the current technologies used to overcome them will be dealt with in Section 2.9;

Although superconducting electric machines offer the potential for significant improvements in efficiency, power density, and reliability compared to traditional electric machines, challenges remain, including cost, materials availability, and integration with existing systems. Those challenges will be dealt with in the following.

2.2. Types of Superconducting Machines

Superconducting windings have zero electrical resistance at very low temperatures, which allows for very high current densities and high efficiency [16]. There are three main types of superconducting machines:

1. Superconducting synchronous machines (SCSMs): These are synchronous machines that use superconducting windings in their rotor or stator. They can be used as generators [8] or motors [17], and provide high power density, high efficiency, and high power factor. Studies have shown that SCSMs can achieve efficiency levels of 99% at full load [7], compared to conventional motors that typically operate at around 94–96% efficiency;

2. Superconducting induction machines (SCIMs): These are induction machines that use superconducting windings in their rotor. They have high efficiency and power density, especially in applications that require high torque and low speed operation, but their power factor is lower than that of SCSMs. Studies have shown that SCIMs can achieve efficiency levels greater than 98% at full load [18], compared to conventional induction machines that typically operate at around 80–90% efficiency;
3. Superconducting homopolar machines (SCHMs): They have been considered for high speed applications [19] and ship propulsion [19]. However, technical problems, mainly related to the complexity of their brushes, have kept these machines at the concept level.

Losses in SCSMs and SCIMs are caused by mechanical friction, electrical resistance within the windings, eddy current effects, and hysteresis.

In addition to power loss, SCMs have several advantages over traditional electric machines:

- High power density: Superconducting windings allow for very high current densities, meaning that the machine can be made smaller and more compact;
- High power factor: Superconducting windings have a very low reactance, meaning that the machine has a high power factor;
- Low noise and vibration: Superconducting machines have low iron losses and winding losses, meaning that they produce less noise and vibration.

However, SCMs also pose some challenges that need to be overcome before they can be widely adopted in the industry. These challenges include the need for low temperatures to maintain superconductivity, the cost and complexity of cryogenic cooling systems, and the need for specialized insulation materials that can withstand low temperatures.

2.3. Cooling Systems of Superconducting Machines

Usually, the selection of the cooling systems for superconducting machines is conducted based on the personal or technical experience of the machine engineers and designers. An incorrect calculation of the cooling system makes the electric machine unreliable or with a high fault rate. The fluids commonly used for both AC and DC electric machines are liquid nitrogen (LN2) or liquid helium (LHe). Cooling systems for superconducting machines are essential to maintain the superconducting state of the materials used in the windings, which typically require temperatures below the critical temperature of the superconducting material.

The most common cooling systems for LN2 or LHe used in superconducting machines are:

1. *Cryocoolers*: A refrigerator designed to reach cryogenic temperatures below −153 °C (120 K) is often called a cryocooler. These are refrigeration systems that use a closed-loop cooling system to maintain the low temperatures required for the superconducting materials [20]. They can be based on Gifford–McMahon [21], pulse tube, or Stirling cycle technology [22]. These cooling systems are typically used in low-power superconducting devices and systems.
2. *Forced-flow cooling*: In this method, LHe [23] or LN2 is circulated through the superconducting windings to cool them. The liquid is cooled in a heat exchanger before being recirculated. Recently a new technique called rotary cryocooler was placed inside the rotating shaft which is used for cryogenic cooling of the rotor coil [24]. The most common solution is to use a rotating cryostat to cool the rotor of the machine as shown in Figure 1;
3. *Immersion cooling*: This method involves immersing the superconducting windings in a bath of LHe or LN2 [25]. This method is more efficient than forced-flow cooling but it is also more complex and difficult to implement Figure 2;
4. *Pumped Two-Phase (P2P) cooling* [26]: This method uses helium (He) or nitrogen (N) in both liquid and gas phases to cool the superconducting windings. The liquid phase absorbs heat, and the gaseous phase carries the heat away Figure 3;

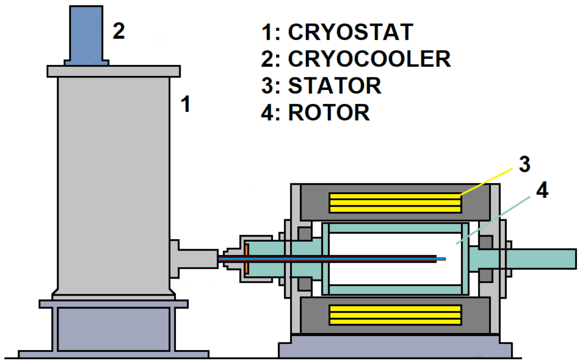

Figure 1. Electric machine with rotating cryostat for rotor cooling.

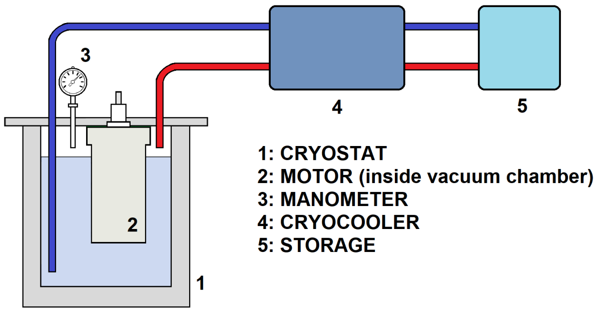

Figure 2. Electric machine cooled in the cryostat.

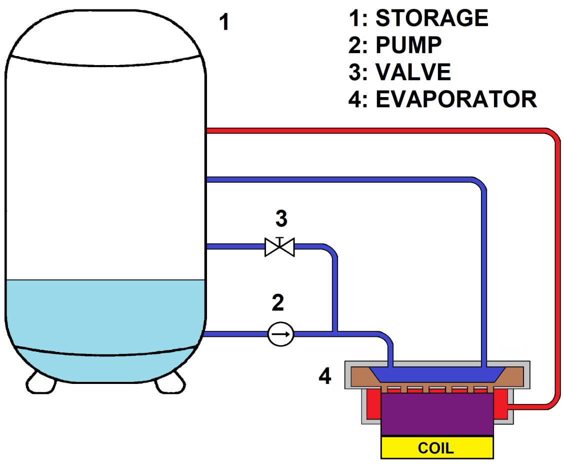

Figure 3. Typical structure of the pumped two-phase (P2P) cooling.

5. *Spray cooling* [27]: LN2 is sprayed onto the stator winding to cool it. This method is also less effective than immersion cooling, but it is simpler to implement;

The choice of the cooling system depends on the specific requirements of the application and the design of the superconducting machine. Figure 4 shows the map of cryocooler applications in the plane of cooling capacity as a function of temperature. Cryocoolers are commonly used in low-power superconducting devices and systems, while forced flow or immersion cooling is used in high-power systems such as superconducting generators or motors.

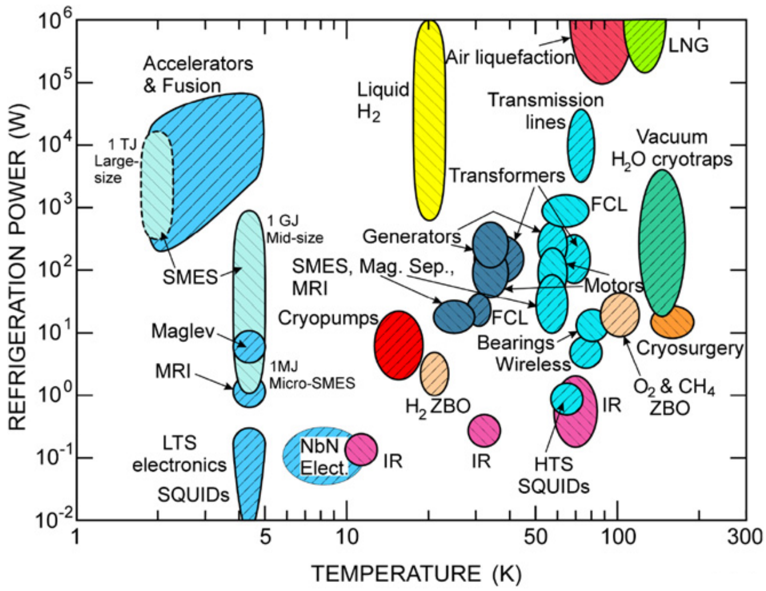

Figure 4. Map of cryocooler applications in the plane of refrigeration power versus temperature [28].

In recent years the aircraft industry has been studying new cooling systems for the electric machine that use hydrogen (H) [29] although it is not as common as other cryogenic cooling methods. There are several ways to use hydrogen as a cooling agent for electric machines:

1. Direct injection cooling: H2 is directly injected into the winding of the machine, where it cools the winding by absorbing heat;
2. Forced-flow cooling: H2 is circulated through the machine's windings using a pump, where it absorbs heat and then is cooled in a heat exchanger before being recirculated;
3. Two-phase flow cooling: H2 is circulated through the machine's windings in a two-phase flow, where it exists both as a liquid and a gas. The liquid phase absorbs heat, and the gaseous phase carries the heat away.

The use of hydrogen as a cooling agent for electric machines has some advantages such as being a clean, environmentally friendly, and non-toxic coolant. However, the technology is still in the development phase, which means that it is not yet widely adopted and it has some technical challenges such as leakage, safety, and reliability issues. Additionally, hydrogen is flammable, which requires special safety precautions to be taken when handling and storing it.

2.4. Cryogenic Fluids

A fluid, to be considered "cryogenic", must be able to operate below the threshold of –153 °C (120 K), as established by the scientific community and widely accepted and used by various industries and fields of study. Cryogenic fluids can be used in various applications, such as cooling, refrigeration, and transportation of materials at extremely low temperatures. The most common types include:

1. *Liquid nitrogen (LN2)*: Nitrogen exists as a liquid at temperatures below −195.8 °C (77 K). It is relatively inexpensive, abundant, and non-toxic. It is commonly used as a coolant in various applications, such as in cryogenic cooling systems for electric machines, cryogenic storage for biological samples, and food freezing;
2. *Liquid helium (LHe)*: Helium exists as a liquid at temperatures below −268.9 °C (4.25 K). It is less abundant and more expensive than liquid nitrogen, but it has a much lower boiling point, which makes it useful in applications that require even lower temperatures. It is commonly used in cryogenic cooling systems for superconducting machines, particle accelerators, and in cryocoolers;

3. *Liquid hydrogen (LH2)*: Hydrogen exists as a liquid at temperatures below −252.87 °C (20.28 K). It is an efficient coolant and has high thermal conductivity and low viscosity. It is used in a variety of applications as a coolant [30], such as in fuel cells, rocket propulsion, and in the aerospace industry;
4. *Liquid neon (LNe)*: Neon (Ne) exists as a liquid at temperatures below −246 °C (27 K). it is similar to liquid helium and liquid hydrogen in terms of cooling performance.

Like liquid nitrogen, liquid helium can be used as a cooling agent for electric machines to improve their performance and efficiency. By using LN2 or LHe, the winding resistance of the machine can be reduced, which leads to a lower copper loss and an increase in the power factor. Additionally, soft materials with high internal resistivity, such as soft magnetic composites (SMCs), can reduce the eddy current loss in the stator core. It has been experimentally proven that the magnetizing characteristic does not change significantly in the range between 77 K and 300 K (−196.15 °C and 26.85 °C), while the presence of the magnetic material increases the useful component of the flux density [31,32]. The overall effect is an increase in the machine's efficiency, which can lead to energy savings.

LN2 cooling can have significant advantages in improving the efficiency of electric machines, but it also requires significant infrastructure and handling precautions. LN2 can be dangerous to handle, and it requires specialized storage and transfer equipment. LHe cooling has similar advantages and disadvantages to LN2 cooling. Like LN2, LHe is a cryogenic fluid, also requiring specialized equipment. LHe is more expensive than LN2, and has a much lower boiling point (Table 1) making it more difficult to handle and requiring more complex insulation materials. Additionally, LHe is a rarer element than Nitrogen. LHe cooling is typically only used in high-performance or high-power machines, such as high-field superconducting magnets in particle accelerators, or cryocoolers. The scientific community is directing research into alternative fluids such as LH2 by developing new, more reliable storage technologies. Hydrogen has a lower liquefaction point and higher thermal conductivity than nitrogen or neon used in available cryogenic systems [33]. Therefore, applying hydrogen to cryogenic systems can be a viable alternative to increase efficiency and stability.

Table 1. Chemical–physical properties of most common fluids in cryogenic cooling systems [34].

Coolant	Critical Temperature (K)	Critical Pressure (kPa)	Density (g/L @ Room Temperature)	Boiling Temperature (K)	Molar Gas (g/mol)	Latent Heat (J/kg)	Specific Heat Ratio of Liquid Phase	Viscosity ($NSm^{-2} \times 10^{-5}$)	Toxic	Flammable
N_2	126.2	3390	1.25	77.35	14.01	199.000	1.4	1.69	No	No
H_e	5.19	228.32	0.178	4.22	4	23.300	1.66	3.16	No	No
H_2	32.938	1285.8	0.089	20.28	2.01	58.000	1.405	1.34	No	Yes
N_e	44.4918	2678.6	0.9	27.1	20.17	331.700	1.66	1.17	Yes	No

For completeness, other cryogenic fluids are also listed [35], but have limited use. Among these we find: fluorine (F), which has a boiling point of −188 °C (85 K), but is highly toxic and is extremely reactive, as it reacts with all other elements except light inert gases; argon (Ar) has a boiling point of −186 °C (87 K) and is a non-toxic, extremely stable, odorless chemical element. However, due to its specific weight, argon tends to stagnate in rooms, therefore storing large quantities of argon in small, closed rooms is dangerous in the event of leaks. Methane (CH4) has a boiling point of −161 °C (112 K), and is normally stable, but burns read. It rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature, so it is dangerous in the event of a leak. Air has a boiling point of −194 °C (79 K), and oxygen has a boiling point of −183 °C (90 F) even if they are part of the cryogenic fluids, but there are problems of use.

2.5. Materials Used for a Cryogenic Electric Machine

The materials used in electric motors for cryogenic cooling systems must be able to withstand the extremely low temperatures and the high thermal stresses caused by the rapid temperature changes associated with the cryogenic cooling process. Some of the materials that are commonly used in electric motors for cryogenic cooling systems include:

1. *Copper*: copper (Cu) is commonly used as the conductor material in the resistive windings of electric motors for cryogenic cooling systems [36,37]. It has good electrical conductivity and is relatively inexpensive. If cooled with LN, the resistivity of copper drops by 90%, therefore, cooling of resistive windings can be considered [38]. However, copper also has a relatively high coefficient of thermal expansion which can make it difficult to use in some applications;
2. *Aluminum*: aluminum (Al) is also used as a conductor material in the windings of electric motors for cryogenic cooling systems [39]. It has good electrical conductivity and a lower coefficient of thermal expansion than copper, which makes it easier to use in some applications;
3. *Superconductors*: Superconductors are materials that have zero electrical resistance at very low temperatures. They are used in the windings of superconducting motors for cryogenic cooling systems. They include materials such as niobium–titanium (NbTi) and niobium–tin (Nb3Sn) [31,40] that are used at temperatures below −269 °C (4 K), and high-temperature superconductors (HTS) such as yttrium barium copper oxide (YBCO) [41] that are used at temperatures above −269 °C (4 K). Superconducting wires are generally composites: the superconducting filament or tape covers non-superconducting matrix material, such as copper or silver. The matrix material provides mechanical support for the superconducting filament;
4. *Insulation materials*: Insulation materials such as polyimide (PI), polyamide–imide (PA) [42], and epoxy [43] are used to insulate the windings of electric motors for cryogenic cooling systems. These materials must be able to withstand the extremely low temperatures and the high thermal stresses associated with the cryogenic cooling process;
5. *Cryogenic steels*: In cryogenic applications, steels have become the preferred/dominant structural material for cryogenic applications. The choice is due to the combination of strength and toughness, and to obtain greater resistance to cryogenic temperatures in recent years, research has led to the development of a wide range of steels tailored with additives for specific applications [44,45];
6. *Bearings*: The use of cryogenic bearings in electric motors can have some disadvantages with mechanical bearings, such as difficult lubrication and short life. The use of superconducting magnetic bearing (SMB) [46,47], compared to traditional bearings, means a longer life due to reduced friction and vibration.However, manufacturing cryogenic bearings in electric motors comes with many challenges, such as the need for specialized materials and manufacturing processes, high cost, and lack of experienced field personnel.

Figure 5 shows the thermal conductivity of materials as the temperature varies [48].

The study concludes that welding on (typically soft) metals, at cryogenic temperatures (e.g., liquid nitrogen), its yield strength increases many times within −196.15 °C (77 K). Consequently, if the rig survives cooling in liquid nitrogen, not much will happen (mechanically) for further cooling to liquid helium temperature [49].

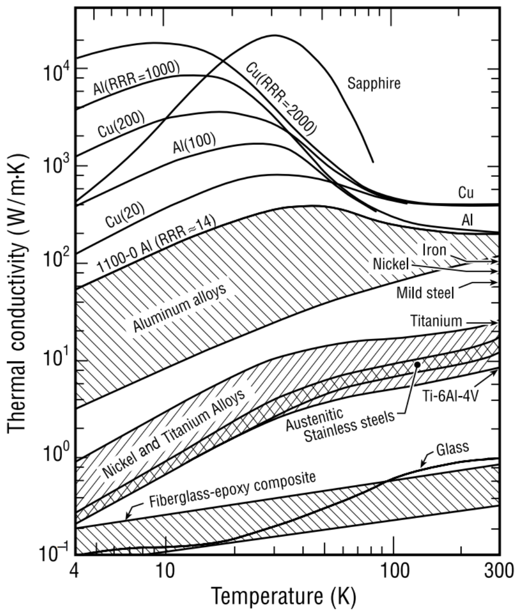

Figure 5. Thermal conductivity of selected classes of materials (ASM 1983) [48].

2.6. Cold and Cryogenic Power Electronics

The latest generation electric motors are usually equipped with power electronics that can be cooled with cryogenic systems. In general, cold power electronics or cryogenic power electronics (CPE) refers to the technology of using power electronic devices and systems that are operated at low temperatures, such as cryogenic temperatures, to improve their performance and efficiency. The main advantage of CPE is that it allows for the reduction of power losses in electronic devices, which leads to an increase in efficiency and power density. CPE uses temperatures below −20 °C (253.15 K), such as liquid nitrogen or liquid helium, to operate electronic devices and systems. The characteristics of various power devices at cryogenic temperatures were studied by Leong [50], and the behavior at various temperatures are summarized in net chart Figure 6. The chart represents the behavior of the semiconductor switch. The 100% represents the optimal regions for the usage, while lower values correspond to the regions where the behavior of the switches shows inadequate behavior.

- Si N-channel MOSFETs in the range, of 20–50 K, show little degradation in ON-state, and negative temperature dependence, while the optimum range of operation is between 60 K and 80 K;
- Si P-channel MOSFETs show non-ohmic behavior due to negative temperature below 60 K, while their optimum operating temperature is over 90 K;
- SiC MOSFETs show no improvements compared to higher temperatures, and their temperature dependence changes its sign around 50 K;
- GAN HEMTS is almost independent of the temperature below 50 K and slightly dependent on the temperature over that temperature;
- GaAs Schottky diodes show not negligible improvements at high currents.

Consequently, silicon N-channel power MOSFETs are most suitable for cryogenic applications as they can achieve extremely low on-state resistance and reasonable breakdown voltages. Other researchers have analyzed power devices at cryogenic temperatures and agreed with this study, but added that the power modules have silicone gels material inside them which makes them less suitable for cryogenics [51]. Consequently, the best modules are those made of ceramics or materials that resist cryogenics.

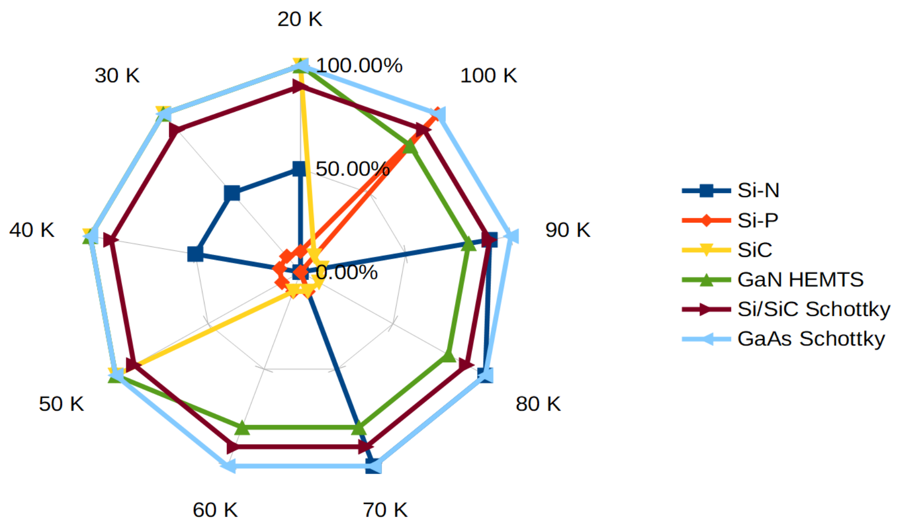

Figure 6. Behavior of the semiconductor switch at cryogenic temperatures (Data adapted from [50]).

2.7. Cryocooler Performance

The efficiency of a cryocooler is a measure of how much energy is required to achieve a given cooling capacity. This parameter is typically measured in coefficient of performance (COP) or terms of the specific cooling power (SCP). The cooling capacity of a cryocooler is the amount of heat that can be removed from the cooled object per unit of time. This parameter is typically measured in watts (W) or watts per hour (Wh). Cryocoolers are designed for specific applications, so the performance parameters vary depending on the specific application. The cryocooler performance is also affected by the environment and the cooling demand of the system, so it is important to match the cryocooler to the specific application. The five kinds of cryocoolers most commonly used to provide cryogenic temperatures for various applications are the Joule–Thomson, Brayton, Stirling, Gifford–McMahon, and pulse tube cryocoolers [28]. A comparison of cryocooler efficiencies near 80 K (the largest application area for small cryocoolers) is given in Figure 7.

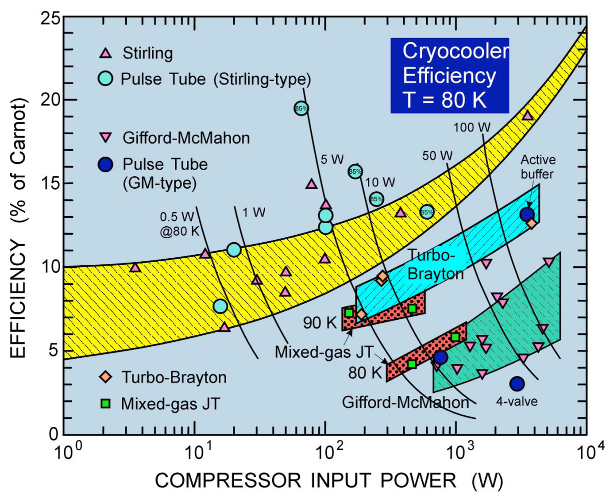

Figure 7. Cryocooler's actual performance at 80 K [28].

For higher operating temperatures the efficiency of the cryocooler will be higher, as shown in Figure 8.

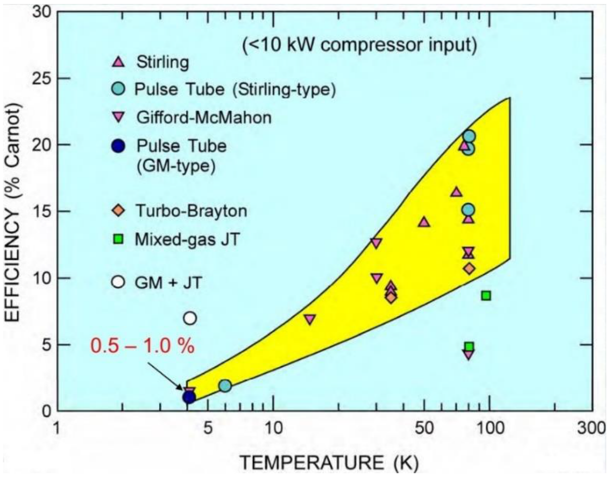

Figure 8. Efficiency of small cryocoolers <10 kW [28].

Efficiencies at 80 K can reach about 20% Carnot for the best cryocoolers (for space), while commercial cryocoolers typically achieve 10–15% Carnot. For low-temperature superconducting (LTS) at 4 K we have the minimum efficiency with a value of about 1%. Various modeling studies [52] have shown that regenerators, optimized for He-3 at a pressure of about 0.5–1.0 MPa can increase efficiencies at 4 K.

2.8. Mathematical Model of Machines with Cryogenic Cooling

Cryogenic and standard electric machines have many common mathematical relationships because they both operate based on the principles of electromagnetic induction. The main difference is that cryogenic machines operate at very low temperatures, where the resistance of the motor windings is greatly reduced due to the superconducting properties of the materials used. Here are some common parts in the mathematical relationships between cryogenic machines and standard machines:

- *Electromagnetic equations*: The basic equations that describe the behavior of electric machines, such as Faraday's law, Ampere's law, and Gauss's law, apply to both cryogenic and standard machines. These equations relate the magnetic field, current, voltage, and other parameters of the machine;
- *Circuit equations*: The circuit equations that describe the behavior of electric circuits, such as Kirchhoff's laws and Ohm's law, also apply to both cryogenic and standard machines. These equations relate the current, voltage, and resistance of the circuit components;
- *Motor equations*: The equations that describe the behavior of electric motors, such as the stator and rotor equations, the torque equation, and the power equation, are also common to both cryogenic and standard machines. However, in cryogenic machines, modifications may be needed to account for the superconducting properties of the materials used;
- *Cooling equations*: Cryogenic machines require cooling systems to maintain their low operating temperatures, so equations that describe the behavior of heat transfer and thermodynamics may be needed to model the cooling system. These equations may be modified to account for the unique properties of cryogenic cooling, such as the use of liquid nitrogen or helium or other as the coolant.

Overall, the main difference in the mathematical relationships between cryogenic and standard machines is that cryogenic machines require modifications to account for their superconducting properties and cooling systems. However, the basic principles of electromagnetic induction, circuit theory, and motor theory still apply to both types of machines. It must be considered that, to avoid saturation of the cores and further reduce losses, very often superconducting machines have no teeth or cores, meaning that the flux lines distribution is more complicated than in traditional machines. A rough comparison between the power densities of standard and superconducting machines can be made based on the air gap power. The air gap power of an induction machine without stator teeth, with less distortion of the induction distribution at the air gap and reduced synchronous reactance (0.3–0.5 per unit) is:

$$S_d = \frac{\pi^2}{60\sqrt{2}} \cdot n \cdot B_m \cdot K \cdot D^2 \cdot L \quad (1)$$

where n is the number of conductors in the slot; B_m is the maximum value of the magnetic induction at the air gap; K is the linear armature current density; D is the bore diameter; L is the active length of machine.

In radial-flux machines, the electric loading is proportional to the slot height:

$$K = J_a \cdot h_a \quad (2)$$

where J_a is the armature current density, and h_a is the slot depth of armature.

On the other hand, in superconducting machines, the excitation flux density is proportional to the height of the excitation coils:

$$B_m \propto h_e \quad (3)$$

where h_e is the height of the excitation coil.

Substituting, we have:

$$P \propto D^2 \cdot L \cdot h_a \cdot h_e \cdot J_a \quad (4)$$

In standard machines, the electric loading reaches around 60,000 A/m and Bm is limited by the saturation of the magnetic circuit. In superconducting machines, the Bm increases with the height of the rotor coil, namely with the machine diameter, thus Bm reaches 0.8T for standard motors and $1.5 - 2T$ for larger cryogenic motors. Therefore, for standard motors, the torque density varies linearly with the third power of the characteristic length, while, for superconducting machines, it depends on the fourth power of this dimension:

$$P \propto D^4 \quad (5)$$

This means that superconducting machines are more advantageous at high powers.

2.9. Problems in the Uses in Industrial Applications

The use of cryogenic electric machines for practical industrial applications can offer many advantages, such as high efficiency, high density of power, and small size and weight. However, several restrictions and challenges must be considered. Some of these include:

- *Material compatibility*: Cryogenic temperatures can cause materials to become brittle, which leads to corrosion or mechanical failure. It is important to select materials compatible with cryogenic temperatures and perform regular inspections and maintenance to ensure materials do not deteriorate over time;
- *Cryogenic fluid leaks*: Cryogenic fluids such as liquid nitrogen and liquid helium are potentially hazardous, and leaks can be dangerous to personnel and equipment;
- *Temperature gradients*: Cryogenic cooling systems can create significant temperature gradients in the equipment being cooled. This can cause thermal stresses and mechanical deformation, which can lead to equipment failure over time;
- *Thermal expansion*: Cryogenic temperatures can cause materials to contract, which can lead to stress and deformation in the machine. This can cause parts to become misaligned and lead to mechanical failure;
- *Electrical insulation*: Cryogenic temperatures can cause electrical insulation materials to become brittle, which can lead to electrical breakdown and failure. It is important to use materials that are designed for use in cryogenic environments and to perform regular insulation testing;

- *AC loss*: Traditionally, the major obstacle to the diffusion of superconducting machines is considered the AC loss behavior of the superconducting windings [53]. Superconductive windings are commonly said to not tolerate high frequencies, as the AC loss increase may lead to thermal instability and, finally to quenching. Quench is a local phenomenon that may lead to winding disruption. This factor has limited the application of superconducting windings to field windings. Today, the availability of rare-earth barium copper oxide (REBCO) superconductors with high critical temperatures, allows the superconductor tape to withstand higher frequencies, opening the way to new machine configurations, with AC superconductive windings. The most common HTS belongs to the REBCO family. In particular, the most used rare earth in HTS is yttrium, which is used in the YBCO superconductor. Unfortunately, the fabrication technology of HTS is complex and expensive, although new production processes produce generations of HTS with increased reliability and cost-effectiveness. Recently, a new technique for fabricating MgB2 based superconductors, called reactive Mg-liquid infiltration [54], has been exploited to evaluate spirals and ring coil windings [55]. An extensive characterization of HTS coils can be found in [31]. The frequency dependence of the coil resistivity with the frequency, in the range 10–100 Hz can be approximated as:

$$R_{coil} = K_{sc} * f \tag{6}$$

  where R_{coil} = resistivity of coil, K_{sc} = constant typical of each superconductor type, f = frequency;
- *Complexity of the cooling system*: Cryogenic cooling systems can be complex, requiring specialized equipment and expertise to design, install, and maintain.
- *Energy consumption*: Cryogenic cooling systems can consume a significant amount of energy, therefore before use, it is necessary to make an overall energy balance of the equipment or system to determine if it is cost-effective for that application;

In addition, cryogenic electric machines also suffer from vibrations and stray magnetic fields affecting the metal part. Vibration is a significant problem due to the high stiffness and brittleness of materials at cryogenic temperatures. At these temperatures, the mechanical properties of materials change, making them more susceptible to cracking and breaking under mechanical stress. This can lead to a decrease in machine performance and reliability. Furthermore, the operating frequency of the machine can influence the behavior of superconducting materials, making it important to design the machine to operate at specific frequencies. To address these issues, the design of cryogenic electric machines must take into account the effects of vibration and frequency on machine performance and reliability. This can include the use of specialized materials and coatings to reduce vibration and improve mechanical stability, as well as the use of specific operating frequencies to optimize machine performance. Furthermore, particular care must be taken in the design of the cryostat due to the stray magnetic fields affecting the metal parts. In the presence of magnetic fields, the choice of materials for cryostat construction becomes more limited. Magnetic fields can induce electrical currents in certain materials, which can generate heat and cause the materials to lose their superconducting properties if they are being used for that purpose. Therefore, in applications where magnetic fields are present, the cryostat must be constructed using materials that are not magnetically conductive. Some materials that are commonly used in cryostats in the presence of magnetic fields include:

- *Non-magnetic stainless steel*: Non-magnetic stainless steel, such as grade 304 L, is commonly used in cryostat construction for applications where magnetic fields are present. This material has low magnetic permeability, which means it is not easily magnetized by an external magnetic field;
- *Aluminum alloys*: Certain aluminum alloys, such as 5083 and 6061, are non-magnetic and are commonly used in cryostat construction for applications where magnetic fields are present. These alloys have low magnetic permeability and are also lightweight and relatively inexpensive;

- *Titanium alloys*: Certain titanium alloys, such as Ti-6Al-4V and Ti-3Al-2.5V, are non-magnetic and are commonly used in cryostat construction for applications where magnetic fields are present. These alloys have low magnetic permeability and are also corrosion-resistant and strong;
- *Copper alloys*: Some copper alloys, such as Cu-Ni alloys (such as Monel) and brass, have low magnetic permeability and are suitable for use in cryostats in the presence of magnetic fields. However, copper alloys can be more expensive than other materials and may corrode in the presence of certain cryogenic fluids.

Thus, the choice of materials for cryostat construction in the presence of magnetic fields depends on a variety of factors, including the strength and orientation of the magnetic field, the specific application, and the required performance characteristics of the materials. It is important to select materials that are not magnetically conductive and that can withstand the stresses and thermal cycling that occur during operation.

Sealing rings in a cryogenic motor can be affected by the presence of stray magnetic fields. These fields can induce eddy currents in the sealing ring, which can lead to heating and a reduction in the sealing efficiency. To prevent the effects of stray magnetic fields, non-magnetic materials are typically used for the sealing rings in cryogenic motors. Materials such as non-magnetic ferrofluid gaskets [56] are often used, which perform very well from this point of view, even if very expensive. These materials have low magnetic permeability and can withstand the cryogenic temperatures of the motor.

Overall, a cryogenic electric machine for use in industrial environments requires careful planning, design and maintenance to ensure safe and reliable operation. The choice of motor materials depends on various factors, including the required magnetic field strength, temperature, and mechanical stress. The material properties also play a significant role in determining the efficiency and performance of the motor. It is important to carefully consider the selection of materials to optimize the performance of the superconducting motor in the presence of magnetic fields to cryogenic temperatures.

3. Prospective Electric Machines with Cryogenic Cooling

The use of electric machines with cryogenic cooling is an active area of research and development. The main perspective is to increase the efficiency and performance of electric machines, which can lead to energy savings and reduced environmental impact. However, some challenges need to be overcome before this technology can be widely adopted in the industry. The challenge we should face in the next 10 years will be to transfer a part of the research to the industries, providing a consolidated design technique for cryogenic engines. Furthermore, the technical personnel currently working in the electric motor industries do not have the training or specialization to operate in this sector. A lot of work will be asked of universities, to integrate courses for cryogenic design, and highly specialized courses for the issue of installation/safety licenses to work in this field.

In addition, there are other challenges to be faced in the field of industrial research:

1. *High-temperature superconductors* (HTS): The research in this field is producing new superconductors with higher critical temperatures. The use of these HTS materials in cryogenic motors could allow for operation at higher temperatures, which would reduce the cost and complexity of the cooling systems;
2. Improved cooling systems: Research is ongoing to develop more efficient and cost-effective cryogenic cooling systems for electric motors, such as two-phase flow cooling systems and immersion cooling systems;
3. Improved insulation materials: Researchers are exploring new insulation materials that can withstand the low temperatures and high thermal stresses associated with cryogenic cooling, which could improve the performance and reliability of cryogenic motors;
4. Intelligent control systems: The use of advanced control systems and artificial intelligence algorithms to optimize the performance of cryogenic motors in real-time;

5. Cryogenic energy storage (CES): Cryogenic energy storage is a promising technology that uses cryogenic temperatures to store energy in the form of liquid hydrogen or liquid helium. This technology could be used in conjunction with cryogenic motors to improve the overall efficiency and performance of the system;
6. Superconducting magnetic energy storage (SMES): Superconducting magnetic energy storage is a new technology that stores electricity from a source within the magnetic field of a coil made of superconducting wire with almost zero energy loss. This technology could bring many benefits to electric motors, for example during the braking phase we could recover a part for the next restart;
7. Advanced materials and manufacturing techniques: The use of advanced materials, such as carbon nanotubes, and manufacturing techniques, such as 3D printing, could allow for the development of more efficient and reliable cryogenic motors;
8. Cryogenic motors with integrated power electronics: Combining cold power electronics and superconducting machines can provide several advantages which lead to an increase in system efficiency with a reduction in power losses. It can also increase the power density of the system, allowing for smaller and more compact designs. Additionally, by operating the power electronics and machines at low temperatures, the system may produce less noise and vibration.

As listed, there are still many issues to be addressed before this technology can reach a wider range of applications. On the other hand, cryogenic cooling systems are complex and expensive to implement and require specialized insulating materials that can withstand the extreme temperatures of cryogenic fluids. The cost of cryogenic fluids, the complexity of the cooling system, and the need for specialized insulation materials are factors slowing market uptake. Furthermore, until all the technological challenges (especially those relating to safety systems in the event of accidental losses or losses caused by third parties, reliability issues in static or dynamic conditions, durability, and predictive maintenance) are addressed, cryogenic electric motors represent a technology that will only operate in the high-level industrial or research field. Despite these challenges, the use of cryogenic cooling in electric motors is an active area of research, and this technology is expected to become increasingly cost-effective in a few years, encouraging its use.

Overall, while the technology is still evolving, cryogenic electric motors have the potential to improve the efficiency and performance of electric motors and other electrical systems in the future, but they still require further research and development to overcome the challenges and make them more cost-effective and practical for wide-scale adoption.

Furthermore, it must be considered that cryogenic motors need special accessories, such as cables fault current limiters (FCL) and fast-acting circuit breakers (FACBs). The use of cryogenic cooling can be extended to these devices to improve motor performance, reduces size, and improves efficiency. The use of cryogenic cables leads to lower energy losses and therefore they achieve a higher power density, and as this technology does not produce heat, it is considered environmentally friendly. The use of cryogenic FCLs and FACBs can provide several advantages, achieving higher efficiency due to reduced power losses, and higher reliability as they are less subject to wear with higher power density in a compact size.

4. Conclusions

This article has summarized the most recent developments in technologies and findings that can boost the application of superconducting motors and generators. Large superconducting machines are currently used primarily in ship propulsion and wind power generation. However, the new generations of HTS, efficient cooling systems and means, and other devices such as superconducting protection systems should help to spread this technology further, opening new technological scenarios with more efficient and powerful machines in the near future. However, for cryogenic electric motors to become a large-scale industrial product, there is still a lot of work to be carried out in various areas, such as research, industry, and regulatory issues. However, the significant benefits of cryogenic electric motors are increased efficiency and power density, resulting in a reduction in mass.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	alternating current
Al	aluminum
Ar	argon
ASCEND	Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator
Cu	copper
CES	cryogenic energy storage
CH4	methane
COP	coefficient of performance
CO_2	carbon dioxide
CPE	cryogenic power electronics
Cu	copper
DC	direct current
F	fluorine
FACBs	fast-acting circuit breakers
FCL	fault current limiters
GA-EMS	General Atomics Electromagnetic Systems
H	hydrogen
H2	chemical formula for hydrogen (dihydrogen)
He	chemical formula for helium
HTS	high-temperature superconductors
LH2	liquid hydrogen
LN2	liquid nitrogen
LHe	liquid helium
LNe	liquid neon
LTS	low-temperature superconducting
N	nitrogen
N2	chemical formula for nitrogen (dinitrogen)
NbTi	niobium-titanium
Nb3Sn	niobium-tin
Ne	chemical formula for neon
PA	polyamide-imide
PI	polyimide
P2P	pumped two-phase cooling
REBCO	rare-earth barium copper oxide
SCHMs	superconducting homopolar machines
SCIMs	superconducting induction machines
SCMs	superconducting machines
SCP	specific cooling power
SCSMs	superconducting synchronous machines
SMB	superconducting magnetic bearing
SMC	soft magnetic composites

SMES	superconducting magnetic energy storage
YBCO	yttrium barium copper oxide

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