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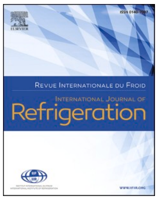

Selecting a cryogenic cooling system for superconducting machines: General considerations for electric machine designers and engineers

Sélection d'un système de refroidissement cryogénique pour les machines supraconductrices : considérations générales pour les concepteurs et les ingénieurs de machines électriques

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ABSTRACT

In this paper, general considerations for selecting a cryogenic cooling system for superconducting machine in different applications were explained with respect to the design, operation, and condition monitoring constraints. These considerations are explained so that they help electric machine engineers and designers to get familiar with cryogenic aspects of selecting and using cryogenic cooling system of superconducting machines. In fact, the main questions are: what are the important factors that one should take into account when selecting a cooling system for a superconducting machine application? Also, which one of these factors could later affect the performance of the cooling system so that it can efficiently cope with the expected heat load withoutfacing a thermal breakdown? To adress these questions, common cooling system structures, different cryogenic fluids, the associated parameters with the value of heat loads, and safety margins were discussed to help the machine engineers to choose the most appropriate cryogenic cooling system that adjusts better with their superconducting machine and the specific considerations that they might have. Some considerations regarding the auxiliary devices such as heat exchangers and pumps, were explained as the next priority in selecting a cooling system. Special challenges and considerations imposed to the cooling systems of superconducting machines in aerospace applications such as electric- and hydrogen-powered aircraft, naval applications, and wind energy application were also discussed. Although all of these applications share similar concerns like weight, cost, and specific mass of cooling systems, each one of them have their specific concerns and constraints which come with higher priority.

1. Introduction

Cooling systems are the beating heart of any superconducting devices, including superconducting machines. Regardless of the type of superconducting apparatus, the cryogenic cooling systems are usually responsible for controlling and stabilizing the temperature of the superconducting components to guarantee the reliable operation in superconducting state. The inputs of the cooling system controller are required cooling power, quench data, as well as expected heat load, and then, it delivers the required cooling power to the superconducting machine and stabilizes the windings temperature (Palmer and Shehab, 2016). Usually, the selection of the cooling systems for superconducting machines, among the machine engineers and designers, is conducted based on their personal-technical experience. In case of a undeliberate mistake or miscalculation, this can results in an inaccurate value for cooling power, a heavy cooling system, and even an unreliable one which is due to the fact that many considerations and factors are neglected during the cooling system selection. To avoid this, cryogenic concepts must be used by machine engineers who are usually unfamiliar with them and this may result in csame problems again. To overcome these issues, this paper presents a set of general considerations for selection of a cooling system so that machine engineers could simply conceive them without any direct engagement with cryogenic concepts. To do this, coolant fluid-related issues are expressed, then heat load issues are discussed, after that more technical and economic

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Nomenclature

Abbreviations

AC	Alternative current
AI	Artificial intelligence
CO_2	Carbon dioxide
ECM	Equivalent circuit model
EMI	Electromagnetic interference
FEM	Finite element method
GH2	Gaseous hydrogen
GHe	Gaseous helium
LTS	Low temperature superconductor
MIS	Microsphere insulations systems
MLI	Multi-layer insulation
MRI	Magnetic resonance imaging
MTBF	Mean time between failure
MTBM	Mean time between maintenance
MTTF	Mean time to failure
MTTM	Mean time to maintenance
NMR	Nuclear magnetic resonance
PD	Partial discharge
PFHX	Plate fin heat exchanger
PPHX	Perforated plate heat exchanger
PTR	Pulse tube refrigerator
PTTI	Periodical test time interval
REBCO	Rare-earth barium copper oxide
RTBCC	Reverse turbo Brayton cryocooler
STBM	Service time between maintenances
SWHX	Spiral wound heat exchanger
TITHX	Tube in tube heat exchanger
WECS	Wind energy conversion system
ZBF	Zero boil-off

Symbols

P_V	Power loss at different temperatures
P_s	Power rating of the superconducting machine
Q_{net}	Net heat load on the cryocooler
T_h	Room temperature
T_c	Critical temperature
T_{cr}	Cryogenic temperature
k_p	Profitability factor
η_C	Carnot efficiency
λ_{sc}	Cryogenic inefficiency
h	Heat transfer coefficient
ΔT_p	The rate of temperature change

considerations are discussed.

2. Cooling systems of superconducting machines

Although the high-field magnets of magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) systems are among the most commercialized applications of superconductors, superconducting machines are promising devices for being commercialized in near future, given the strong momentum around using them in future transportation systems including aircraft, ships, as well as power system applications such as wind energy systems. In fact, superconducting machines will be applied in heavy duty vehicles, and electric aircraft and marine applications, in a near future (Berg et al., 2017; Haran et al., 2017; Staines et al., 2017). Prior to know the challenges of selecting the cooling systems, there is a need for introducing different components and elements of a typical cooling system used for superconducting machine applications. As illustrated in Fig. 1, a typical cryocooler-based cooling system consists of different components such as coolant tank or fluid reservoir, cryocooler, heat exchangers, pumps or fans, valves, insulated and flexible flow paths/pipes, and control units. Each part has its own specific function and sometimes subcomponents. The tank is used as a reservoir for coolant fluid and injects it to the refrigeration cycle when it is necessary. The amount of injection is controlled through a valve by controller unit. The size and the weight of the tank is very crucial when designing a superconducting machine for airborne or marine applications (Bejan, 1976). There are also many factors that could affect the heat load of superconducting machines, alter their efficiencies, weight, cost, and also the specific mass of cryocoolers. .

It should be also mentioned that in case of dry magnets or dry machines, where no cryogenic fluid is required, the magnets and windings

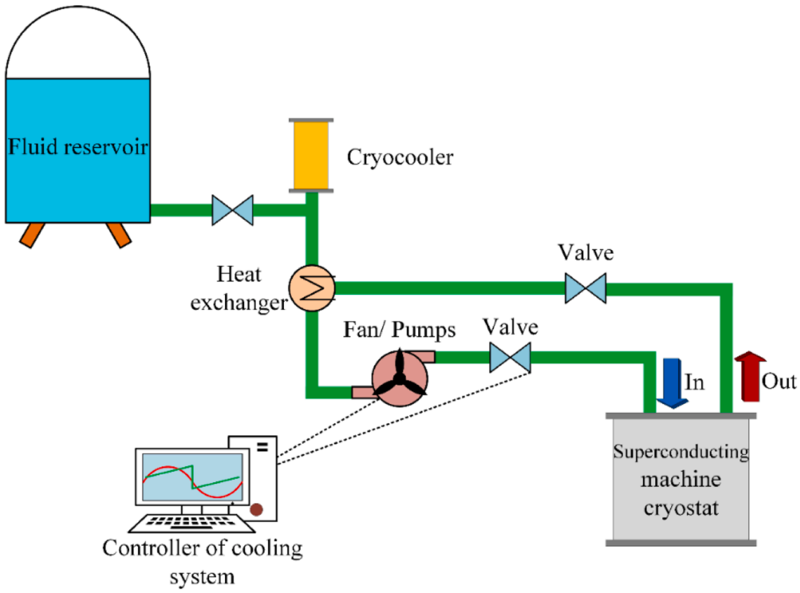

Fig. 1. The most important components of a typical cryocooler-based cooling system for superconducting machines.

are cooled only by the cryocooler (using copper braids). Under such circumstances, the cooling procedure is not directly dependent on the properties of the cryogenic fluid. These systems are usually smaller and are currently very popular. However, for large-scale and high-power applications, this cryogen-free concept does not seem to be fitted due to their lower power range.

3. The selection of a cryogenic fluid

3.1. Type of cryogenic fluid

Selecting the proper type of coolant fluid is one of the most important aspects for choosing a cryogenic cooling system of any large-scale power application. The most common cryogenic fluids for superconducting power components are liquid nitrogen (LN2), liquid and gaseous helium (LHe & GHe), liquid hydrogen (LH2), liquid neon (LNe), or their mixture (Sato et al., 2013). The evaporation/boil-off temperature, freezing point temperature, latent heat, and other chemical and thermal properties of these coolants are very different. Therefore, the design constraints would be absolutely different when using each one of theses coolant fluids. The LN2 could be used as a coolant fluid for temperatures above 65 K up to 77 K in sub-cooled or saturated vapor pressure conditions. While LHe, LH2, and LNe can be used for applications with lower temperatures. On the other hand, the type of coolant changes the power, efficiency, type and the size of the cryocoolers, the size and the weight of reservoir tank, pipes, type and thickness of thermal insulations, and also other components of the cooling system. Usually, one main consideration for the selection of acoolant fluid is related to the type of superconductor, its critical temperature, and the demanded operational temperature based on the design of superconducting devices/machines. If the winding of superconducting machine is made out of MgB_2 wires, the operational temperature must be lower than 39 K and is better to be around 18–22 K (Feddersen et al., 2017; Kalsi et al., 2018). To provide such temperature, it is more efficient to use LHe, LH2, or GHe as cryogenic fluids, and even in lower power, conduction cooling might be an option. Meanwhile, REBCO tapes can operate at any temperature lower than 77 K. Thus, LN2 is the first and the cheapest option for cooling down the REBCO-based machines if temperature is above 65 K. However, for temperature below 77 K (normal boiling temperature of Nitrogen), the cooling systems call for a vacuum operation condition in some specific applications. However, if reaching to high current carrying capacity is a target especially for MW power machines, it would be better to use LH2, LHe, and LNe as cooling fluid rather than LN2.

3.2. Material properties considerations

Physical and chemical properties of the aforementioned coolant fluids are the function of numerous factors such as heat and pressure which can affect the cooling performance. The specifications of these working fluids are discussed in detail in (Leachman et al., 2017; Poling et al., 2001) and the most important parameters are tabulated in Table 1. To date, among the conventional coolant fluids, LN2 is the cheapest and LNe, LHe, and LH2 have much higher prices, respectively. Besides the physical and chemical properties of different working fluids, there are economic concerns and limitations in any large-scale superconducting applications including machines. So, the cost of cooling fluid plays an important role in the final cost determination of the cooling system.

3.3. Environmental and safety considerations

For airborne and marine applications of superconducting machines, the coolant fluid of the propulsion systems should be environmentally friendly and also operate at the highest possible safety. Superconducting machines, unlike conventional combustion engines, release the lowest possible greenhouse gasses into the atmosphere. Also, the flammability of the selected coolant fluid is a significant aspect which takes a part in safety considerations of cooling systems (Cashdollar et al., 2000; Pio and Salzano, 2018; Sánchez and Williams, 2014). However, for superconducting machines designed for airborne applications, it is important that whether the coolant fluid could be used as a fuel or not. Future hydrogen-based aircraft would take the advantage of LH2 as the fuel of their non-electrical conventional engines, as announced by Airbus in (Hydrogen 2020) (*Hydrogen An important pathway to our zero-emission ambition*, 2021). If conventional engines are used together with superconducting machines, LH2 can be used as fuel in combustion-based engines and also as coolant fluid for electric propulsion machines (Khandelwal et al., 2013; Nøland, 2021).

3.4. Possibility of reliquefaction

Due to the heat loads of superconducting machines, liquid coolants in some cooling systems could be evaporated. In closed cycle cooling systems, the reliquefaction process is an important part of the cooling procedure. As matter of fact, reliquefaction should be carried out at the lowest possible space and cost. However, it should be noted that in some applications of superconducting machines, such as Hydrogen-based aircraft, reliquefaction of the evaporated LH2 is not a concern. In such applications, evaporated Hydrogen is used as fuel for engines or to feed in the fuel cells to generate electrical energy, depending on the Hydrogen usage scenario in these aircraft (Baek et al., 2011; Wang et al., 2020).

3.5. A discussion about the cooling systems required for Helium

Regardless of the type of superconductors, liquid, gaseous, and supercritical helium are three forms that can be used as coolant fluids (Spaven et al., 2021). However, gaseous and liquid helium are used more often for cooling down the high temperature superconducting machines and also for superconducting machines with windings based on NbTi superconductors. To design a cooling system based on Helium, there are some considerations to make (Sciver et al., 2012), including the duty cycle of the total cooling system, operation cost, and total size of the system as well as usual thermodynamic considerations such as pressure, flow rate, etc. When designing a cooling system based on Helium, these considerations result in options as illustrated in Fig. 2 (Sciver et al., 2012). The first option is providing LHe and using it also in liquid state and vent the vaporized Helium in an open cycle system. Second option is providing GHe and liquefying it. After that and due to heat loads, the liquid is vaporized and can be vented in gaseous form. Third option is exactly same as the second one with a little change. After

Table 1
Chemical-physical properties of most common fluids in cryogenic cooling systems.

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 Ratioof Liquid Phase	Toxic?	Flammable?	ViscosityNSm^{-2} *10^{-5}
He	5.19	228.32	0.178	4.22	4	23,300	1.66	No	No	3.16
H_2	32.938	1285.8	0.089	20.28	2.01	58,000	1.405	No	Yes	1.34
N_2	126.2	3390	1.25	77.35	14.01	199,000	1.4	No	No	1.69
Ne	44.4918	2678.6	0.9	27.1	20.17	331,700	1.66	Yes	No	1.17

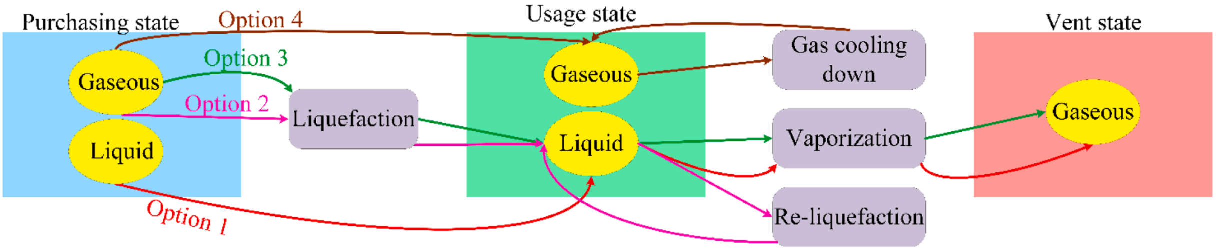

Fig. 2. Options for cooling of a superconducting machine using helium.

the vaporization of LHe, it will be re-liquefied and returns to cooling process. At last, the helium can be provided and used as gas to cool down the superconducting machine in very low temperatures. When the GHe is warmed, its temperature is reduced and returns to the cycle.

4. Heat load considerations of a cooling system

4.1. Safety margin of heat load

One way to help the cooling system to tolerate some extra loads is to consider a sufficient and reasonable safety margin for heat load estimation. In other words, the calculated heat load at design stage of the superconducting machine must be always reasonably higher than the rated heat load of the cooling system. On the other hand, by considering the values of cooling power and safety margin as fixed and constant values for all cases and all superconducting machines, the safe operation of these machines may be compromised. This is due to the fact that if the cooling system is unable to suppress the increased heat load, the temperature become unstable and might increase while the critical current of superconductors downgrades. The reduction of critical current speeds-up the temperature increase and subsequently, the critical current reduces significantly, again. This continues until either the superconducting tapes/wires transit to the normal state or somehow the cooling system stabilizes the increasing temperature. Therefore, it is absolutely preferable to have a higher safety margin, but most of the times, designers end up with choosing a compromised value. Because a very large margin would lead to a heavy, bulky, and possibly less efficient refrigeration system with too many stages (Spaven et al., 2021) which makes the superconducting machines and their cooling systems heavier and less efficient. On the other hand, a smaller margin might end up with the thermal breakdown of the cooling system or the superconducting machine. It should be mentioned that these trade-offs depend on many different factors such as system design, the performance of the machine, as well as importance and sensitivity of the main application of the superconducting machine. For example, the safety margin for designing a cooling system for an electric aircraft that flies full of passengers in the sky would be much higher than that of a superconducting machine of a wind turbine which is installed somewhere in the power grid. As a matter of fact, to obtain the safety margin of cooling units in superconducting machines, there is a need for precise calculation of heat load, historical data about the operation of the cryocoolers and other components of cooling system (Kittel, 2007), reliability indices i.e. mean time between failure (MTBF) and mean time to failure (MTTF) (Brake and Wiegerinck, 2002), cryogenic loss and leakage data, type of cryogenic fluid, type of cryocooler (Radebaugh, 2009), etc. By considering such information, the estimation of the safety margin might be conducted more precisely. In this stage, many estimation techniques based on artificial intelligence (AI) could be also really helpful as they would be able to consider many hidden interdependencies among input data, among which neural network-based methods are more applicable (Yazdani-Asrami et al., 2020b).

4.2. Transient heat loads of superconducting machines

AC loss and other electromagnetic losses of superconducting machines could vary in a wide range, because of different transients such as short- or long-term over-loads, current or voltage harmonics, over-voltages/under-voltages, different types of short circuit faults, sudden temperature changes, among others. Usually, these transients increase the temperature of the coolant fluid and superconducting tapes, significantly. This is often due to the injection of a higher current to the windings of the superconducting machine, in comparison to nominal and critical currents. Under such circumstances, if the cooling system be unable to stabilize the temperature, burnout of superconducting tapes and wires is very likely. So, for having a stable and reliable cooling system, these transient heat loads must be taken into consideration when designing the machine and its cooling system. On the other hand, over-voltages are also capable of generating sparks and arcs which may cause the breakdown of gaseous and liquid insulations. As a result of this, insulation materials experience malfunctions which results in a higher value of heat leakage. Also, under-voltages can also cause the overheating in superconducting motors which imposes a higher heat load to the cooling system (Yazdani-Asrami et al., 2021a, 2021b, 2020a). Therefore, during the design stage of the cooling system, accurate loss modeling is needed to estimate the corresponding heat load for the cooling system. For example, demanded load/torque/power would change during the operation of an electric machine. It causes different losses, different heat loads, and different cooling requirements/efficiencies. Note that predicting some of these transients is way too difficult. Therefore, just extreme cases need to be modeled and analyzed at the design stage.

Frequency is another important factor that could significantly change the total loss of the superconducting machine (Chen et al., 2020). Along with the increase of the frequency, the cooling system should suppress a higher amount of heat, generated by loss and leakage. So, for superconducting machines and their cooling systems, a confident coefficient may be needed to address the frequency oscillation-related issues. The term of confident coefficient is defined based the calculation of the maximum possible increase in the frequency and its impact on the heat load. This means that one must calculate that how much frequency increase is possible and how much extra heat load is imposed to the cooling system in th worst-case scenario. These oscillations may occur when a generator/motor of a distributed generation/propulsion system with multiple units, like an aircraft, is out. So, other units have to operate at a higher power and speed till the outage is resolved. This causes a variation in the frequency of generators/motors and could increase losses and heat loads.

By the occurrence of partial discharges (PD), as another possible phenomenon, the quality of the dielectric material deteriorates and this could lead to insulation failure, breakdown, or short circuit faults with large fault currents. Therefore, current level increases and consequently temperature rises. PDs can be considered as a reason for occurring internal faults and short circuits and their related concerns must be considered for guaranteeing the safe operation of cooling systems against PDs (Chen et al., 1997; Rigby and Weedy, 1976).

Electromagnetic Interferences (EMI) are another consideration to make when selecting a cooling system with highest possible efficiency and reliability. EMIs, especially radiated EMIs, increase the heat load of the system and so must be reduced to the minimum possible values. Usually, magnetic shielding methods, and EMI filters could reduce the aforementioned impact, however, to increase the reliability of the cooling system it is better to consider them when choosing the cooling power. At last, it must be mentioned that there are standards in aviation industry to mitigate these EMIs, such as DOD–160 (RTCA, Inc., 2010) and MIL–STD–461 (Department of Defense, 2015) as mentioned in (Jansen et al., 2017).

4.3. The precision of heat load estimation

Heat load is a function of numerous factors which complicate the procedure of exact estimation of required cooling power for a superconducting machine. Some sources of heat load in superconducting machines is the total loss, conduction, and radiation, as an external source of heat loads. Total loss of a superconducting machine consists of many loss components, such as eddy current loss, coupling loss, hysteresis loss, ferromagnetic loss, core loss, and stray loss. Usually, the total loss of a superconducting machine could be evaluated according to voltage, frequency, current, and harmonics order of input current/voltage (X. Song et al., 2016; Stavrev and Dutoit, 1998; Yazdani-Asrami et al., 2021a). However, the exact value of heat load in steady state is higher than the estimated heat load for machine losses. In addition, there are also other losses in machines that originate from the nature of non-superconducting elements, like insulations, ordinary metals in the structure of machines, and outside induced magnetic fields. There is also viscosity loss which is a result of passing the coolant fluid through the corrugated cryostats. At last, there is also heat leakage loss which is a result of the imperfect operation of thermal insulations. This type of loss could occur in multiple sources, such as non-superconducting parts which lay outside of cryogenic temperature, superconducting parts in coolant, as well as ambient to cryostat due to huge temperature gradient between inside and outside of superconducting machine cryostat, etc. (P. Song et al., 2016). There are also some other losses which were discussed less frequently. One of them is residual gas conduction loss which occurs due to the venting the vaporized or warmed fluid. This gas touches the surface of the cryostat and causes a heat load to the cooling system. Conduction with rods, torque tube conduction loss, and index loss are other type of losses which can change the heat load of the cooling system. It should be mentioned that index loss is originated in the intrinsic index value of superconducting materials that based on E-J power law causes the current to decay (Le et al., 2015). Another important factor that affects the heat load of the superconducting machines is inhomogeneity of the magnetic field. Due to the inhomogeneity of the magnetic field, the AC loss distribution varies in different locations of superconducting coils and this results in unbalanced heat load. Consequently, temperature distribution inside the machine varies, heat balance will be lost, and this results in overloaded operation of cooling system, and also in establishment of hot spots inside the machine windings. To avoid this, the machine must be designed so that the homogeneity of the field is maximized. Although the inhomogeneity could be reduced to zero in simulations and modeling phases, due to some manufacturing tolerances, fabrication superconducting machines with fully homogenized magnetic field is not possible in real world. Thus, when choosing a cooling system for superconducting machines, it is better to consider a coefficient which compensates the inhomogeneity of the field. This coefficient must be selected wisely to avoid bulky cooling systems with too many stages.

5. The cryocooler as a main part of cooling systems

Another cooling consideration for superconducting machines is the type of cryocoolers. Two well-known major types of cryocooler exist, regenerative and recuperative. Regenerative cryocoolers are usually very heavy and massive and operate based on the heat transfer between warmed and cold fluid. While recuperative cryocoolers work based on the continuous flow of coolant through a proper heat exchanger (Berg et al., 2017; Kittel, 2007; Lin et al., 2018; Radebaugh, 2004; Satyanarayana et al., 2018) and they come in a lighter weight. At the moment, the most interesting, reliable, scalable, modular, and flexible recuperative cryocooler for modern high-power applications seem to be the reverse Turbo Brayton cryocooler (RTBCC) (Palmer and Shehab, 2016). Although, RTBCCs are very expensive, they are favorable for applications that would need high power, highly reliable and light cryocoolers such as electric aircraft and spacecraft. While there are some other types of regenerative cryocoolers that are heavy and bulky and possess higher penalty factor. The most famous regenerative cryocoolers are Gifford-McMahon (GM) and Stirling types (Staines et al., 2017). Industrial Stirling cryocoolers operate in a 50 W to 6 kW cooling power while temperature could be varied in 15–150 K range. To implement them in required applications, they are usually used in one or two stages (*Stirling Cryogenics*, 2010). According to (Cardwell and Ginley, 2003), the Carnot efficiency of Stirling cryocoolers is in the range of 4% to 30%. This value for RTBCC is about 6% to 14% and for GM cryocoolers is about 1% to 9%. There should be also mentioned that the cooling power which GM can provide is about 1 W to lower than 1 kW in one stage at a temperature range of 10 K to 300 K. On the other hand, refrigeration power of turbo Brayton cryocoolers is 10 W to 1 MW while the temperature is about 4 K to 300 K (Cardwell and Ginley, 2003). It is obvious that the low power cryocoolers could operate in lower temperature and with the increase at the refrigeration power of cryocoolers, their operating temperature increases. For instance, GM cryocoolers offer their 1 W refrigeration power at 10 K and 1 kW power is related to temperature around 300 K. The penalty factor of the GM cryocoolers is typically about 15 to 20 at 77 K. It means that for extracting 1 W out of the cryostat at 77 K, 15 to 20 W should be consumed in cryocooler. On the other hand, for extracting 1 W heat by a Stirling cryocooler, there is a need for 18.3 W of electrical power at temperatures around 77 K. However, penalty factors of modern cryocoolers depend on operating temperature, i.e. in lower temperatures penalty factor increases drastically, e.g. for GM cryocoolers about 1400 and 100 at 4.2 K and 20 K, respectively (Malozemoff et al., 2015; Radebaugh, 2012). It is worth noting that the GM and Stirling cryocoolers have a low capability in cooling down the warmed coolant. To solve this issue and by generating a pressure wave, more reliable cryocoolerswere proposed by Gifford and Longsworth in 1961, known as Pulse Tube refrigerators (PTR) (Gifford and Longsworth, 1964; Radebaugh, 2012, 1990) The PTRs will be slowly replacing the GM cryocoolers and this is due to the fact that they do not have a moving part, displacers. The vibration level, therefore, is a few orders less than GMs and Stirling cryocoolers. This results in better signal to noise ratio in many cases and applications. Also due to absence of rubbing seals or moving parts, they are proving to be much more reliable (Atrey et al., 2006).

One more consideration about the cryocoolers is the fact that the performance of cryocooler degrades over a period of time due to impurities in cryogenic fluids, especially in the gas form, and also due to rubbing of moving parts or gas leaks. Thus, injecting cryogenic fluids with high levels of purity is absolutely essential for improving the performance of cryocoolers, increasing their efficiency, and also enhancing their reliability.

Noise and vibrations are two other important considerations when selecting a cooling system for superconducting machines. Usually the origin of the acoustic noise and vibrations are cryocoolers with moving mechanical parts or valves such as vibrations in GM and Stirling cryocoolers. The noise of GM cryocoolers is due to the alternatively operation of valves while in Stirling-type cryocoolers the noise and vibrations are due to the rapid movements of the expander. To reduce the noise and vibrations numerous methods were proposed such as active noise cancelation techniques for pulse tube refrigerators (D'Addabboa et al., 2018) and multi-axis vibration cancelation (Collins et al., 1994). Thus, during the selection of cryocoolers and cooling systems for superconducting machines, the vibration and noise must be considered, especially for the aviation applications.

Wind energy systems could use NbTi superconductors to form the coils of superconducting machines (Jie et al., 2014). NbTi coils operate in 4.2 K, thus a specific type of cryocoolers is needed, known as 4 K cryocoolers. To reach such low temperature, Zero Boil-off (ZBF) systems using 4 K cryocoolers are very common. They are widely being used where the boil-off Helium gas is re-condensed. It may also be worth pointing out that the cost of LHe is increasing almost 15% every year and therefore it is essential to recover Helium gas and re-liquefy it or re-condense it using 4 K cryocoolers (Hirayama et al., 2019; Morie and Xu, 2012; Sato et al., 2021).

The properties of most common cryocoolers which are used or can be used for superconducting machines are listed and compared in Table 2.

In airborne applications, there is a need for cryocoolers with a specific mass less than 3 kg/kW (Cardwell and Ginley, 2003), while this value is at the moment around 4 kg/kW. Cryogenic inefficiency which is stated in eq. (1), and mass reduction possibility are other important factors of choosing a cryocooler for superconducting machines (Radebaugh, 2012).

$$\lambda_{sc} = \frac{Q_{net}}{P_s} \tag{1}$$

where, λ_{sc} is cryogenic inefficiency, Q_{net} is net heat load on the cryocooler, and P_s is the power rating of the superconducting machine.

The cryogenic inefficiency, as reported in (Radebaugh, 2012), depends on many factors such as operating temperature of superconducting machine, maximum heat load, and power range of machine. The lower the temperature gets, the inefficiency reduces while the reduction of the power rating of superconducting machine, causes the inefficiency to increase. Safe to say, for operating temperatures lower than 65 K and superconducting machines in range of MW power, the range of inefficiency is between 1.3×10^{-5} and 5×10^{-4}.

The system configuration and the structure of the cooling system is another important consideration in superconducting machine applications. All types of cooling structures are (Atrey, 2020; Chen et al., 2007):

Remote Cooling (Le et al., 2016)

- Cryogen Circulation
- Thermosiphon Cooling (Felder et al., 2012; Yamaguchi et al., 2019)

Direct Cooling

- Conduction Cooling
- Thermosiphon Cooling (Frank et al., 2004; Yamaguchi et al., 2015)

Table 2

The properties of most common cryocoolers for superconducting machines (4 K/1 K Cryocoolers; RDE-412D4 4 K Cryocooler Series; Pulse Tube Cryorefrigerators, 2021; Atrey, 2020).

Supplier	Type	Single-stage T - range	*T* bottom (at 60 Hz)	MTBF (hours)
Cryomech	GM	600 W @ 80 K	25 K	10,000
Cryomech	PTR	130 W @ 80 K	9 K	25,000
Sumitomo	GM	200 W @ 80 K	20 K	15,000
Leybold/Oerl.	GM	140 W @ 80 K	18 K	*
Chart/Qdrive	Stirling	>1 kW @ 80 K	40 K	129,760
Creare	Stirling	>1 kW @ 80 K	*	180,000
STI	Stirling	>100 W @ 80 K	45 K	>1000,000
Sunpower	Stirling PTR	>16 W @ 80 K	40 K	>1000,000
Stirling SV	Stirling	>1.3 kW @ 80 K	38 K	*
Linde	Reverse Brayton	0.9 kW @ 20 K	*	*
Air Liquide	Turbo Brayton	>50 kW	35 K	*
Sumitomo Heavy Industries	JT	40 mW @ 4.5K	4 K	*
SHI cryogenic group	GM	0.5–2 W @4.2	3.5 K	10,000
Cryomech	PTR	0.25–2.7 W @ 4.2	2.8	>20,000

Remote term means that the cooling system and superconducting machine are connected to each other by means of transfer pipes of cryogenic coolant. In cryogen circulation, the coolant fluid is injected to the refrigeration system by means of impellers, fans, or turbines and cools down the superconducting machine. On the other hand, the natural convection and heat exchangers play the main role in Thermosiphon cooling. In conduction cooling, the superconducting machine is in direct contact with a cold mass. This results in cooling of the machine by means of conduction (Atrey, 2020). Also heat pipes are widely being used for cooling the magnets or windings, at the moment. Pulsating heat pipes, on the other hand, show an appropriate performance for cooling down the superconducting machines.

6. Reliability, redundancy, and economic issues

Apart from technical design issues related to heat load, there are other considerations related to reliability such as maintenance period, aging, and fatigue issues and their effects must be considered on the performance of cooling systems and cryocoolers when one chooses the type of cooling system in the design stage of a superconducting machine. However, the superconducting component issues related to different fault modes, maintenance, and their reliability as well as those for the cooling system are major issues that would need to be discussed and addressed independently in a paper, itself. Some reliability parameters and factors such as MTTF, mean time to maintenance (MTTM), periodical test time interval (PTTI), service time between maintenances (STBM), as well as redundancy would affect cooling performance and therefore, must be considered in the machine design stage (Flynn et al., 2019). This procedure usually involves some sort of economic study to determine the optimal power and number of redundant cooling units. Depending on the application, it could be a simple or a sophisticated economical study. AI techniques can be used for such studies. In addition, one must consider that normally cooling system is designed for a base temperature in a specific range. Therefore, the efficiency of the cooling system might not be optimal out of that range, which may end up with imposing a fluctuation on the operating temperature of superconducting components, tapes, and coils; as well as, higher AC loss in superconducting machine as a consequence. This must be considered in the machine design stage to choose the correct type and the number of refrigeration systems and pumps or even using the proper cryogenic fluid.

7. Modeling and operational issues

7.1. Practical and operational considerations

Even after coming up with a specific number for safety margin and calculating the final design heat load and cooling power, one must keep in mind that usually, cooling system components do not come in continuous power ratings, i.e. cryocoolers, pumps, and other required components come in discrete sizes determined by the manufacturer, rather than designers' choices. Thus, when estimating the heat load for the cooling system, one better bear this in mind to add it up to design considerations.

Apart from these technical considerations, there are some operational/speed considerations, as well. In some applications, the superconducting machine doesn't work at a constant speed or power; e.g., the superconducting machine needs to produce different torques/power and as a consequence, would experience different loss, heat, heat loads, and efficiency levels. Therefore, the safety margin would be even speed/torque-dependent and more difficult to be accurately determined (Masson et al., 2007; Radebaugh, 2012).

7.2. AI techniques for the optimal design of the cooling system

To date, the design of a refrigeration system, and choosing the parameters of a cooling system were accomplished using thermodynamic equations and mostly relied on the technical knowledge of the designers rather than a purely theoretical and systemic approach. As a result, the final estimated heat load and heat leakage could be dramatically far away from the real values, which can be measured after the installation of the cooling system and machine. To avoid this, designers have to consider a significant safety margin for their estimated values (typically between 25 to 100% depending on the size and type of the cooling system), which further increases the final cost and complexity of the designed cooling system.

AI-based strategies can assist to optimally design a cooling system for superconducting machines. Keeping the weight of cooling system as light as possible would be highly critical, for some of the future sensitive applications such as electric aircraft. For this purpose, a range of potential values for following parameters would be needed, winding heat load, leakage heat load, heat transfer coefficient, working pressure, pressure drop, and cooling fluid flow rate. By assuming an appropriate range for these parameters as well as entering data from capability curves of all different types of industrial cryocoolers, a multi-objective optimization problem can be set to optimally calculate all the design parameters both for machine and for cooling system. Different scenarios can be considered for this purpose based on requirements and constraints of a specific application to find the optimal number and type of cold head(s), optimal pressure, and flow rate. The considered scenarios can be set to reach the minimum cost or the maximum efficiency in the cooling system (Panda et al., 2021; Yazdani-Asrami et al., 2021d, 2022a).

7.3. Interdependency of cooling parameters

So far, the main discussion of this paper was about the thermal, economical, mechanical, reliability, and safety margin considerations of a cooling system. It should be mentioned that all aforementioned parameters have interdependency with each other. This means that by increasing one, another can be reduced/increased, and maybe a third factor changes. For example, if the heat leakage or any drastic electrical fault causes higher heat loads, then cryocooler efficiency will reduce, then operating temperature increases, then critical current of superconductors may reduce, then loss will increase, then other parasitic losses will increase as well, then the operating temperature will increase and this will continuously happen in a loop until a breakdown happens or protecting measures come into action.

Fig. 3 represents a general interdependency of multiple factors/considerations in a cooling system. According to Fig. 3, any change in the cooling system directly or indirectly affect the cost of the refrigeration system. Fig. 3 indicates on the importance of the shown parameters for providing a stable temperature. The temperature stability itself avoids the quenching of superconductors.

7.4. Challenges of cooling system modeling

It is very important to model the characteristic of the cooling units before implementing them in the system. The first step is to model the exact thermomagnetic behavior of the superconducting machine at the highest possible accuracy to gain the exact values for losses. This can be conducted using finite element methods (FEM), equivalent circuit models (ECM), or even AI techniques. Afterwards a thermohydraulic analysis should be accomplished to gain the overall value of the heat load imposed to the cooling system (Palmer and Shehab, 2016). Usually, mechanical, hydraulic, and electrohydraulic analyses are conducted firstly to gain the values of pressure drop, imposed mechanical/-magnetic stresses, breakdown possibility of dielectrics, etc. However, before getting into this stage, some parameters, factors, and considerations must be chosen: type of cryocooler and coolant fluid, operating temperature, critical temperature with respect to the variations of magnetic field, type of pumps or fans, etc. After this, the weight, reliability, economic, and stability indices are defined. Now it is time for performing a sensitivity analysis or even multi-objective optimizations to improve all indices of the cooling system, as the most significant and complicated stage of the modeling.

8. Auxiliary units in cooling systems

8.1. Pump selection

Pumps are devices that should deliver the amount of required

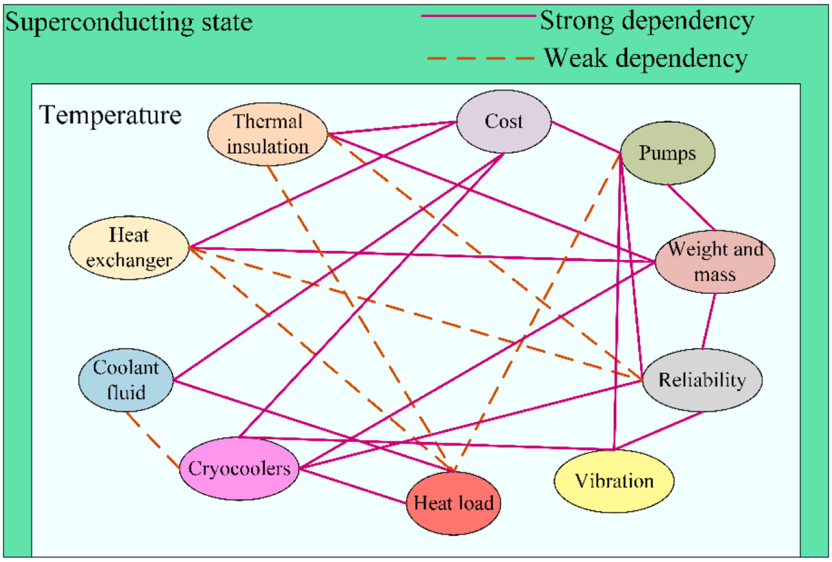

Fig. 3. Multiple interdependencies between different factors in a cooling system of a superconducting machine.

cooling fluid at any time for cooling down the superconducting machines or providing proper flow rate/speed, especially in machines that are cooled by "*Forced Cooling*" method. They can impact the total efficiency, reliability, and total cost of the cooling system. There are some considerations for the pumps, which one needs to pay attention during the design stage of the refrigeration system. Firstly, the cost of pumps should be taken into account. Secondly, the weight of pumps plays an important role which could highly increase the total weight and specific mass of the cooling system and as a consequence specific mass of the machine. Using a pump also varies the total efficiency of the cooling system. The power of the selected pump must be high enough to compensate the pressure drop of the coolant fluid. This pressure drop could occur in pipe of coolant fluid, in valves, or even in cryostat (Chen et al., 2012).

8.2. Thermal insulation

Another crucial step during the design and selection stages of cooling systems for superconducting machines is selecting a proper thermal insulation material. There is a thermal gradient between warm and cold parts inside and outside of the cryostat of machine. Thermal insulations are used to avoid this thermal gradient impacts the operating temperature of the superconducting coils. The first and the most important challenge which designers must face is choosing cost-effective materials. However, usually, most economic materials have a common disadvantage which is their heavy weight that in some applications of machines, like aviation and marine, machines with the cheapest thermal insulations no longer are capable of passing the specific power density concerns. After that, there is thermal resistivity of the thermal insulations. The higher it is, the lower heat penetrates into the machine's cryostat, and therefore, cooling inefficiency reduces. There are also electromechanical considerations like the behavior of insulation at the cryogenic environment, the aging process at very low temperatures, and their tolerance against the electrical, magnetic, thermal, and mechanical stresses (Gerhold, 1998; Kalia and Fu, 2013). So, cost, weight, thermal resistivity, and lifetime of thermal insulations are vital factors which impact the proper function of them. The most common type of thermal insulations for superconducting applications are Microsphere Insulations Systems (MIS) and Multilayer Insulations (MLI). MLIs, also called as superinsulation, are comprised of shields with low emissivity which are separated by the means of low conductivity materials with a high vacuum (Bapat et al., 1990; Kanda et al., 2021). Shield layers are normally aluminum foil or aluminized Mylar while spacers are fiberglass paper, glass fabric, or nylon net. MLIs have a thermal conductivity between 10 and 50 μW/m.K at temperature range of 20–300 K (Meyers, 2002). This insulation is usually used in conduction cooled systems to avoid any radiation heat loads. For this purpose, MLI needs to be wrapped around the superconducting parts. Heat Load calculations and also the performance of thermal insulations, especially MLIs, are related to the vacuum levels of cooling system. As the vacuum degradation starts to happen over a period of time, the performance of the MLI or other vacuum insulations degrades. Thus, constantly monitoring the vacuum level of cooling systems is vital and the required monitoring devices must be considered in selecting the cooling system for superconducting machine.

8.3. Heat exchangers

Unlike thermal insulations, the heat exchangers are the part of the cooling systems that enable heat transfer in the form of conduction, and convection. These elements are used in closed-loop cooling systems to cool down the warmed fluid. They have multiple types and classifications which can strongly impact the efficiency, the specific mass, and the weight of the cooling system (Kakaç et al., 2002). Their classifications according to the structure are listed as Table 3.

Table 3
Properties of most common heat exchangers (Kakaç et al., 2002).

Type	Advantages	Disadvantages
Spiral wound heat exchangers (SWHX)	High efficiency Compactness Low pressure drops High overall heat transfer coefficient	High welding quality Difficult maintenance Heavy weight Poor rigidity
Plate fin heat exchangers (PFHX)	High efficiency Larger heat transfer area Able to withstand high pressure	Difficult to clean the pathways Cannot be mechanically cleaned
Perforated plate heat exchangers (PPHX)	High efficiency Very compact	High cost
Tube in tube heat exchangers (TITHX)	Operation under high pressure Operation at very low temperatures Resistant to thermal shocks	Low heat transfer efficiency Difficult cleaning and maintenance Constant capacity

9. Economic considerations

9.1. Cost components of a cooling system

In order to cool down any superconducting machine, the cost of the cooling procedure must be considered and optimized. There are several types of costs which need to be considered in an economic analysis of any cooling system for superconducting machines, as discussed in the following.

The cost of any cooling system depends on multiple factors such as type of cryocoolers, coolant fluids, type and number of pumps, valves, the specific mass of cryocooler, estimated cooling power along with safety margin, nominal frequency of the superconducting machine and operational frequency of the cryocooler, the voltage of superconducting machine, the available space, in which cooling system and machine must be installed, etc. In some applications of superconducting machines like aviation and transportation systems, the priority of some constraints is higher than the others, namely specific mass.

Another type of cost is known as operational cost which is related to the continuous operation of the cooling system and machine. For instance, any sudden change in working conditions of the superconducting machine leads to variations in heat load. These variations should be compensated by the cooling system which demands more electrical power and this increases the operational cost of cooling units (Luyben, 2017).

The cost of purchasing coolant fluid, increasing the reliability and the redundancy of the cooling system, periodic repairing, and cost of energy consumption by a cooling system can be categorized as another type of cost known as maintenance and auxiliary services cost (Yang et al., 2020).

If the coolant fluid is selected to be anything rather than LN2, there is a need for an extra cooling phase to reach a cryogenic temperature that is considered in design stage for cooling down the superconducting machine. This extra cooling phase is known as sub-cooling, which is the case for fluids like Hydrogen, Helium, Argon, and Neon. This extra phase imposes an extra cost for all cooling units with the aforementioned cooling fluids. This cost is composed of the cost of turbines, valves, cryostats, and other devices. This also imposes an extra weight on the total weight of cooling units (Flynn, 2004).

By the summation of all aforementioned costs, the total ownership cost of any cooling systems is accessible. This is a fair index to economically prefer one type of cooling unit to another. There is also another economic factor that must be discussed about the cooling systems, known as levelized cost of energy (LCOE). LCOE is defined as the ratio of the total ownership cost in a specific period of time to the delivered cooling energy at the same time period. As a matter of fact, it compares the life cost of two cooling unit and make it easy for machine engineers to prefer a cooling system over other one. Thanks to this measure, just by calculating the cost and delivered cooling energy in a specific time, the economic choice of a cooling system could be conducted without any complicated calculations.

9.2. *Integrating power electronic system of superconducting machine in cryogenic temperatures*

Power electronic equipment is an inseparable part of any electrical machine, including superconducting machines. They are used to control the speed, the torque, and also drive the electrical machines. Usually, these elements operate at room temperature to avoid refrigeration costs. However, in applications of superconducting machines with a central cooling system, cryogenic power electronics could be used to reduce their losses. This can even increase the integrated power density in aerospace and marine applications. The heat load of power electronics consist of two types, resistive loss caused by internal wires and external cables and conduction loss of Si and GaN transistors. Effective dissipation of these losses could increase the efficiency of the power electronic devices. However, before using power electronic devices at cryogenic temperature, an analysis must be conducted to weight the advantages over the disadvantages which are higher cooling costs and some possible aging, defects, and deteriorations in switches. This analysis estimates the profitability of cryogenic power converters according to eq. (2) (Büttner and März, 2022; Yao and Ma, 2021). The operation of cryogenic power electronic devices at temperature T_{cr} is profitable whenever eq. (2) is fulfilled.

$$k_p = \frac{P_V(T_h) - P_V(T_{cr})}{P_V(T_h)} \frac{1}{1 + \eta_C\left(\frac{T_{cr}}{T_h - T_{cr}}\right)} \tag{2}$$

where, k_p is profitability factor, P_V is power loss at different temperatures, η_C is Carnot efficiency, and T_h and T_{cr} are room and cryogenic temperature (Büttner and März, 2022).

10. Cooling considerations for different superconducting materials used in electrical machines

The cryogenic environment for providing a stable low operating temperature is vital for superconducting machines to operate at lower AC loss, higher electrical performance, high specific power density, and higher efficiency. However, selecting the range of this cryogenic temperature is a bit challenging for different machine applications. This is due to the fact that each application of superconducting machines, has its own economic and technical limitations and constraints. For instance, in cryo-electric aircraft, the weight and the mass of cooling system must be minimized and thus, temperatures lower than 20 K are not a realistic choice for aviation application of superconducting machines, at the moment. In future hydrogen-based cryo-electric aircraft, the operating temperature of superconducting machines will be around 20–30 K while in wind application, temperature could be reduced further around 4.2 K when NbTi-based coils are used, as weight of cooling system is less critical in this application. NbTi windings are cooled down usually by LHe making use of forced cooling procedure or bath cooling. In bath cooling, there is an important consideration which is known as critical heat flux which is defined as the maximum value of heat flux at the surface of the NbTi wires that LHe can remove it to keep the NbTi wires ate superconducting state (Kalsi, 2011). On the other hand, for HTS materials, there are two other methods rather than those for NbTi, Thermosiphon cooling and conduction cooling (Stautner et al., 2015). Some of the cooling properties of different superconductors are tabulated in Table 4 (Green, 2003).

Table 4
Cooling properties of different superconductors (Green, 2003).

Superconductor	Type	Tc (self-field) (K)	Likely operation temperature (K)	Application	Fitted Cryogen
NbTi	LTS	~9.5	~4.2	wind conversion systems	LHe
MgB_2	HTS	~39	~20	wind conversion systems Aircraft and ships	LH2
Bi-2223	HTS	~108	Lower than 25	prototypes	LH2&LN2
YBCO	HTS	~92	65–77	Aircraft and ships wind conversion systems	LH2&LN2

11. Special considerations for airborne, marine, and wind applications

Superconducting machines will be used in future in a vast range of cryo-electrified applications in industries, namely power systems in wind farms, the aviation industry, space programs, marine applications, and other transportation systems/vehicles. Some of these applications like those related to airborne, marine, and other transportation units demand some extra constraints (Arish et al., 2021; Messina et al., 2021; Yazdani-Asrami et al., 2021c). These special considerations may arise for these specific applications especially for cooling system as discussed in the following:

11.1. *Airborne applications*

Cooling system architecture in any electric aircraft could be classified as one of the following classes (Berg et al., 2015), fully decentralized, partially centralized, and fully centralized. More details about these structures are discussed in (Brown, 2011). After choosing the cooling architecture, there are some constraints which one should take into account while selecting a cooling system for a superconducting machine used in airborne applications. First of all, imposing the efficiency of the cooling system to the calculation procedure of the total efficiency of the superconducting machine, leads to a reduction in the total efficiency of the electric system of aircraft. As a matter of fact, the efficiency of the superconducting machine without considering the cooling system is about 99.9% or above while by considering the cooling system this value lays significantly below 99%. Knowing the high power of superconducting machines in future electric aircraft that are porbably going to be in MW range, the aforementioned efficiency drop is catastrophic. For such an application, it is more important to have maximum efficiency, instead of minimizing the cost. Another consideration is weight, which can be at least doubled if we consider the weight of a cooling system. Under such circumstances, weight also is a more important factor than cost (Brown, 2011). Other important parameters that draw special attention for the aircraft application, are safety concerns about fluid flammability, and the possible condensation procedure of vaporized fluid. Low reliability characteristic of refrigeration units causes the reduction of total reliability of the whole system which means that failures become more possible to happen. To avoid this, the total reliability of the cooling system must be increased by enhancing the reliability of each component specially pumps, cryocoolers, heat exchangers, and valves.

When the aircraft takes off until it reaches the desired altitude, it enters an operational zone with a higher load than cruise mode. This is a short period transient load for airborne applications which can significantly impose higher thermal load to the cooling system compared with cruise mode. To avoid any cooling problem during takeoffs, the value of heat load safety margin for aviation applications must be further increased.

It should be also mentioned that in the near future and with the transition from fossil fuels to fuels like hydrogen, the need for high-power cryocoolers would be downgraded, and as a result of this mass, weight, and cost of cooling system would be significantly reduced. During the last few years, hydrogen has turned into a very special material that is now targeted to be used in many applications, especially in aircraft. Hydrogen aircraft is a concept that was introduced in the late 19th century. These aircraft use gaseous or liquid hydrogen as a fuel to provide the motion thrust. Recently, along with the re-appearance of the hydrogen-based aircraft, using the electrical superconducting machines has become a popular option. In this type of aircraft, hydrogen operates as a cooling fluid for superconducting machines in liquid form and when it has turned into gaseous form, it can be used in a fuel cell to produce more electricity or can be directly fed into engines as their fuel. The most important point is that the cooling system of hydrogen-based aircraft differ from those with LN2 or LHe (Azizi, 2021). It might be better to keep the LH2 away from direct contact to active parts of superconducting machines in aircraft, as suggested in (Dezhin et al., 2020). These cooling systems normally consist of many stages of cooling through multiple heat exchangers (Berstad et al., 2010). So, when a cooling system is adapted to operate in hydrogen aircraft, new issues must be taken into account. They can include the type of heat exchangers and their variety, the process of cooling down by vaporized hydrogen and its re-cooling, characteristics of electrical insulations under gaseous and liquid hydrogen, dielectric behavior of LH2, and at last and the most important, safety considerations of LH2. The structure of the cooling units for LH2-based aircraft must be selected so that the cooling system be capable of adapting with all cooling strategies. The first strategy is that when the LH2 is warmed-up, it returns to cooling system to be cooled down by cryocoolers. Under such strategy, in future, reverse turbo-Brayton cryocoolers are the most possible cryocoolers to cool down the warmed LH2. The second strategy is sending the warmed LH2 toward the fuel cells and at last the vaporized LH2 (GH2) is used directly as fuel for engines of aircraft (Nøland, 2021). As suggested by (Nøland, 2021), the efficiency of fuel cells used in hydrogen aircraft is less than 60% while the efficiency of the superconducting machine is about 99.8%, so the combination of such cells in hydrogen-based aircraft could lead to a reduction in total efficiency of the bulk cooling system. However, this depends more on the structure of the cooling system, superconducting/cryogenic machine, and fuel cells. Also, in full electric aircraft, in future, fuel cells could highly reduce the total weight of the aircraft drive train. To accomplish such structure, power density of fuel cells needs to be much increased (Nøland, 2021).

In aircraft application of superconducting machines, the used thermal insulations must be providing the thermal shielding and insulation at the lowest possible weight. So, the MLIs are one of the used materials as thermal insulations. Another possible type is Aerogel blanket as one of the lightest thermal insulations. They have a low density (0.036 to 0.196 g/cm3 (Liu et al., 2021)), low thermal conductivity (14.5–17 mW/m-K (Fesmire et al., 2017)), and low dielectric constant (Yazdani-Asrami et al., 2022b).

Another challenging issue which is imposed on hydrogen-based aircraft is to select a proper type and structure of LH2 tank. There are some considerations to make, such as the possibility of implementing integral or non-integral tanks, the possibility of implementing spherical or cylindrical tanks, and the type of insulation, internal or external (Yang et al., 2021). After considering these options, the main challenge is to choose the proper materials for structure, insulation, etc. (Podlaski et al., 2021). To select the appropriate material, there is a need to conceiving the heat transfer procedure in LH2. So, the heat transfer coefficient of the LH2, under different operational regime is expressed in eq. (3) (Podlaski et al., 2021), as follows:

$$h = \begin{cases} \textit{Natural convection or conduction regime}: \ 100\left(\Delta T_p\right)^{5.3} & \Delta T_p < 3\ K \\ \textit{Nucleate boiling regime}: \ \dfrac{10^5}{\Delta T_p} & 3\ K \leq \Delta T_p < 100\ \ K \\ \textit{Film boiling regime}: \ 10^3 & \Delta T_p \geq 100\ \ K \end{cases} \tag{3}$$

where, ΔT_p is the rate of temperature change and h is heat transfer coefficient expressed in W/m^2K.

Any change in temperature of superconducting devices in the power or propulsion systems of future aircraft is likely to be less than 1.63 K under normal operation without any short circuits (Podlaski et al., 2021). This means that under the steady state, superconductors would operate below the film boiling region. On the other hand, if a short circuit happens, ΔT_p would be higher than 3 K which increases the possibility of occurring the film boiling or thermal runaway. Due to the higher specific heat capacity and thermal conductivity of the LH2, the application of LH2 is advantageous in aircraft and other stand-alone grids compared with other coolants such as LN2. This can result in lower temperature increase, faster recovery time, and better cooling performance for superconducting devices including superconducting propulsion machines (Lévéque et al., 2007; Podlaski et al., 2021).

11.2. *Wind farms application*

Wind turbines are another possible application for superconducting machines. To select a proper cooling system for wind application, there are considerations to make (Haran et al., 2017). The first group of considerations is related to the size, weight, and reliability of cooling systems. In near future, the nominal power of wind turbines will be increased to levels above tens of MW. This means a higher heat load for the cooling units of the superconducting machines used in wind turbines. According to (Brown, 2011), around 50% of the weight in any superconducting machine belongs to cooling unit. Thus, by the increase of the nominal power of wind turbines and also their heat load, the weight of cooling unit will be significantly increased . This makes the nozzle, as a ducted rotor design, much heavier and as a consequence impose many technical problems for the structure of the wind turbine tower, and makes whole structure much more expensive. To overcome this problem, hydrogen-based cooling systems can be used. Usually, wind farms produce huge amount of green electricity as renewable energy sources which makes them a great option to produce green hydrogen which could be generated by electrolysis of water. This green hydrogen can be used as coolant for superconducting machine into the nozzle, and eliminate existing heavy and bulky cooling systems from it. This can reduce the total weight of superconducting machines of wind turbines and increase the cooling system efficiency.

By the presence of wind energy conversion systems (WECS) in modern power system, the value of fault current increases. This causes a higher heat load to the cooling system of superconducting machines if a short circuit event occurs in the upstream grid. As result, the value of the safety margin must be also recalculated. Power grids, unlike stand-alone grids of aircraft and ships, experience different types of abnormalities. One of them is Low Frequency Oscillation (LFO) which occurs due to the outage of generation units in a system. Due to this a higher current in comparison to nominal current passes through the windings of superconducting machines with a different frequency from the nominal frequency. Therefore, the magnitude of the overcurrent imposes a higher heat load in comparison to pre-calculated heat load for steady state. Also, the frequency variations resulted by LFO could change the value of AC loss and heat load. They impose a higher thermal load to the machines and their cooling system. There are also non-power frequency faults like switching and lightning overvoltages. They impose a massive overcurrent and overvoltage to the grid and superconducting system connected to it. Thus, the strategy of choosing a safety margin for cooling systems with respect to these events differs completely. Islanding is another typical phenomenon in power systems with wind farms which is occurred due to the inability of upstream grid in supplying the demanded load. As a result of this, a non-power-frequency, and ultrafast current wave is injected to the wind farm. This causes an extremely rapid increase of the superconducting machine temperature and if the cooling system is unable to stabilize the temperature, superconductors will experience the thermal runaway and burnout. Thermal characteristic of insulated and bare REBCO tapes under different current is discussed in (Yazdani-asrami et al., 2020c).

11.3. Marine applications

Superconducting machines can be installed in propulsion systems in marine applications (Haran et al., 2017). Superconducting machines in ship propulsion systems are usually high torque and low speed machines. These machines experience different operating schedule, as different torque, or speed would be needed to effectively have a maneuver. These transients especially in a harsh sea environment will impose a huge variation on AC loss, heat load, and efficiency of the cooling system which needs to be considered in the design stage.

Usually, propulsion units in a ship need to continuously work much longer time than in electric airplanes. So, there is a need for a very long time operation of cryocoolers without any malfunctions. This means that there is a need for cryocoolers with the highest reliability that can be reflected in indices such as MTBF, MTTF, and Mean Time Between Maintenance (MTBM). Thus, the priority must be reliability issues rather than cost or the special mass of cooling units. Reliability can be increased by using redundant cooling units; however, this may lead to ships with a heavier weight that imposes a higher heat load to the cooling unit.

Ships may work in a very harsh environment and under such circumstances, any failure in thermal insulation of the cooling units causes a devastating heat load to the cooling units and may even cause the total failure of these units and superconducting machine.

12. Conclusion

In future, superconducting machines will play a remarkable role in cryo-electrification of aviation, marine, and wind power industries. Cooling units are the beating heart of superconducting systems, as either 2G HTS or MgB_2 superconductors in electric machines need to work at stable cryogenic temperatures. Thus, proper selection of features and elements of cooling systems affect their appropriate functionality. There are many considerations to make when selecting or purchasing a cooling unit for superconducting machines. This paper has explained difficulties, complexities, and considerations during the selection of a cooling system for machine application from a viewpoint of an electric machine engineer/operator rather than a cryogenic engineer. Cooling fluid concerns, heat load concerns, economic considerations related to coolant and cryocoolers, mechanical-related issues, and reliability-related issues and challenges were discussed in this paper. Also, specific considerations and limits for some applications of superconducting machines were discussed separately to help the readers and engineers to familiarize themselves with specific requirements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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