Insulation materials and systems for superconducting powertrain devices in future cryo-electrified aircraft: part I – material challenges and specifications, and device level application

Mohammad Yazdani-Asrami, Seyyed Meysam Seyyedbarzegar, Min Zhang, and Weijia Yuan
Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK
Faculty of Electrical Engineering, Shahrood University of Technology, Shahrood, Iran
Email: m.yazdaniasrami@gmail.com

Abstract – Superconducting technology for aerospace application is enabled by emerging development around hydrogen cooled electrically powered aircraft, aiming at zero-emission aviation. Superconductors, typically in the form of tape or wire in a composite architecture, can not only carry current density which is over 100 times that of copper and aluminium, but are also characterized by much lower losses. This property of superconductors makes them good candidates for the fabrication of superconducting devices of high specific power density, i.e. lower size and lighter weight, which is critical for aerospace applications. Superconductors, like any other conductors, require standard insulation to function safely and reliably in the electrical apparatus of aircraft, especially due to the special architecture, operating temperature, and operating condition of superconducting apparatus at high altitude. Extra attention should be drawn to choose proper insulating materials for such applications. In this paper, the challenges and considerations for choosing insulating materials for superconducting devices in cryo-electrified aircraft are reviewed and discussed.
Keywords: Cryo-electrification, Dielectric, Electric aircraft, Hydrogen, Insulating systems, Insulation materials, Superconductor.

I. An introduction to zero-emission aviation: motivation, and opportunities for cryo-electrification

The global warming crisis caused by massive production of CO_2 and other greenhouse gases is one of the biggest concerns globally, and it is drastically changing the climate and putting many human inhabitants in danger. The annual average global temperature rise was more than 1.2 ^{o}C above pre-industrial levels in 2020[1]. This is not only a major environmental issue, but will also bring many economic, social, and political consequences in the near future if significantly meaningful and effective steps are not taken by governments all around the globe. For this purpose, world leaders met for the UN Climate Change Conference (COP26)[2] on November 2021 in Glasgow, Scotland, hoping to respond to these concerns and issues in a united way. What is going to change the tide is to commit to reduce production of CO_2 as an immediate action. The UK government is one of the world leaders on curbing emission through the design and implementation of the Net Zero 2050 program[3]. According to this plan, the UK aims to reach carbon neutrality by 2050.

The restriction on CO_2 production need to be implemented in many sectors, including transportation sector, which is responsible for 20 to 25 % of direct CO_2 emission[4]. This is simply due to the massive amount of fossil fuels burnt in combustion engines every year. Furthermore, such global transportation emissions are increasing every year, as international businesses rely on fossil fuel-based systems to transport and distribute their products. The aviation industry is one of the main contributors to global CO_2 emissions in the transportation sector, being responsible for 2 to 4 % of annual emissions[5]. While this might not look very significant compared to other contributors, one needs to consider the fact that the aviation industry is one of the fastest-growing sectors among different transportation means, annually increasing by 4 to 8 % globally[6]. Assuming 5 % annual growth for the aviation sector, its flight demand will double every 15 years [5]. Considering the large number of flights in a year and knowing that, at the moment, all commercial aircraft are burning fossil fuels in their engine/turbines, the aviation industry will become a key contributor to greenhouse gas emissions, as well as other pollutants such as NOx, soot, and water contrails. Without any intervention to curb these emissions, the aviation sector's contribution to global CO_2 emission would be doubled up by 2050[7]. Therefore, to break this cycle, programs such as Flightpath and Net Zero are necessary effectively to curb emissions. For example, the Flightpath 2050 program of the European Commission demands 75 % and 90 % reductions in CO_2, and NOx respectively, compared with a typical new aircraft in 2000, as the baseline[8]. To satisfy such demanding targets, electric systems need to be implemented in the propulsion unit to replace existing turbine engines, which burn kerosene, leading to a greener aviation industry.

The main problem confronting electric aircraft in large fleets is the low specific power density of existing electric machines, which makes them unrealistic for use in larger aircraft. Though conventional electric machines (large scale MW power machines) offer specific power density of about 4 to 8 kW/kg, these are too heavy for onboard use in medium to longer ranges flights. In addition, electric energy storage systems such as batteries are not yet sufficiently well-developed for higher power applications, as they offer storage capacities less than 0.4 kWh/kg, which is some 40 times less than kerosene [7]. Therefore, disruptive technologies with radical solutions are demanded drastically to increase both the specific power densities of electric propulsion machines and the energy to weight ratio of energy storage systems. Cryo-electrification has been foreseen as the enabling technology, as it takes advantage of cryogenic and superconducting technologies, simultaneously. Many major aviation companies, such as Airbus, have already announced plans to adopt liquid hydrogen (LH2), as a cryogenic fluid, in their aircraft by 2035[9]. In future aircraft, hydrogen could be used either as fuel, being either burnt in the engines or fed into fuel cells. Furthermore, to address the low specific power density of existing electric propulsion units, superconducting technology could increase the specific power density by of the order of two to five times. In addition, superconductors would drastically increase the current carrying capacity of other power system components of an electric aircraft, such as cables, busbars and fault current limiters (FCL), compared with conventional conductor devices. Superconductors can carry more than 100x current compared to copper and aluminium with no loss in DC system and only very tiny AC losses in AC systems. Therefore, fabricating superconducting rotating machine with a specific power density above 20 kW/kg and an efficiency above 99 % would be achievable.

So, if superconductivity can offer such great performance and become the "holy grail" of the aviation sector in curbing emissions, why have major players in the aviation industry only recently started to invest in developing superconducting powertrains? The reasons include the following.

Superconductivity was discovered early in the 20th century and started to be implemented in electric power applications by the late 20th and early 21st centuries. The bottleneck of the commercialization of superconducting devices is that commercially available superconductors need to be cooled down to the cryogenic temperatures below 77 K. For this purpose, a cryogenic cooling system with small cryocooler (playing the role of refrigerator) is usually needed, which was and is quite heavy and bulky, as well as being very low in efficiency. The cryogenic cooling system maintains the operating cryogenic temperature of superconductors within the designed range and hence, it should continuously remove the heat load from the system of superconducting devices and the connections. As a rule of thumb, to remove 1 W heat load at 70 K from a superconducting system, about 18 to 25 W will be consumed in the cooling system. The efficiency gets worse at lower temperature; e. g. 100 W will be consumed from the cooling system to remove 1 W heat load at 20 K[10]. But what has changed recently – which places superconductivity in a promising position for implementation in the aviation industry – is that new plans and roadmaps for using hydrogen in future electrically powered aircraft have been announced, i.e. cryo-electrification. As such, LH2 will be onboard electric aircraft to be used either as a fuel or as a coolant fluid to cool down superconducting systems freely, noting that the boiling temperature of LH2 is about 20 K. This will not only avoid the need for extra bulky cooling systems to provide cryogenic operating temperature for superconductors, but it will also enable the implementation of new superconductors with operating temperature below 40 K. Working at temperatures around 20 K will enhance the current carrying capacity of superconductors, which will lead to the fabrication of superconducting devices with higher specific power densities.

Using hydrogen on board will enable the concept of having not only superconducting motors in propulsion units, but also a fully superconducting powertrain, by making all the constituent elements/components superconducting, including cables, busbars, FCLs and power electronic converters functioning at cryogenic temperature. This will revolutionize the whole powertrain technology, making all components much lighter, more compact, and more efficient. However, by making these electric components superconductive, one may need to consider how electrical and thermal insulation for superconductors will perform at cryogenic temperature, as compared with conventional copper conductors. Note that most superconductors have composite materials, in contrast to conventional conductors. There are insufficient data, studies or standards in the literature regarding this topic. In this paper, the proper insulating materials and systems for superconductors and superconducting devices are discussed, considering future cryo-electrified aircraft as the main application.

II. Most suitable superconductors for aerospace applications

Since the discovery of superconductivity in 1911, many different superconducting materials have been synthesized, but the majority of these are only applicable in low power applications or in the form of thin films in experimental laboratory conditions, either under high pressure or in clean rooms. The most common commercially available superconducting materials are classed as low temperature superconductors (LTS) or high temperature superconductors (HTS). LTS and HTS materials are those which can operate below and above 30 K, respectively. Therefore, LTS materials need more sophisticated cryogenic cooling systems, such that associated devices end up being bulkier and heavier. HTS materials can operate at temperatures below 92 K, and hence, they are preferable for large scale power AC applications, where more heat load would be produced in the superconductor, with the consequent requirement to be effectively dissipated from the cryostat. Amongst HTS materials, which have many kinds, second generation (2G) rare-earth (Re) materials are most commonly available in long lengths for use in large scale power applications. Examples of such systems include yttrium barium copper oxide (also referred to as YBCO) and gadolinium barium copper oxide (also referred to as GdBCO) coated conductors. These rare-earth barium copper oxide (ReBCO) superconductors are often favored because of their high current carrying capacity (linked to their high critical current density) and low AC loss profile. Despite their extraordinary electromagnetic performance, ReBCO tapes are still much more expensive than conventional conductors; a cheaper option is magnesium diboride (MgB_2) wire, which was discovered less than two decades ago. MgB_2 exhibits a critical temperature around 35 K and it was up to ten times cheaper than ReBCO in 2021. In view of its critical temperature, evolving hydrogen technology opens the doors for MgB_2 in superconducting powertrain applications in future cryo-electrified aircraft. Having LH2 onboard is the most likely scenario accepted by Tier 1 aerospace industry players. The LH2 could cool down superconductors to temperature around 20 K, which makes both ReBCO tapes and MgB_2 wires promising conductors for the future of cryo-electrification within the aerospace sector. The LH2 will first provide almost free-cooling for superconducting devices in stand-alone power system and propulsion system of an aircraft and, then, warmer hydrogen can be injected into a fuel cell for producing electricity. Therefore, a devastating concern about using bulky, heavy, multi-stage cooling system onboard an aircraft would be resolved by using LH2. The propulsion motors, power generators, FCLs, busbars, and power cables are among those components that can be superconducting now. In addition, having enough coolant on board enables the option of cryogenic temperature electronics and power electronics. However, many technical and practical considerations and concerns need to be addressed before implementing this technology in commercial aircraft. One of the major concerns is to make superconductors and superconducting devices electrically insulated at low cryogenic temperatures. Note that material properties, technical considerations, and requirements for insulating materials at cryogenic temperatures are very different from the same material at room temperature. In this regard, providing a clear and correct definition of insulation and determining the purpose of its application will benefit the optimal design of insulation systems for use at cryogenic temperatures.

There are two commonly used terms for electrically isolating materials, i.e. ideal insulator and dielectric. A very simple definition for these materials is provided here:

- Ideal insulator: The electrical conductivity in ideal insulators is zero. An important feature of these materials is the lack of polarization in the presence of an electric field. Their molecular structures have tightly bound electrons which cannot readily move. Ideal insulators do not store charge and are generally used as a barrier against the flow of charge and current.
- Dielectric: it has a very limited electrical conductivity and low energy losses. Dielectric materials are divided into two categories polar and non-polar. The dielectric constant or relative permittivity is the ability to store electric energy in an electrical field. Dielectric loss coefficient is measured as an important indicator in condition assessment of these materials[11,12].

In practical superconducting applications, dielectrics can generally be used for three main purposes:

- Insulating: for electrically isolating layer-to-layer or tape-to-tape in coils and winding, or coils and windings against each other in a superconducting device. These insulating materials can take the form of solid, liquid, or gaseous insulation.
- Impregnating: some dielectrics would be used not only electrically to insulate a coil or a winding against other coils and windings but also to immobilize them mechanically against movement and vibration, hoop stresses in short circuit fault cases and other electromechanical and Lorentz forces during transients or the normal operation of a superconducting device. This normally happens by penetration of usually an epoxy or an acrylic resin material into the layers of coils and windings. For high quality impregnation process on superconducting coils and windings, the process needs to be conducted under vacuum[13].
- Encapsulating: encasement by the encapsulating materials onto the coils and windings. This mostly happens when a coil under rotation and thermal load needs to be totally covered by a material and mechanically reinforced and, then, reliably located in the superconducting system.

The durability and stability of electrical apparatus – employing either conventional conductors or superconductors – is highly dependent on the proper use of insulating materials, especially in applications such as electric aircraft where safety comes as the first priority. In general, high electrical, thermal and mechanical strengths, good thermal conductivity, and low dielectric loss are the main desirable parameters of an excellent insulating material. In addition, resistance against oxidation, deterioration, moisture absorption, and evaporation are some of the factors that guarantee the performance of an excellent insulation material. Moreover, ease of use, low weight, low toxic risk, long lifetime, and high reliability are other important factors from a utilization point of view[14].

Many different types of dielectric and insulating materials are used in electrical applications. However, choosing the best type of insulating materials for superconducting devices and finding the optimal thickness of insulation are not straightforward and require technical knowledge and experience, depending on factors such as the voltage level, operating temperature, number of turns in coils and windings, thickness of superconductor, type of coolant, as well as thermal expansion coefficient and thermal conductivity of insulating materials, etc[15]. In this paper, we only focus on electrically insulating materials for superconducting applications; thermal insulators like multilayer insulation (MLI) or superinsulation are not discussed. However, in the case of most electrical insulating materials for superconducting applications, it is desirable to have high thermal conductivity and high heat diffusivity.

III. Most common insulating materials for superconducting applications: technical considerations and challenges

All these insulating materials and dielectrics are commercially available and their technology readiness level (TRL) is high.

III.A. Solid insulation

- ✓ ***Polyimide tape:*** Polyimides constitute a category of high-performance polymers. Kapton is the most famous insulation in this family for superconducting applications, such as superconducting transformers, FCLs, and magnets, etc. Kapton tape is available in both adhesive and non-adhesive versions with different widths and thicknesses. In most low power small scale prototypes, Kapton simply covers the surface of tape or wire between turns. However, in higher power applications, Kapton tape should be wrapped (e.g. spiral wrap) around the superconductors under a proper tension. Kapton tape performs well as the insulation in low voltage/low power applications and there is no need for curing after application to a superconductor surface. As such, there is no need for any extra devices such as a UV lamp or a furnace. It is nevertheless of note that a problem with adhesive Kapton is that, in some applications, the adhesive will be deteriorated at elevated temperatures, which could be caused by thermal cycling, short circuit fault, local hotspot heating, etc. In the worst case, the tape could be burnt, which might cause an inter-turn short circuit fault in superconducting coils. Even if the Kapton is not burnt, local adhesive burning might lead to film boiling when liquid coolants such as liquid nitrogen (LN2) are present beneath the Kapton. Therefore, non-adhesive Kapton polyimide tapes would be recommended for high power applications. There are almost no health and safety risks for the operators associated with the use of Kapton tapes. From a cost point of view, Kapton is one of the most affordable options for superconducting applications. Above all, Kapton tapes are suitable for insulating superconducting materials, coils, and winding, but not for impregnation or encapsulation purposes. Kapton insulation can be easily undone or removed from the surface of a tape or a coil if needed without impacting the performance of the superconductor.
- ✓ ***Epoxy resin:*** Epoxy resin, also called polyepoxides, refers to a type of reactive prepolymer and polymer containing epoxide groups[16]. These resins react either with themselves in the presence of catalysts or with many co-reactants, such as amines, phenols, etc. Epoxy resin shows better mechanical properties and higher thermal and chemical resistance than many other types of resin and, therefore, it has exclusive use in electrical and mechanical components in aircraft. In addition, epoxy resin could be used for insulating, impregnating, and encapsulating superconducting tapes, wires, coils, and windings in future electric aircraft.

  The most common members of the epoxy resin family that are utilized in high power superconducting applications are STYCAST (thermally conductive, and non-conductive), Araldite, and ER2220. These epoxy resins need to be cured either at room temperature, or by heating in an oven, which has the disadvantage of adding an additional curing time (after using the mixed epoxy resin with catalyst or hardener) of up to 24 hours to insulation manufacturing process. Furthermore, there is significant health and safety concern when using epoxy resins in laboratories, including allergic reactions and skin dermatitis caused by contact with the compound, as well as respiratory problems from vapor inhalation during the preparation or curing process. Therefore, strict precautions should be taken when using an epoxy resin. Once it is cured, it is safe.

  Cured epoxies are generally very hard, and hence, the thickness of insulation needs to be thin enough to allow bending of the tape after curing when one needs to make coil using insulated tape. This hardness could be a plus if the epoxy resin is used for the purposes of impregnation or encapsulation, by consequently offering great mechanical stability. Undoing epoxy resin insulation from the surfaces of tapes or wires is, however, almost impossible without damaging the superconductor.

  Another concern relating to the use of these materials on the surface of superconducting tapes is that the expansion and contraction (shrinkage) coefficients of epoxy resins after curing are usually quite different from those of superconductors. This could be catastrophic since, on cooling down, the epoxy resin coating and superconducting conductor shrink of a different degree, which could cause longitudal and transverse stresses on the surface of coated conductor, delamination, serious mechanical damage, reduction of current carrying capacity, as well as an increase in AC loss. Therefore, to address this challenge, composite coatings are proposed to reduce the risk of delamination[17], by adding appropriate fillers into the epoxy compound before applying it to the surface of a superconductor. A variety of different materials can be used as filler to match the expansion and shrinkage coefficients of composite coating to those of superconducting conductors. The filler can not only adjust the shrinkage properties of insulating materials but can also change their electrical and thermal parameters. Thus, the type and size of fillers and thickness of composite coating on the surface of superconductor need to be chosen carefully. The most commonly used fillers for making composite insulation are as follows: alumina; aluminum nitride; boron nitride; beryllia; silicon dioxide; clay; calcium carbonate; carbon nanotubes; boron trichloride; diamond particles; zinc naphthenate. Using these materials, one can manipulate the electrical and thermal properties of the composite coating to meet the needs of a specific application, based on technical knowledge and experience of working with them, as at the moment, no technical standards or technical instructions are available.

  Avoiding the formation of voids or air bubbles in an epoxy material during its preparation or curing process is an important requirement. The epoxy resin compound should be degassed under a proper vacuum level before being applied to the surface of the superconductor. It is very important for aviation applications that the insulating and impregnating processes be completely done under vacuum to avoid introducing any voids and air bubbles into the compound. In addition, heat curing is suggested, as it will accelerate curing process and reduce the chance of introducing or establishing any voids or bubbles during the curing process. Any voids and air bubbles could be a source of partial discharge (PD) in the coil and winding after assembly. However, the level of heat must be critically monitored and controlled as any extra heating may damage the superconducting layer and induce aging.

  Special categories of cryogenic epoxies include: electrically conductive; thermally conductive/electrically insulative; cryogenic shock resistant; optically clear; NASA low outgassing approved; mechanical shock resistant[18].
- ✓ ***Acrylated Urethane:*** Polyurethanes constitute a mature class of industrial insulating material and have been used in various industries since 1940, because of their attractive properties, which include good electrical properties, strong bonding performance,

toughness in harsh environments, etc. Radiation-curable polyurethanes have been implemented for industrial purposes during the last two decades. Usually, a UV lamp is needed for curing the acrylated urethane. Such coatings are successfully applied for protection purpose in automotive or aerospace industries, as well as in applications such as electronic boards. They are commercially available in many different types and could be purpose-designed for some specific aviation applications. After curing, the produced insulating material offers a good combination of toughness and elasticity and other valuable properties.

An advantage of acrylated urethanes over epoxy resin is that superconductors coated with acrylated urethane are flexible enough to form a coil and winding even with a small internal diameter. Acrylated urethanes generally offer a better match of expansion/contraction coefficient compared with epoxy resins which, therefore, reduces the risk of delamination from the superconductor. Therefore, acrylated urethanes are favorable for insulating superconductors for electric machine, FCL, and transformer applications. However, still epoxy resins remain a better option for impregnating superconducting coils and windings. Like many other insulating materials, acrylated urethanes need to be degassed and applied to superconductor surfaces under vacuum, to avoid the formation of voids and air bubbles in the cured coating. Removing a cured acrylated urethane from a superconductor surface is much easier than an epoxy resin, which causes less risk to the conductor. One disadvantage of acrylated urethane is that majority of them naturally have very low thermal conductivity. This factor needs to be considered in designing the insulation and cooling systems for a superconducting device, especially in conduction cooled systems. One way to solve the issues caused by the low thermal conductivity of acrylated urethane insulation when using in conduction cooled systems is to produce composite coatings by adding appropriate fillers to increase the thermal conductivity. In liquid coolant systems, using acrylated urethane would however be desirable, as it can avoid thermal runaway caused by film boiling[19],[20]. Note that acrylated urethane would not let the liquid touches the hot surface of the tape and therefore, no gas sheath can be produced around the superconductor to reduce the heat transfer or cause film boiling. Other challenges are curing the acrylated urethane using UV lamp at a proper temperature and also curing it on surface of tape uniformly. Non-uniform coating will cause electrical, heat transfer, and thermal issues.

- ✓ ***Paper insulation:*** Paper insulation is made of fibers in the form of sheets. The tape obtained from this insulation is used in situations that require high strength[21]. One of the most famous members of the paper insulation family that is implemented in superconducting applications is Nomex paper. Nomex sheet is actually a paper made by a calendaring manufacturing process and, technically, it is a product of aramid fibers. Nomex has very good electrical insulation properties that make it suitable for use in electric machines and transformers. Nomex papers are available commercially in many different grades and also in saturated mode, with some resins such as phenolics. Nomex paper insulation offers high inherent dielectric strength, mechanical toughness, high conformability, flexibility, and resilience. Generally speaking, paper insulation including Nomex are not good options in liquid cooling system, since liquid may penetrate underneath the paper insulation, forming a gas sheath and eventually causing electrical and thermal problems. In addition, some Nomex grades are very brittle at cryogenic temperatures. In case of any short circuit fault during which winding is under high stress and high electromechanical force, paper insulation may break and later cause interturn faults in the winding. In terms of paper insulation removal, this is quite easy and there is little risk of damage to the tape.
- ✓ ***Varnish:*** Varnish is used electrically to insulate tapes, coils, and windings and to form a protective layer on the surface of a superconductor[22] to avoid contamination, short circuit, mechanical damage, atmospheric and chemical erosion. Varnish is mostly used in low power and non-critical applications. Depending on its thickness and type, some cracks might be developed on the surface at lower cryogenic temperatures, which will increase concerns over the occurrence of interturn short circuit faults. However, polyvinyl phenolic varnish has good thermal conductivity and mechanical strength at cryogenic temperatures[23]. Four common varnishing methods include dip and bake epoxy varnishing, trickle varnishing, vacuum pressure impregnation and ultra-sealed winding[24].

  PPLP: Polypropylene laminated paper also called as PPLP is an insulator made out of polypropylene placed between Kraft papers[25] [26]. PPLP dielectrics exhibit high AC, DC, and impulse strengths, while the dielectric loss is lower than cross-linked polyethylene (XLPE) dielectrics. PPLP has excellent electrical behavior under cryogenic temperatures, which makes it an effective option for superconducting applications[27]. PPLPs are widely used as insulation for superconducting cables and busbars. However, the polypropylene mechanical behavior strongly depends on the temperature, e.g. at cryogenic temperature it changes from "rubbery" to "glassy" state with 2x higher failure stress compared with room temperature, as well as reduced elongation[28].
- ✓ ***G10:*** Glass reinforced epoxy (GRE), also called glass fiber reinforced polymer (GFRP), is a type of composite material of which G-10 is the most famous member of this family. G10, a high-pressure reinforced fiberglass laminate, is created by stacking multiple layers of glass cloth, soaked in epoxy resin as the polymer matrix. By compressing the resulting material under heat until the epoxy cures, G10 sheets are produced. G10 is, however, a hazardous material under harsh environment and, for example: a hazardous glass-epoxy dust is produced during cutting or machining, which can cause cancer in the respiratory system; touching it without gloves may cause skin dermatitis. In superconducting applications, G10 is used not only as an electrical insulator, but also as a structural body/former supporting the superconducting coil and winding in superconducting fault current limiters (SFCL), HTS transformers, and superconducting machines, during normal, fault, and transient operation. During fault and transient conditions, huge currents flows into the superconducting winding, such that large electromagnetic forces will be applied to the winding, whereupon, the former needs to protect the winding from deformation. In addition, there are AC magnetic fields everywhere inside the cryostat. Therefore, a cryostat made of GRE as a non-magnetic, non-conductive electrical insulating material is commonly used in many superconducting applications[29]. Better GRE and GFRP composites have been developed recently to replace G10.
- ✓ ***Nylon:*** Nylon is a thermoplastic with good wear properties, high compressive strength and good resistance to chemicals and high voltages. It is often used to manufacture electro-mechanical components because it is very easy to machine. Nylon is extruded and cast and can be filled with a variety of other materials to improve impact resistance, coefficient of friction, stiffness, etc. The disadvantage of Nylon is that it is very susceptible to moisture absorption. Nevertheless, in superconducting applications, it remains a good option for use in dry cryostat rather than wet-cryostat applications. Furthermore, it can be coated with urethane to render it liquid-proof. Nylon has been used as an insulation material for supporting and immobilizing purposes in superconducting applications, rather than as electrical insulation for tapes and wires. This is because complex electromagnetic fields exist around superconductors and using nylon to immobilize the superconductor avoids field distortion and extra losses in metallic bolts and holders.
- ✓ ***Heat-shrink tube:*** This is a radially shrinkable plastic insulation made out of polyolefin for wires and connectors, which is highly resistant to extreme environments such as high temperature, cryogenic temperature, and UV radiation. It can work without cracking at cryogenic temperatures, even down to liquid helium temperature. When using heat-shrink tube as superconductor insulation, it will also protect the superconductor from abrasion and coming directly into contact with any coolant or epoxies. Heat-shrink tubing does

not need any adhesive or epoxy resin to stick to the surface of a superconductor, instead, it mechanically couples to the surface of the coated conductor by the friction caused by the shrinkage. A properly sized heat-shrink tube, once cooled to cryogenic temperatures, fits tightly and uniformly to the surface and edges of coated conductor tape. Another benefit of using heat-shrink tubing for insulating superconductors is that it will protect the conductor tapes from delamination without the need to use a composite coating with nanoparticles.

If epoxy resin is used for impregnating a superconductor tape or coil insulated by heat-shrink tubing, the superconductor will be decoupled from the epoxy resin because of the tube. Therefore, during cooling down process, longitudinal or transverse strains and stresses are not applied to the surface of the superconductor, but to the heat-shrink tube. This will bring a huge advantage of having a conductor free of degradation caused by delamination during thermal cycling[30]. It can be effectively used in superconducting cable and machine applications.

- ✓ ***PVC:*** Polyvinyl chloride (PVC) is a type of thermoplastic insulation material that can be used in superconductor equipment[31]. Features such as electrical, mechanical and chemical strength, proper conductivity and flexibility as well as low cost make it suitable for use as a functional insulator. However, due to cracking and brittleness, PVC should not be directly used at cryogenic temperatures. In addition, it is a good conductor for heat. In superconducting applications, PVC is mostly used for insulating superconducting cables in a level that it has no direct contact with cryogenic fluid.
- ✓ ***PEEK:*** Poly(ether ether ketone) (PEEK) is an opaque high-performance semi-crystalline thermoplastic polymer with outstanding resistance to chemicals, wear, fatigue and creep. It has long life, very low moisture uptake, high temperature resistance, good fire-retardant performance and excellent mechanical strength across a broad temperature range. However, the high price of PEEK limits its application to sensitive and demanding applications in aerospace and automotive industries for insulating electric machines and power cables. On the challenge side, it needs to be processed at high temperature, is attacked by some acids and is vulnerable to degradation by exposure to UV light. In superconducting applications, it is mostly used as insulation for superconducting cables[32]. However, there are opportunities for PEEK to be implemented as insulation in the slots of superconducting machines for electric aircraft in future.
- ✓ ***PTFE:*** Polytetrafluoroethylene (PTFE) is a thermoplastic polymer which is used for low friction bearing components and electrical insulation. It has excellent chemical resistance, low coefficient of friction, low moisture absorption and high electrical resistance, but poor mechanical properties compared to some other polymers. In superconducting applications, PTFE is usually used as an insulated former for coils and windings at lower power applications. It maintains high strength and toughness at cryogenic temperatures down to 5 K. It can also be used as insulation for superconducting wires, tapes and, especially, cables and connectors.
- ✓ ***Micro-multilayer multifunctional electrical insulation (MMEI):*** MMEI is one of the famous new electrical insulation systems because of its lightweight and high voltage durability characteristics. MMEIs are capable of suppressing corona partial discharges, providing shield for electromagnetic interferences, temperature management and mechanical durability against stresses. This makes these systems a promising option to be used in electric aircraft. MMEI normally consists of multiple layers, namely, thermal insulation for dissipating heat from the conductor, a high strength dielectric layer, a layer for protection against mechanical stresses, a layer that acts as a corona and PD barrier and a bonding layer. The application of conventional materials in this new structure could increase the voltage withstand ability of the dielectric; the voltage withstanding performance of MMEI is the function of the type and thickness of the dielectrics used in its structure. Normally, Kapton polyimide, PTFE, PEEK and PPLP are used as dielectric layers. However, the challenging issue is to provide an appropriate inter-layer bonding integrity to gain a high value of voltage strength. Due to the structure of these insulation systems, they can face cracking, cavity, charging, melting, channeling, and debonding of layers[33], especially at cryogenic temperatures, which can increase the probability of PD initiation.
- ✓ ***Mica:*** if reinforced with support materials and the impregnating resin, it can be a good alternative to mica paper which was traditionally used as electric machine insulation. Mica is produced in the form of sheets on insulating paper and some other materials such as glass fabric, Kapton polyimide films and Nomex aramid fibers. It has not been used extensively in superconducting applications yet[34], but perhaps would be a good alternative to currently used materials if one decides to fabricate high power, high voltage superconducting machine for electric aircraft.
- ✓ ***Composite polymeric coatings:*** The use of polymer insulation at cryogenic temperatures for superconducting applications is challenging due to concerns regarding cracking, mechanical strength, shrinkage factors, and thermal conductivity. Researchers suggest the use of a composite polymeric coating composed of micrometer size fillers in an appropriate polymer, but research has shown that this weakens the electrical performance of the polymeric insulation[35]. In order to improve performance, the implementation of nanometer-sized particles such as barium fluoride, barium titanate, silica, aluminium oxide, titania, quartz, beryllia, and cobalt ferrite has been suggested. Results obtained from AC withstand voltage tests show that composite coating with nanomaterials perform better than those with micromaterials at cryogenic temperatures. In addition, nanocomposite polymers have good resistance against PD and electrical treeing[36]. However, making composite coating needs experience and some trial and error before the proper structure is reached. As part of this, many electrical high voltage tests need first to be done on short sample lengths.

III.B. Liquid and gaseous insulation

LN2 has been extensively used as a cryogen and an insulating material in superconducting applications. The main advantages of LN2 are as follows: ease of access; low production cost; high heat capacity. However, the application of this cryogen is mainly limited to terrestrial or ground-based applications of ReBCO superconductors, due to the fact that its minimum operating temperature is 64 K under subcooled situation, below which temperature, it freezes. In order to achieve higher current carrying capacity and higher power density in superconducting equipment, much lower operating temperatures are required compared to 77 K LN2 temperature[37]. Gaseous helium (GHe) has the ability to work at lower cryogenic temperatures with a lower risk of suffocation compared with LN2. However, the low breakdown voltage is a limiting factor for GHe compared to LN2. A method to increase the breakdown voltage of GHe in superconducting applications at medium and low voltage levels is to increase the pressure. Accordingly, by increasing the gas pressure to 1.5 MPa, it is possible to attain an acceptable electrical strength along with other benefits of helium at a higher cryogenic temperature. This leads to the use of high pressure GHe as cryogen in superconducting devices such as cables[38]. Another method that increases the electrical strength of GHe is to use a gas mixture by adding another gas into it. An 80% increase in GHe electrical strength can be achieved only by adding 4 mol% H2 into GHe. In addition, it is possible to achieve higher electrical strength by increasing the percentage of moles of the mixed H2 or by creating a ternary combination of 88 mol% helium, 4 mol% hydrogen, and 8 mol% nitrogen. Compared to GHe, the breakdown voltage was increased by up to 300% using a ternary combination[39]. When a short circuit occurs in a superconducting device , a large electric field is created. Therefore, if GHe is used as insulator, a breakdown may happen. To prevent electrical failure of GHe, it is highly recommended to mix it with H2[40,41]. The electrical stability of liquid insulation is reduced by the presence of bubbles. Increasing the pressure of these liquid dielectrics is an effective way to solve this problem, which has the advantage of also increasing the partial discharge inception voltage (PDIV). Unfortunately, there are insufficient reports in the literature concerning the use of LH2 as an insulation medium for superconducting devices, which needs to be addressed in the next couple of years before hydrogen-based aircraft are ready to take off.

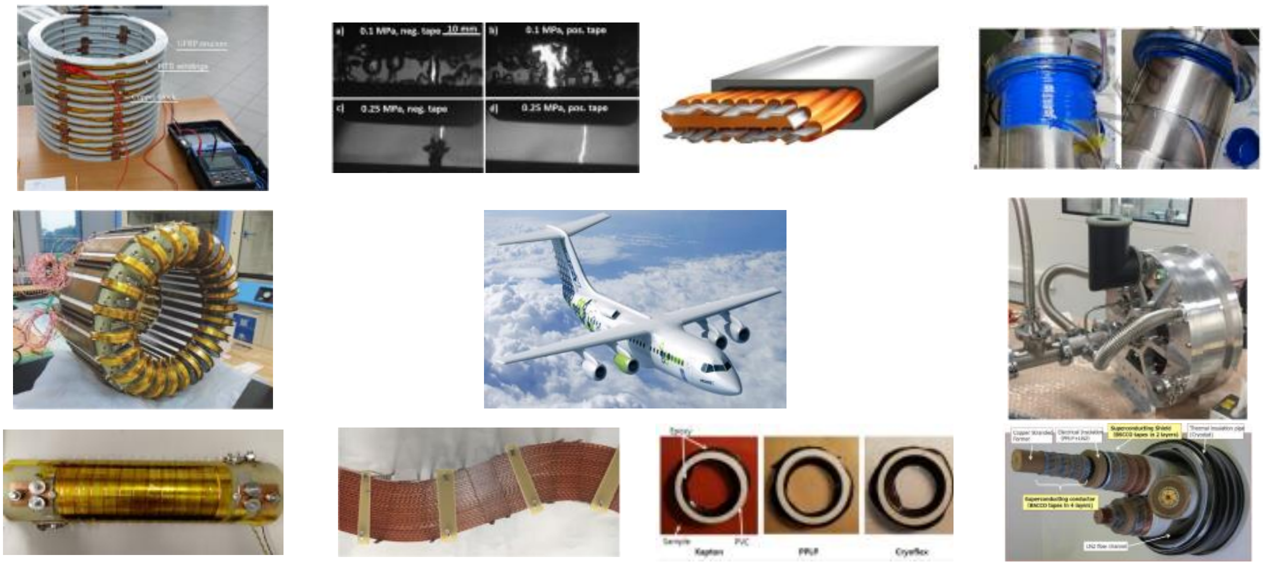

Figure 1. Different insulation materials for different powertrain components[42,43,44,45,46,47,48,49,50,51,52]

IV. Different dielectrics in superconducting applications: device level considerations

In this section, the most commonly used dielectrics as insulation in superconducting devices considering aircraft applications are reviewed and discussed. Figure 1 shows a range of different superconducting equipment, with their insulation, which provides valuable reference for a superconducting powertrain in a cryo-electrified aircraft.

IV.A. Superconducting cable

There are, technically, two types of superconducting cables from a dielectric viewpoint, i.e. warm and cold dielectrics[53]. Unlike the warm dielectric design proposed in traditional cables, the superconducting cable design often adopts cold insulation because it has good thermal compatibility at cryogenic environment. The warm dielectric cable has faster recovery, lower complexity in terms of the cooling system and a much lower cooling penalty, whilst the cold dielectric configuration offers a lower leakage current, greater ampacity and lower inductance. In general, thermal matching between different layers of insulation and the superconductor should be considered as an important factor in cable design. If there is any large mismatch between the thermal expansion coefficient of different parts of the cable, mechanical forces between the tape and the insulation layers will lead to delamination, voids, and finally destruction of the cable[54].

Increasing the voltage or current level represent ways to increase the transmission power of cables, which affects the thickness of the insulation and finally the volume of the cable. In HTS cables, this complicates the cable structure. PD is also an important issue in this regard, which should be considered during design stage[55].

Issues with superconducting cables concern quality control and condition monitoring of the insulation system, since a defect in the insulated part of the cable may happen time to time. Unfortunately, this has to be done after installation and operation of the cable at cryogenic temperature, not in the manufacturing environment. Consequently, this can involve significant cost to address any problems relating to the quality of the insulation or cooling and operating problems, knowing that the cable is already installed and cooled down to operating temperature through a difficult procedure. Taking mechanical and thermal stresses into account, it should be critically considered to determine the reliable insulation material and method for superconducting cable. Insulating each individual tape separately by the heat-shrink tubing method will reduce the mechanical stress on the tape compared with using an epoxy resin on its surface and will reduce the complexity of the manufacturing process of a superconducting cable[56].

Some superconducting cables are designed with multilayer insulation. The breakdown voltage of multilayer insulation in HTS cable depends on the number of layers. For example, the breakdown voltage of multi-layered of laminated polypropylene (LPP) reduces with increasing the number of LPP layers if butt-gap is considered. Therefore, it is necessary to study the process of changing the breakdown voltage in multilayer insulation based on the number of layers[57].

IV.B. Superconducting fault current limiter

Resistive SFCLs are foreseen as being used against electric faults in future electric aircraft[58]. The quench resistance of SFCL can effectively limit the peak of fault [59]. Most SFCLs are designed for use at relatively low electric field, below 200 V/m, and usually around 30-50 V/m. Consequently, in the case of proper placement of tapes on the GFRP former with sufficient separation from each other, there would be no need to insulate the tapes and, rather, simply use an insulating support such as G10 or PTFE. This former/support will then protect the SFCL coil from electromechanical forces during a fault. In the case where an insulating layer is required on the surface of superconducting tape, the type and thickness of the insulation is very important in determining the recovery time of the SFCL, since the heating phase during a DC fault is almost adiabatic, but recovery will depend on heat transfer, thermal conductivity, as well as the type, and uniformity of the insulating layer on the surface of the superconductor. Kapton polyimide and Nomex tapes are some of the common insulating materials used for SFCLs, although the use of a Kapton polyimide insulation layer makes recovery rather slow compared with bare tape at temperatures near the operating temperature, since heat transfer in convection mode takes a much longer time. In contrast, the recovery time of slot insulation, which is a composite material, is very similar to that of bare tape[60]. One of the most important insulating parts in resistive SFCLs is the thermal stabilization layer, which is made using a resin-like polymer and which is used to increase the electrical withstand of tapes[61]. This must have good thermal conductivity, high electrical resistance, high heat capacity and an appropriate thermal expansion.

IV.C. Superconducting rotating machine

In order to insulate turns from each other in a coil, immobilize the tapes in the final assembled coil and increase the heat transfer, it is necessary to use optimized insulating materials in superconducting machines[62]. In electrical machines, the insulation can be divided into slot insulation, over hang portion insulation, terminal insulation and rotor insulation or pole insulation[63].

The structural characteristics of superconducting coils depend on the insulation type and its materials, which influence the parameters of the superconducting machine[64]. Induction voltage, inductance, magnetic field distribution and time constant are some of the parameters that are affected by differences in the structural proportions[65].

MgB_2 cable with S-glass or polyester braided insulation is commonly used for the stator winding in superconducting electrical machines. These insulators are used to withstand turn-to-turn voltage and help epoxy wicking to the interior of the coil cross section[66].

Polymer coatings, polymeric films and papers are used as insulation materials in electric machines for aircraft applications. Kapton and Nomex are practical examples of such insulation, which have high electrical resistance but very poor thermal conductivity. In addition, they are easily degraded under electrical discharges. The weakness of these insulation materials in terms of heat transfer affects the power density of electrical machines[67].

Epoxy resins are also widely used in superconducting electrical machine applications for impregnation purposes[68]. Amongst the different options, STYCAST black[69] has been popular because of its excellent mechanical, thermal, and electrical performance, as well as good stability after thermal cycling.

IV.D. Superconducting busbar

In order to connect different equipment within the superconducting powertrain of an electric aircraft with equal phase and voltage level, busbars are called for. Busbars contains stacks of superconductors that should be insulated for the sake of electrical isolation as well as increased heat transfer. A busbar joint is an important component that connects different sections of busbar to other superconducting components[70]. Several busbars are connected to the feeder to communicate with each other. In relation to the application of busbar and feeders, insulation and joints are the most significant challenges[71]. In this context, three methods for the insulation of feeders and busbars are introduced as follows: winding wetted tapes (wet-winding); winding pre-impregnated dry tapes; winding dry tapes by vacuum pressure impregnation[72].

For busbar applications, voids and air pockets, which can be introduced through the wrapping and curing processes, are the main sources of PD and breakdown. The curing of resin without vacuum in the wet-winding approach produces more voids than does the pre-impregnation technique. In the pre-impregnation method, the pressure of curing plays an important role in determining the void content created. Kapton, fiberglass, and resin pre-impregnated glass tapes have been used to produce superconducting busbar insulation. The curing temperature, heating rate and viscosity of the resin all have a significant impact on the quality of the insulation in the busbars [48].

Busbar and joint have limitations in terms of insulation system, such as: 1) It is not possible to cure busbar insulation in the heater due to its length. 2) Joint insulation and its quality play an important role in the electrical performance of the busbar. However, it is difficult to insulate the joints due to its irregular configuration and complex structure. 3) Large electromagnetic forces caused by huge current and magnetic field of busbar affect the mechanical load of the insulation system under cryogenic conditions [48].

IV.E. Cryogenic temperature power electronics

The use of power electronic devices at cryogenic temperature increases their efficiency compared with room temperature. In fact, the use of suitable conductors, semiconductors, and insulating materials creates optimal operating conditions at cryogenic temperatures. At cryogenic temperatures, most carrier devices show low leakage current, low latch-up susceptibility and increased speed[73].

Insulation materials such as classic printed circuit board (PCB) materials, epoxy encapsulants and most insulation papers are appropriate dielectrics for power electronic converters at cryogenic temperatures. The PCB provides mechanical support, electrical connection as well as dielectric material in the circuit[74]. GFRP is one of the main materials used in PCBs. However, due to thermal expansion mismatches, the insulation material is subjected to fatigue during thermal cycling[75]. In addition, insulation layers will play an important role in the thermal management of power electronic converters at the system level since, if any fault happens in one of the switches or converters, a large huge amount of heat will be produced that needs to be effectively dissipated to avoid burning other switches through heat accumulation[76]. In liquid dielectrics, under proper operating pressure, nucleate boiling will happen and, by using an appropriate insulation, this can increase the heat transfer by a factor of ten, thereby dissipating the heat from the switch. Therefore, even for cryogenic temperature power electronics, the choice of insulation system should not be taken lightly.

The reliability of insulation layers can be considered as a limiting factor in power electronics technology. Aging and PD are significant limitations for the use of thin layers of electrical insulation. Breakdown of insulation is a very important consequence of the implementation of thin insulation layers, as are electrostatic discharges. Formex, Mylar, Valox, Lexan, PVC, and Kapton are some of the most appropriate materials for use as power electronic insulation[77].

One of the main problems with cryogenic temperature power electronics for superconducting equipment is their heating on-state losses. Therefore, installing them outside the cryostat of superconducting equipment has been proposed to solve this problem. Novec 649 was used as a dielectric and coolant in power electronic equipment for a variety of room temperature applications. Novec 649 is used in solid form in HTS cables and in liquid form in electronic converters[78].

V. Conclusion

The mainstream of future developments in the aviation sector is zero-emission aircraft, which is very likely to be achieved through the concept of cryo-electrified aircraft. A major challenge in this field is the power to volume ratio – achieving higher power in a reduced volume. Also, the sharp decrease in electrical insulation strength due to the pressure reduction at higher altitude is a major challenge for electric aircraft. In this respect, the use of superconducting equipment plays an important role in facilitating the transmission of enormous amounts of electrical energy with high efficiency at low voltage and also in reducing equipment size. However, the use of superconducting equipment requires access to cryogenic fluids at very low temperatures. Liquid hydrogen is very promising cryogenic fluid for use in future cryo-electrified aircraft, since it can be used as both coolant and fuel. Operation of superconductors at cryogenic temperature brings the ability to transfer much higher power than equipment at ambient temperature. In addition, their use in the rather constant or controlled pressure of a cryostat has the benefit of eliminating the destructive effect of pressure drop at higher altitude that dielectrics face in conventional aircraft. In fact, pressure drop reduces the electrical strength of the insulation system. Accordingly, the behavior of the insulation system at cryogenic temperature is an important challenge in the proper operation of equipment in aviation application. Increasing the voltage level to increase the electrical power transmission is limited by the properties of existing electrical insulation systems. Also, the properties of some insulators at cryogenic temperatures degrades, which limits their use in electric aircraft. Therefore, determining the appropriate insulation system that can show good insulating properties at cryogenic temperature and is not affected by changes in operating conditions should be considered as a basic but vital requirement. Due to this need, this article first studies the types of electrical insulations and then the common insulation materials reported in literature for superconducting equipment is reviewed for cryo-electrified aircraft applications. Apart from challenges related to design at device and system levels, there is a serious concern about insulation materials and systems that need to be used in superconducting powertrain components such as motor, generator, cable, busbar, SFCL, as well as cryogenic temperature power electronics.

In a subsequent article, we will discuss system level challenges for insulation systems of superconducting powertrain devices in a cryo-electrified aircraft. Considerations relating to aging, fatigue, oxidation, electric discharges, PDs, etc. are discussed there. In addition, technology and manufacturing readiness levels for existing insulation materials and systems will be reported and future trends for research and development are discussed.

Reference

[1] climate.copernicus.eu/copernicus-climate-change-service-c3s-confirms-july-2019-temperatures-par-warmest-month-record

[2] https://ukcop26.org/

[3] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law

[4] International Energy Agency report

[5] P. J. Ansell and K. S. Haran, "Electrified Airplanes: A Path to Zero-Emission Air Travel," IEEE Electrification Magazine, vol. 8, no. 2, pp. 18-26, June 2020, doi: 10.1109/MELE.2020.2985482.

[6] https://www.icao.int/sustainability/pages/facts-figures_worldeconomydata.aspx

[7] J. K. Nøland, "Hydrogen Electric Airplanes: A disruptive technological path to clean up the aviation sector," IEEE Electrification Magazine, vol. 9, no. 1, pp. 92-102, March 2021, doi: 10.1109/MELE.2020.3047173.

[8] The High Level Group on Aviation Research, Flightpath 2050: Europe's Vision for Aviation; Maintaining Global Leadership and Serving Society's Needs; Report of the High-Level Group on Aviation Research (ser.Policy/European Commission). Luxembourg: Publications Office of the European Union, 2011.

[9] https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html

[10] Y. Terao, W. Kong, H. Ohsaki, H. Oyori and N. Morioka, "Electromagnetic Design of Superconducting Synchronous Motors for Electric Aircraft Propulsion," in IEEE Transactions on Applied Superconductivity, vol. 28, no. 4, pp. 1-5, June 2018, Art no. 5208005, doi: 10.1109/TASC.2018.2823503.

[11] Y.M. Poplavko," Electronic Materials, Chapter 7 - Dielectrics" Elsevier, Pages 287-408,2019.

[12] https://www.electricaltechnology.org/2018/03/insulating-and-dielectric-materials.html

13 https://www.gei-journal.com/enqkxx/journalEN/201805/20181226JGEI201805005.html

[14] M. T. Demko *et al*., "Thermal and mechanical properties of electrically insulating thermal interface materials," *2017 16th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2017, pp. 237-242, doi: 10.1109/ITHERM.2017.7992477.

[15] G. Messina, M. Yazdani-Asrami, F. Marignetti and A. della Corte, "Characterization of HTS Coils for Superconducting Rotating Electric Machine Applications: Challenges, Material Selection, Winding Process, and Testing," IEEE Transactions on Applied Superconductivity, vol. 31, no. 2, pp. 1-10, March 2021, Art no. 5200310, doi: 10.1109/TASC.2020.3042829.

[16] https://www.corrosionpedia.com/definition/1746/epoxy-resin

[17] C Barth et al, Degradation free epoxy impregnation of REBCO coils and cables, Supercond. Sci. Technol. 26, 2013, 055007.

[18] https://www.masterbond.com/properties/epoxy-adhesives-cryogenic-applications

[19] Mohammad Yazdani-Asrami et al, Heat transfer and recovery performance enhancement of metal and superconducting tapes under high current pulses for improving fault current-limiting behavior of HTS transformers, Supercond. Sci. Technol. 33, 2020, 095014.

[20] Mohammad Yazdani-Asrami et al, Fault current limiting HTS transformer with extended fault withstand time, Supercond. Sci. Technol. 32, 2019, 035006.

[21] Z. Jin, A. Lapthorn and M. Staines, "The Dielectric Strength of Nomex 410 Paper in Liquid Nitrogen Under Boiling Situations," *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 7, pp. 1-10, Oct. 2017, Art no. 5500710, doi: 10.1109/TASC.2017.2732282.

[22] L. Yan, Q. Lin and Y. Li, "A high current density bath-cooled superconducting solenoid with varnish-coated conductor," in *IEEE Transactions on Magnetics*, vol. 24, no. 2, pp. 1078-1081, March 1988, doi: 10.1109/20.11416.

[23] C. R. Morelock, M. R. Suchomel, and A. P. Wilkinson, "A cautionary tale on the use of GE-7031 varnish: low-temperature thermal expansion studies of ScF3," *J. Appl. Cryst. (2013). 46, 823–825*, doi:10.1107/S0021889813005955.

[24] P. A. Timmins, "Epoxy "trickle" impregnation with solventless resin vs. dip and bake in solvent varnish," *Proceedings: Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Technology Conference (Cat. No.03CH37480)*, 2003, pp. 633-639, doi: 10.1109/EICEMC.2003.1247963.

[25] A. B. Gorospe, and H. S. Shin, "Mechanical Properties of PPLP Material at Cryogenic Temperature," Superconductivity and Cryogenics, vol.14, no.4, pp.16-19, 2012. http://dx.doi.org/10.9714/sac.2012.14.4.016

[26] G. Chen and Z. Xu, "Polypropylene laminated paper (PPLP) insulation for HVDC power cables," 2018 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), pp. 28-32, 2018. doi: 10.1109/ICPADM.2018.8401279.

[27] S. H. Kim et al., "Electrical Insulation Characteristics of PPLP as a HTS DC Cable Dielectric and GFRP as Insulating Material for Terminations," in IEEE Transactions on Applied Superconductivity, vol. 22, no. 3, pp. 7700104-7700104, June 2012, Art no. 7700104, doi: 10.1109/TASC.2011.2181470.

[28] J. Chen, G.A. Bell, H. Dong, J.F. Smith and B. D. Beake, "A study of low temperature mechanical properties and creep behavior of polypropylene using a new sub-ambient temperature nanoindentation test platform", J. Phys. D: Appl. Phys. vol. 43, no. 42, 2010. doi: 10.1088/0022-3727/43/42/425404.

[29] H Mitsuii, " Review of the research and development for insulation of superconducting fault-current limiters, Cryogenics," Cryogenics, vol. 38, no. 11, pp.1159-1167, 1998.

[30] Andrew Whitttington, "Shrink Tube Insulation Apparatus for ReBCO Superconducting Tapes for Use in High Field Magnets, "Electronic Theses, Treatises and Dissertations, Florida State University, July 2014.

[31] https://omnexus.specialchem.com/selection-guide/polyvinyl-chloride-pvc-plastic

[32] https://www.gtweed.com/materials/peek-vs-pek-vs-ptfe/

[33] E. E. Shin, "Development of high voltage micro-multilayer multifunctional electrical insulation (MMEI) system," in Proc. AIAA/IEEE Electr. Aircr. Tech. Symp. (EATS), Indianapolis, IN, USA, Aug. 2019, pp. 1–14.

[34] N. Andraschek, A. Johanna Wanner, C. Ebner and G. Riess, "Mica/Epoxy-Composites in the Electrical Industry: Applications, Composites for Insulation, and Investigations on Failure Mechanisms for Prospective Optimizations," polymers, Vol. 8, No. 5, 2016.

35 M. Borghei and M. Ghassemi, "Insulation Materials and Systems for More- and All-Electric Aircraft: A Review Identifying Challenges and Future Research Needs," *IEEE Transactions on Transportation Electrification*, vol. 7, no. 3, pp. 1930-1953, 2021, doi: 10.1109/TTE.2021.3050269.

36 E. Tuncer et al., "Nanodielectrics for Cryogenic Applications," IEEE Transactions on Applied Superconductivity, vol. 19, no. 3, pp. 2354-2358, 2009, doi: 10.1109/TASC.2009.2018198.

37 B. K. Fitzpatrick, J. T. Kephartl and E. M. Golda, "Characterization of Gaseous Helium Flow Cryogen in a Flexible Cryostat for Naval Applications of High Temperature Superconductors," IEEE Transactions on Applied Superconductivity, vol. 17, no. 2, pp. 1752-1755, 2007, doi: 10.1109/TASC.2007.897763.

38 H. Rodrigo, D. Kwag, L. Graber, B. Trociewitz and S. Pamidi, "AC Flashover Voltages Along Epoxy Surfaces in Gaseous Helium Compared to Liquid Nitrogen and Transformer Oil," IEEE Transactions on Applied Superconductivity, vol. 24, no. 3, pp. 1-6, June 2014, Art no. 7700506, doi: 10.1109/TASC.2013.2286744.

39 P. Cheetham, C. Park, C. H. Kim, L. Graber and S V. Pamidi, "Dielectric properties of cryogenic gas mixtures for superconducting power applications," IOP Conf. Series: Materials Science and Engineering, CEC 2017, doi:10.1088/1757-899X/278/1/012040.

40 T. Stamm, P. Cheetham, C. Park, C. H. Kim, L. Graber and S. Pamidi, "Novel gases as electrical insulation and a new design for gas-cooled superconducting power cables," IEEE Electrical Insulation Magazine, vol. 36, no. 5, pp. 32-42, Sept.-Oct. 2020, doi: 10.1109/MEI.2020.9165697.

41 P. Cheetham, W. Kim, C. H. Kim, L. Graber, H. Rodrigo and S. Pamidi, "Enhancement of Dielectric Strength of Cryogenic Gaseous Helium by Addition of Small Mol% Hydrogen," IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-5, June 2017, Art no. 4800805, doi: 10.1109/TASC.2016.2642539.

[42] S. Elschner et al., "3S–Superconducting DC-Busbar for High Current Applications," IEEE Transactions on Applied Superconductivity, vol. 28, no. 4, pp. 1-5, June 2018, Art no. 4800805, doi: 10.1109/TASC.2018.2797521.
[43] A Colle, et al., Test of a Flux Modulation Superconducting Machine for Aircraft, J. Phys.: Conf. Ser., 1590, 2020, 012052.
[44] Uglietti, D.; Bykovsky, N.; Sedlak, K.; Stepanov, B.; Wesche, R.; Bruzzone, P. Test of 60 kA coated conductor cable prototypes for fusion magnets. *Supercond. Sci. Technol.* 2015, *28*, 124005.
[45] Zhang, H.; Wen, Z.; Grilli, F.; Gyftakis, K.; Mueller, M. Alternating Current Loss of Superconductors Applied to Superconducting Electrical Machines. Energies, 2021, 14, 2234. https://doi.org/10.3390/en14082234
[46] M. Biasion, J. F. P. Fernandes, S. Vaschetto, A. Cavagnino and A. Tenconi, "Superconductivity and its Application in the Field of Electrical Machines," 2021 IEEE International Electric Machines & Drives Conference (IEMDC), 2021, pp. 1-7, doi: 10.1109/IEMDC47953.2021.9449545.
[47] Takato Masuda, *et al*., The 2nd in-grid operation of superconducting cable in Yokohama project, *J. Phys.: Conf. Ser.*, 1559, 2020, 012083.
[48] D C Van Der Laan, *et al*., A CORC cable insert solenoid: the first high-temperature superconducting insert magnet tested at currents exceeding 4 kA in 14 T background magnetic field, *Supercond. Sci. Technol.*, 33, 2020, 05LT03.
[49] J. Kozak, M. Majka and S. Kozak, "Experimental Results of a 15 kV, 140 A Superconducting Fault Current Limiter," IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-4, June 2017, Art no. 5600504, doi: 10.1109/TASC.2017.2651120.
[50] R. Chassagnoux et al., "Study of Turn-to-Turn Electrical Breakdown for Superconducting Fault Current Limiter Applications," IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-5, Aug. 2019, Art no. 7701705, doi: 10.1109/TASC.2019.2902117.
[51] W. Kim et al., "Comparative Study of Cryogenic Dielectric and Mechanical Properties of Insulation Materials for Helium Gas Cooled HTS Power Devices," in IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-5, June 2017, Art no. 7700605, doi: 10.1109/TASC.2016.2642581.
[52] W. Song, X. Pei, J. Xi and X. Zeng, "A Novel Helical Superconducting Fault Current Limiter for Electric Propulsion Aircraft," IEEE Transactions on Transportation Electrification, vol. 7, no. 1, pp. 276-286, March 2021, doi: 10.1109/TTE.2020.2998417.
53 H. Suzuki, T. Takahashi, T. Okamoto, S. Akita and Y. Ozawa, "Electrical insulation characteristics of cold dielectric high temperature superconducting cable," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 9, no. 6, pp. 952-957, Dec. 2002, doi: 10.1109/TDEI.2002.1115489.
54 S. Pamidi, C.H. Kim, L. Graber, "High-temperature superconducting (HTS) power cables cooled by helium gas," Superconductors in the Power Grid, Materials and Applications, pp. 225-260, 2015, http://dx.doi.org/10.1016/B978-1-78242-029-3.00007-8
55 J. Rivenc et al., "An Evaluation of Superconducting Power Cables for Airborne Application," 2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), 2018, pp. 1-21.
56 Peter Cheetham, Jose Viquez, WooJin Kim, Lukas Graber, Chul H. Kim, Sastry V. Pamidi, "High-Temperature Superconducting Cable Design Based on Individual Insulated Conductors", Advances in Materials Science and Engineering, vol. 2018, Article ID 3637873, 10 pages, 2018. https://doi.org/10.1155/2018/3637873
57 H G Cheon, D S Kwag, J H Choi, H J Kim, J W Cho and S H Kim, "A study on thickness effect of HTS cable for insulation design," Journal of Physics: Conference Series, 7th European Conference on Applied Superconductivity, Vol43, pp. 889–892, 2006.
[58] S. M. Blair, "The Analysis and Application of Resistive Superconducting Fault Current Limiters in Present and Future Power Systems," Doctor of Philosophy to thesis, University of Strathclyde, April 2013.
59 W. Song, X. Pei, J. Xi and X. Zeng, "A Novel Helical Superconducting Fault Current Limiter for Electric Propulsion Aircraft," IEEE Transactions on Transportation Electrification, vol. 7, no. 1, pp. 276-286, March 2021, doi: 10.1109/TTE.2020.2998417.
60 K. Yang et al., "Insulation supporter selection for winding in superconducting fault current limiter," 2015 3rd International Conference on Electric Power Equipment – Switching Technology (ICEPE-ST), 2015, pp. 221-225, doi: 10.1109/ICEPE-ST.2015.7368372.
61 M.Pekarcikova´, M. Drienovsky´, J. Krajcˇovic, J. Misˇı´k, E. Cuninkova´, T. Hu´ lan2, O. Bosˇa´k, M. Vojencˇiak, "Analysis of thermo-physical properties of materials suitable for thermal stabilization of superconducting tapes for high voltage superconducting fault current limiters," Journal of Thermal Analysis and Calorimetry, Vol. 139, pp. 4375–4383, 2019.
[62] G. Messina, M. Yazdani-Asrami, F. Marignetti and A. della Corte, "Characterization of HTS Coils for Superconducting Rotating Electric Machine Applications: Challenges, Material Selection, Winding Process, and Testing," IEEE Transactions on Applied Superconductivity, vol. 31, no. 2, pp. 1-10, March 2021, Art no. 5200310, doi: 10.1109/TASC.2020.3042829.
63 A.K. Gupta, D.K. Chaturvedi, P.K. Basu, "Ensuring High Quality Insulation System Of Large Motors – Design & Testing Requirements," Cigre, A1-105, 2016.
[64] Y. S. Chae et al., "Design and Analysis of HTS Rotor-Field Coils of a 10-MW-Class HTS Generator Considering Various Electric Insulation Techniques," IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-7, June 2020, Art no. 4601707, doi: 10.1109/TASC.2020.2973589.
65 J. H. Kim *et al.*, "Characteristic analysis of various structural shapes of superconducting field coils," *IEEE Trans. Appl. Supercond.*, vol. 25, No. 3, Jun. 2015.
66 S. S. S. Kalsi, R. A. Badcock, J. G. Storey, K. A. Hamilton and Z. Jiang, "Motors Employing REBCO CORC and MgB_2 Superconductors for AC Stator Windings," in *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 9, pp. 1-7, Dec. 2021, Art no. 5206807, doi: 10.1109/TASC.2021.3113574.
67 W. Yin et al., "Highly Thermally Conductive Insulation for High Power Density Electric Machines," 2019 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), 2019, pp. 1-7, doi: 10.2514/6.2019-4510.
[68] S.Kalsi, K. A Hamilton, and R.A Badcock, "Superconducting rotating machines for aerospace applications," AIAA Propulsion and Energy Forum, July 9-11, 2018, Cincinnati, Ohio, DOI : 10.2514/6.2018-4796.
[69] D. H. Tien, J. Park, S. A Han, M. Ahmad and Y. Seo, "Electrical and Thermal Conductivities of Stycast 1266 Epoxy/Graphite Composites," Journal of the Korean Physical Society, Vol. 59, No. 4, October 2011, pp. 2760_2764.
70 F. Schreiner et al., "Design and Manufacturing of a Multistage Cooled Current Lead for Superconducting High Current DC Busbars in Industrial Applications," IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-5, June 2017, Art no. 4802405, doi: 10.1109/TASC.2017.2655108.
71 N. Clayton, M. Crouchen, A. Devred, D. Evans, C-Y. Gung, I. Lathwell, "Manufacture and Mechanical Characterisation of High Voltage Insulation for Superconducting Busbars - (Part 1) Materials Selection and Development," Cryogenics, Vol. 83, pp. 64-70, 2017.
72 C. Wang, X. Huang, K. Lu, G. Li, H. Zhu, J. Wang, C. Wang, Z. Dai, L. Fang, Y. Song, "Influence of void defects on partial discharge behavior of superconducting busbar insulation," Fusion Engineering and Design, Vol. 119, pp. 29-34, 2017.
73 Ray B, Gerber S, Patterson RL, Myers I. "Power control electronics for cryogenic instrumentation," Advances in Inst and Control, Vol. 50, No.1, pp. 131–139, 1995.
[74] H. Gui et al., "Review of Power Electronics Components at Cryogenic Temperatures," IEEE Transactions on Power Electronics, vol. 35, no. 5, pp. 5144-5156, May 2020, doi: 10.1109/TPEL.2019.2944781.
75 Hwang W and Han K, "Statistical study of strength and fatigue life of composite materials," Compos, vol. 18, no. 1, pp. 47–53, 1987.
[76] M. M. Hossain, A. U. Rashid, Y. Wei, R. Sweeting and H. A. Mantooth, "Cryogenic Characterization and Modeling of Silicon IGBT for Hybrid Aircraft Application," *2021 IEEE Aerospace Conference (50100)*, 2021, pp. 1-8, doi: 10.1109/AERO50100.2021.9438422.
77 B. Cella, T. Lebey and C. Abadie, "Partial discharges measurements at the constituents' level of aerospace power electronics converters," 2015 IEEE Electrical Insulation Conference (EIC), 2015, pp. 274-277, doi: 10.1109/ICACACT.2014.7223587.
78 P. Mensah,P. Cheetham,C. H. Kim, and S. Pamidi, "Novel Dielectric Fluids for Superconducting Electric Aircraft," AIAA 2021, Session: Superconducting and Cryogenic Systems and Components, 2021, https://doi.org/10.2514/6.2021-3295.