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Isolating electrical and cryogen flow for safe operation and design validation experimentation of HTS power cables for electric transportation

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Abstract. The need for protecting the cryogenic infrastructure during a fault in high-temperature superconducting (HTS) power distribution systems of electric transport platforms is highlighted. A dual grounding scheme with an isolator between the electrical and cryogen flow paths of HTS power cables is needed. Finite element analysis of the electric field distribution of the vacuum jacketed isolator showed electric field intensity at the triple points. The electric field intensity at the triple points is reasonable if high vacuum quality is maintained. There is a need for further investigations for design validation with experimentation of practical designs for effective isolation and protection of cryogenic infrastructure from damage during an electrical fault in a section of the power distribution network of electrical transport platforms, such as an electric aircraft or ship.

1. Introduction

With the rising prominence of electric transportation, there has been an increased interest in the need for highly efficient and compact power distribution systems. To support electric ships and aircraft with the increasing power requirements, novel concepts, and designs, including experimental validation of model circuit designs, are needed. Electric power systems of large ships and aircraft are expected to be at 100 MW and 40 MW, respectively [1]–[5]. For the specific power demands of both electric transport platforms, it is necessary to employ medium voltage levels [6], [7]. As a transformative technology for power distribution in electric transport platforms, high-temperature superconducting (HTS) power cables are attractive due to their exceptional current-carrying capability. The performance of HTS cables in electric aircraft and ships relies on the effective integration of robust and efficient cryogenic cooling systems. Maintaining a cryogenic environment is essential for HTS power cables to sustain their superconducting state, characterized by zero resistance, thereby significantly reducing energy losses in power distribution systems [8]. The need for a cryogenic environment presents additional design constraints for the overall power system as well as performing design validation experiments to ensure that an electrical fault in the power distribution system does not propagate to the cryogenic system that will serve other superconducting and power electric systems.

The interdependence of the electrical and cryogenic thermal properties of HTS power cables requires the selection of a suitable cryogen to achieve the required operating temperature that influences the highest allowed voltage and current. Gaseous helium-cooled cables are preferred for electric transport platforms [9]. Gaseous helium (GHe) provides an extended temperature range, spanning from 4-80 K, surpassing the limited operational temperature range of 64-80 K, possible with liquid nitrogen (LN_2) [10]. Additionally, GHe mitigates the asphyxiation risks of LN_2 in confined spaces of ships and aircraft [11]. Liquid hydrogen (LH_2) is being explored as a dual-purpose fuel and cryogenic heat sink [12]. LH_2 is the fuel and the primary cryogenic heat sink, while GHe is the cryogen for HTS cables, forming a secondary cooling loop. For electric ships and aircraft, the wide operating range of GHe facilitates the system optimization of multiple HTS devices and electrical devices, such as power electronic systems operating at different temperatures. Many devices can be effectively cooled with integrated cryogenic systems in a closed-loop configuration with a cryocooler or LH_2 as the cooling source. Liquified natural gas (LNG) is also being considered as fuel for aircraft, offering some cooling for cryoresistive power cables [13]. GHe cooled HTS degaussing technology has been demonstrated successfully on Naval ships[14]. When performing experimental validation of prototype GHe-cooled HTS cables, it is necessary to protect the expensive cryogenic infrastructure from damage due to a fault in the cable.

HTS power distribution systems for electric transport platforms is a research focus area of the Center for Advanced Power Systems (CAPS). Novel GHe-based cooling methods, high voltage designs, and cryogenic dielectrics are being developed. Experimental testbeds which replicate the operational conditions of HTS cables are being established. The testbeds enable comprehensive experiments and testing for GHe cooled HTS power cable design validations. In establishing the experimental testbeds, new challenges are identified, and solutions for the challenges of GHe cooled HTS cables on electric transport platforms are devised. One of the challenges is the need to effectively isolate the electrical components from the cryogenic infrastructure to mitigate the potential damage to equipment in the event of an electrical fault in the cable.

This paper discusses the various types of potential electrical faults in GHe cooled HTS cables and their implications for the overall HTS cable system and the associated cryogenic system. The paper introduces the technique of using isolators as part of the testbed to create two distinct ground potentials for the cryogenic hardware. This concept includes the development of a vacuum-jacketed isolator designed for the experimental cable testbed at CAPS.

2. Electrical Faults and Their Effects on HTS Cables

The possibility of electrical faults exists in any power system. Effective protection and mitigation measures are essential to safeguard the system. Power systems are susceptible to faults resulting from various events, including loose connections, the interaction between conductors operating at different voltage levels, equipment malfunction, and natural disasters [15], [16]. Arc faults are an especially hazardous type of failure that demands attention. These faults can be classified as either series or parallel faults. Series faults are a type of fault that frequently arises from loose connections of conductors or wiring, resulting in intermittent conduction. In contrast, parallel faults occur due to discharges between two conductors operating at different voltage levels [15]. Parallel faults in a power system can be catastrophic. In the event of an electrical fault in an HTS power cable, either the increase of current beyond the critical current of the cable or the increase of operating temperature due to the heat produced forces HTS material to undergo a transition from a superconducting state to a normal state which is referred to as quench. Transition to the normal state resistive conductor, resulting in the generation of significant energy that leads to the heating of the cable. Consequently, the thermal effect associated with a quench of the cable can cause permanent damage.

The cryogenic cooling infrastructure is susceptible to failure if not electrically isolated and protected from the cable system. The cooling system has various failure modes, such as over-pressurization, thermal runaway, or cryostat damage. Over-pressurization specifically occurs when the cooling system cannot sufficiently remove the heat from a fault, leading to a sudden increase in temperature and pressure in the system. The potential risk of over-pressurization in the cryogenic cooling system of HTS cables depends on the cryogen used (GHe, LH_2, LN_2). In the case of LN_2 or LH_2, the risk stems from the phase change from liquid to gas, which increases pressure. For GHe systems, achieving the desired mass flow rates typically requires operating pressures between 1.5-2 MPa. However, higher working pressure and lower heat capacity in GHe systems lead to over-pressurization. Another factor to consider is a thermal runaway, which occurs when the system's temperature rises uncontrollably due to the cooling system's inability to restore the desired operating temperature after a fault. This uncontrolled temperature increase can damage the cryostat and the cooling system. Preventing and mitigating the potential risks is vital for maintaining the integrity and efficient operation of the cryogenic cooling infrastructure in HTS cable systems. Another potential failure mode in the cryogenic cooling system of HTS cables is cryogen leakage from the cable cryostat, which can occur following a type of parallel fault (pole-ground fault) in the cable system. The fault generates electric arc plasma, reaching temperatures of several thousand degrees Celsius due to the high current in the kiloampere (kA) range. The intense heat produced by the plasma causes significant damage to the cryostat and surrounding materials, potentially resulting in a puncture in the cryostat. Such a puncture allows the cryogen to escape into the surrounding environment. To minimize thermal mass and achieve the required bend radius, the inner walls of cryostats are made with a thin corrugated steel wall. Managing the risk of cryogen leakage requires careful design considerations and protective measures to prevent and mitigate the damage caused by pole-ground faults in HTS cable systems. Figure 1 illustrates different fault scenarios that may occur in HTS cable that can lead to fault propagation to the cryogenic cooling system.

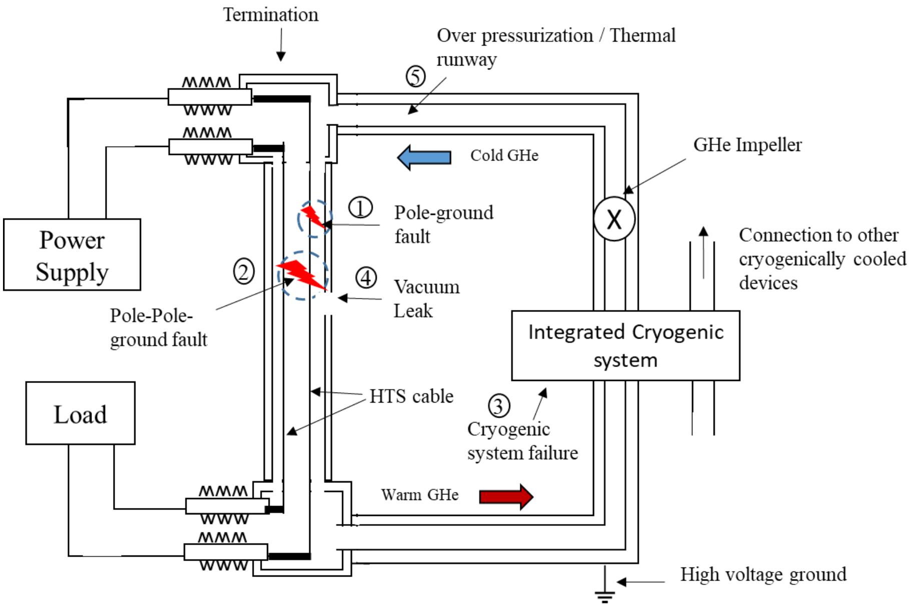

Figure 1. A schematic of the HTS cable system with potential electrical faults [17].

As electrical faults in HTS cables pose a safety risk in electric transport applications, it is crucial to devise appropriate safety mechanisms to identify and isolate a fault promptly. It is essential to ensure the fabrication of HTS cables without defects and their strict adherence to specific design specifications. This includes incorporating a design margin for electrical insulation that aligns with the intended operating voltage. Additionally, the implementation of cable condition monitoring systems serves as an additional layer of protection, effectively monitoring and preventing the occurrence of faults during operation.

2.1 HTS cable design for protection against electrical faults

The design of HTS DC cables includes careful consideration of multiple factors to ensure optimal performance and reliability. Critical design factors include the individual conductor elements, such as the manufacturing method, stabilizer layer, substrate material, and bonding techniques. Additionally, cable manufacturing methods include the choice of a hollow core versus a solid core, and monopole versus dipole arrangements require a thorough consideration based on the intended application. Additionally, selecting the dielectric insulation system, where the decision between solely gas insulation or composite insulation of solid and gas systems, significantly impacts performance. The performance parameters include partial discharge inception voltage, cryogenic heat transfer and thermal management

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efficiency, the operating voltage, operating current, and the system's ability to withstand faults without catastrophic damage [6].

HTS power cables present unique design constraints absent in conventional power cables. These constraints arise due to the requirement of a cryogenic operating environment and the resulting mechanical stresses caused by the mismatch in coefficients of thermal expansion (CTE) of the electrical insulation and HTS materials used. To mitigate the challenges, HTS cables typically employ a cold dielectric design. Cold dielectric design is employed for HTS cables to build effective electrical isolation between the cable and the grounded cryostat. The insulation is at cryogenic temperature, a notable difference of conventional electrical insulation methods that use extrusion of the insulation over the entire cable. This distinction is significant as conventional methods result in degradation due to the mechanical stress in HTS cables. The prevailing approach for applying electrical insulation to HTS cables involves the helical wrapping of multiple layers of tape insulation, such as CryoFlex™, a proprietary polymer based tape from Southwire Company [18] or polypropylene laminated paper (PPLP), onto the conductor [14]. The lapped tape accommodates expansion and contraction as the HTS cable transitions from room to cryogenic temperatures. The challenges related to applying the wrapped tape insulation of HTS cables have been studied [15].

The fabrication and experimental verification of test cables is one method that enables the multi-physics of the HTS cable topology to be explored. Several techniques have been adopted, including bath cooling of the GHe pressure vessel in LN_2 to enable measurements at 77 K. This works well for short cable characterization as it reduces the complexity of the cryogenic setup as well as ensures constant temperature for the collection of statistically significant data. For long prototype cable tests, a cryogenic circulation system is required. The circulation systems use cryocoolers and impellers to establish the cryogen flow at the required operating temperature. Typical characterization of long test cables, the high voltage and high current measurements are performed separately. High current power supplies have low output voltage of 10 V and high voltage power supplies have an output current of 50-200 mA.

High voltage measurements on long HTS cables require a technique to decouple the high voltage ground used for the power supply from the ground used for the cryogenic plant. Decoupling of the two grounds lowers the risk of a circulating ground current from damaging any of the cryogenic infrastructure in the event of an electrical breakdown event in the cable during the test. As the high voltage power supply has a low operating current the risk of vacuum leak, over pressurization, or thermal runaway when an arc is formed.

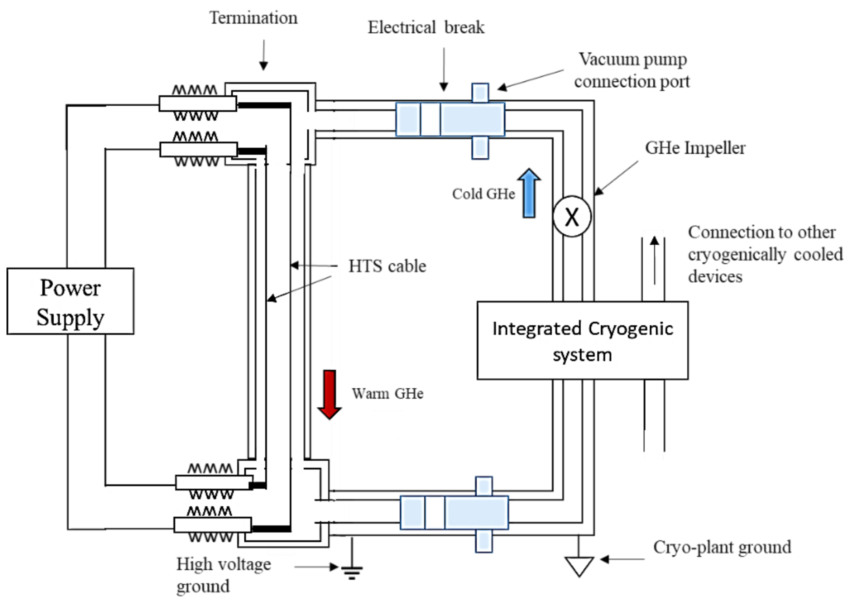

Figure 2. A schematic of an HTS cable system with an isolator between the cryogenic and electrical subsystems.

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Figure 2 illustrates a schematic of a cooling loop of an HTS cable on an electric ship. This diagram demonstrates the implementation of a dual grounding scheme, incorporating electrical isolators that effectively isolate the cryogenic system, impeller, and other ancillary devices, including vacuum pumps, from the cable system. The concept of utilizing two different grounds is often employed by high voltage power supplies to achieve a separation between the high voltage ground from the building ground. For high voltage power supplies this includes the use of transformers, fibre optic connections, and use of PVC conduit in place of metallic conduit to prevent the formation of unintended ground loops. For HTS cable systems, it is necessary to use isolators rated for the required cryogenic temperature, pressure rating, and reduces ambient heat leak.

3. HTS cable system with decoupled electrical and cryogenic loops

In cryogenic systems, commercial ceramic isolators are commonly employed for voltage levels ranging from 5-80 kV. The ceramic isolators have a weld gland or mounted onto ConFlat hardware. Introduction of a ceramic isolators introduces a potential vulnerability because of their poor mechanical strength and weak bonding between the ceramic edge and stainless-steel pipe/flange held together by a thin braze. Therefore, it is essential to implement a robust design with mechanical strength and durability to prevent any catastrophic failures. The design of the cryogenic isolator proposed here takes into consideration a seamless integration of the HTS cable system while providing the necessary electrical isolation. To design electrical isolators for the CAPS testbed, a survey was performed on commercial off-the-shelf ConFlat hardware. From the survey two electrical isolators were identified to create, an inner and an outer, electrical break as part of a vacuum jacketed design. A summary of the relevant material properties of both electrical breaks are listed in Table 1.

Table 1. Physical properties of the ceramic isolator.

Electrical Break	Conflat Flange size (in)	Inner diameter (mm/in)	Outer Diameter (mm/in)	Length (mm/in)
Inner	2 3/4 / NW35CF	33.0 / 1.3	43.2 / 1.7	154.9 / 6.1
Outer	4 1/2 / NW63CF	63.5 / 2.5	76.2 / 3.0	185.4 / 7.3

Table 1 shows that the inner electrical break was selected to have an inner diameter equivalent to the inner diameter of a Nexans 39 mm inner diameter cryostat used in the long cable testbed at CAPS. Both ceramic breaks have a withstand rating of 65 kV at room temperature and atmospheric pressure in air. The dielectric rating of the ceramic isolator is a function of the dielectric strength of the medium on both the inner and outer wall. The length of the electric break also plays a critical role in achieving the required voltage level necessary to prevent a surface flashover. The electrical isolators for CAPS test require a rating of at least 30 kV, as this represents the maximum voltage used for testing HTS cables for electric transport applications.

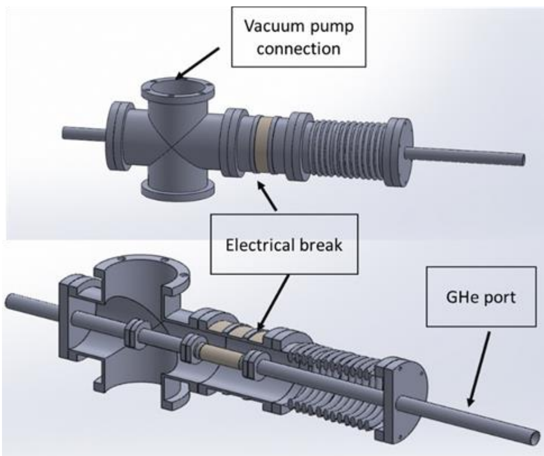

Figure 3. Conceptual illustration of the proposed electrical isolator.

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Figure 3 depicts a schematic of the conceptual isolator design utilizing commercial hardware. The only custom pieces required for fabrication are the CF plates with a male bayonet connection to interface with the existing cryostats and transfer lines. Before fabrication of the electrical isolator in the cryogenic system, where diverse electrical insulation media coexist, including high vacuum, air, and cryogen, multiple triple points are formed at the interfaces. A Finite Element Analysis (FEA) was conducted to comprehensively assess the electric field stress experienced by the device and to determine potential areas susceptible to surface flashover.

3.1 Simulation of the Electrical Field distribution at the Electrical Isolator

An electric field study was carried out using FEA to investigate the electric field enhancement at the various triple points. The parameters for the finite element analysis were established by accurately modelling the geometry of the different components of the electrical break. The dimensions of each component were determined based on the specifications provided by the manufacturers and drawn to scale for precise representation. The key physical properties are the same as listed in Table 1. The boundary conditions were defined according to the expected behavior and operational characteristics of the device. A nominal 1 kV voltage was applied to one end of the electrical break while the other end was held at ground potential. The presence of multiple triple points was observed within the system. One triple point is formed at the interface between the vacuum, the inner ceramic break, and the surrounding stainless-steel housing. Another triple point is established at the interface between the outer ceramic break, the surrounding air, and the stainless-steel housing. Upon analyzing the electric field distribution for the applied 1 kV voltage, the highest electric field intensity was observed to be 0.28 kV/mm. The peak electric field is located precisely at the triple point interface formed at the intersection of the vacuum region, the inner ceramic break, and the surrounding stainless-steel housing. Figure 4 illustrates the electric field distribution with a color scale set to a maximum value of 0.12 kV/mm. This adjustment was made to enable clear visualization of the variations in the electric field across the analyzed region.

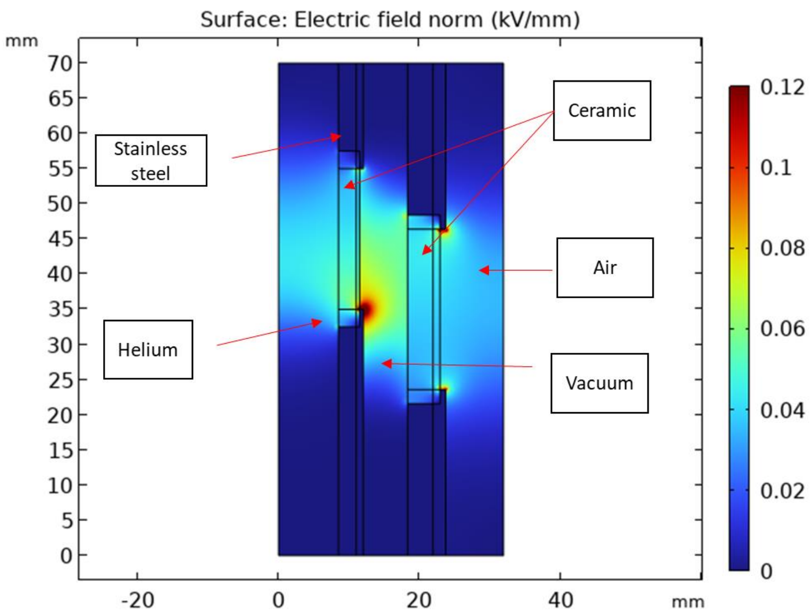

Figure 4. FEA simulation depicting the electric field distribution at the isolator.

4. Discussion

On electric ships and aircraft, implementing a dual grounding scheme ensures that a fault in the power cable does not propagate to the cryogenic system. Dual grounding offers multiple benefits, enhanced system reliability, safety, and fault tolerance. By segregating the grounding paths for the electrical and cryogenic subsystems, the risk of fault propagation is significantly reduced, avoiding potential damage and service disruptions. Uninterrupted service is particularly crucial for electric transport systems with HTS power distribution systems, where an electrical fault will have severe consequences for the entire power distribution network. For experimental testbeds to characterize HTS power distribution systems and design validation, the dual grounding approach enables safe experimentation without the risk of damaging the cryogenic cooling infrastructure. The isolation ensures the integrity of test results, allowing the researchers to assess cable performance under various fault conditions comprehensively.

The proposed isolator design is suitable for testbeds or electrical transport systems operating at voltages up to 30 kV. The analysis conducted using the finite element method demonstrated that the electric field stress within the isolator remains within an acceptable range when the system operates at 30 kV, as long as the high vacuum condition is maintained. The occurrence of surface flashover on the inner or outer isolator is influenced by the specific boundary conditions in the system. Maintaining a vacuum environment is critical to preventing flashover and heat leaks. While the electric field remains consistent for a given voltage, the dielectric strength of the media can vary. Hence, the susceptibility to surface flashover will change depending on the dielectric properties of the media. In the finite element analysis simulation conducted for this study, the dielectric strength of air at 1 atmosphere and room temperature was used. However, it is essential to acknowledge that the results obtained, as well as the rating of the isolator, will vary depending on the environmental conditions, such as varying moisture content, pressure, or temperature. This variability is particularly pertinent in scenarios like electric aircraft applications, where diverse operational conditions are encountered.

Currently, the design study, fabrication of the electrical break, and experimentation are ongoing. The findings reported here demonstrate the promise of the design, affirming its potential for practical implementation. The results of the experimental investigations will facilitate a thorough examination of the effectiveness of electrical breaks in isolating the electrical and cryogenic subsystems and lead to robust designs.

5. Conclusion

A dual electrical grounding scheme consisting of an electrical isolator between the HTS cable and the cryogenic cooling system of the power distribution network was proposed to prevent the propagation of an electrical fault in the cable to the cryogenic cooling system. The need for protecting the cryogenic infrastructure during a fault in HTS power distribution systems of electric transport platforms is highlighted by discussing the potential of damage to the cryogenic system due to the excessive heat generated. Finite element analysis of the electric field distribution of the vacuum jacketed electrical isolator showed field intensity at the triple points. The electric field at the triple points is manageable if vacuum quality in the jacket is maintained. Further investigations are needed to validate the designs through experimentation to produce effective and practical designs of isolators. Effective and robust electrical isolators will protect the cryogenic infrastructure from damage during an electrical fault in the power distribution networks of electrical transport platforms.

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