Liquid Nitrogen Cooled Superconducting Power Cable with No Solid Insulation

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Abstract. In an attempt to eliminate solid insulation challenges in cryogenic superconducting power cables, a new design concept for liquid cryogen cooled superconducting power cable was investigated. The design is based on superconducting gas insulated line (S-GIL). The design used liquid cryogen as the sole insulation medium. The suitability of the design for medium voltage power cables is discussed and the benefits of eliminating a solid insulation were identified. Experiments on 1-m long model cables with insulator tubes as spacers showed that the design is suitable for cables at 50 kV or higher. The actual limits could not be identified because of the experimental limitations originated from limited standoff distances in the measurement setup used. On a fundamental level, the investigations presented in the study showed a direct correlation between the intrinsic dielectric strength of the cryogen used and the maximum tolerated voltage for a given diameter of the cable system. The results show the promise for liquid nitrogen (LN₂) and liquid hydrogen (LH₂) cooled cables for various medium voltage applications, including electric aviation and electric ships.

1. Introduction

When designing high temperature superconducting (HTS) power cables for medium voltage applications, it is necessary to consider the interdependencies between the electrical and thermal aspects. For HTS power cables the temperature gradient along the cable route reduces both the voltage and current ratings. Superconductivity is a function of temperature, current and applied magnetic field [1], therefore, the maximum current which the HTS cable can carry before quenching is a function of the highest temperature along the cable route. By minimizing the temperature gradient along the cable route, higher power rating of an HTS cable can be achieved for a given design. When a liquid cryogen is used, the temperature gradient along the cable route needs to be maintained to prevent a phase change. The presence of bubbles within a liquid cryogen significantly reduces the dielectric strength of the cryogen and increases the potential of an in-service electrical fault occurring. The temperature rise which exists along an HTS cable is proportional to the losses generated within the cable as well as the cooling capacity of the cryogenic system. For DC applications, the heat loads within an HTS cable come from the terminations and the heat leak through the cryostat. Terminations provide the necessary interfaces between the power devices at the room temperature and the HTS cables operating at cryogenic temperatures. The heat load produced by a termination depends on the design and rated current of the HTS cables and are typically a few hundred watts [2]. The heat load from the cryostat is approximately 1 W/m. For AC applications an additional heat load exists from the AC losses which is typically 2 W/m for 60 Hz operation. From the heat loads described above, for cable lengths less than 100 m the dominant
heat load is from the terminations. However, for AC cables longer than 100 m, the AC losses generated in the HTS conductor become the dominant heat load.

There are several potential applications for medium voltage HTS power cables which vary in cable length. These applications include the electrical power grid, industrial applications, data centers, electric ships, and electric aircraft. Long length HTS power cables have been envisioned to enable the integration of renewable energy sources into the electrical power grid [3]. Liquid nitrogen is the cryogen used for the majority of HTS electrical power grid applications due to its low cost and large heat capacity. LN$_2$ cooled AC and DC HTS cables have been demonstrated in electrical power grids in a point-to-point configurations for short distances, and a few of them are currently in operation [4–6]. Lapped-tape insulation has been used with LN$_2$ as the dielectric medium in all the designs and the HTS cable covered with the insulation sits directly on the cryostat at ground potential. Some LN$_2$ cooled HTS cables used a more compact design that utilizes one cryogenic envelope for all the poles/ phases. Such configurations are used for medium and low voltage applications. Solid insulation was used between the phases and on the whole cable [5–7].

For shipboard applications helium gas is the preferred cryogen for HTS power cables due to its larger operating temperature range and reduced risk of asphyxiation in the event of a cryogen leak [8]. Our recent work has focused on developing helium gas cooled power cables for medium voltage DC applications. This includes designing a superconducting gas insulated transmission line (S-GIL) which utilizes helium gas as both the cryogen and dielectric medium for the HTS power cable [9]. It has been demonstrated that for a given geometry the dielectric strength of the S-GIL is a function of the dielectric strength of the cryogen. This promising result led us to investigate the applicability of liquid cooled HTS power cables with no solid insulation.

For aircraft application such as NASA N3-X program, liquid hydrogen (LH$_2$) is being considered as a potential cryogen. Utilizing LH$_2$ as the cryogen would allow it to be stored within a fuel tank which eliminates or reduces the need for cryocoolers. LH$_2$ absorbs the heat loads from HTS devices and evaporates. The evaporated gas is used as fuel in the engines [10]. The designs developed here for LN$_2$ cooled HTS power cable with no solid insulation are directly applicable for LH$_2$ or LN$_2$ cooled HTS power cables. The changes in the intrinsic properties of the cryogen which include operating temperature range, dielectric strength, heat capacity, and mass flow rate have to be adjusted depending on the liquid cryogen used.

This paper discusses the design consideration and potential system level benefits by developing LN$_2$ cooled HTS power cables with no solid insulation. Several 1-m long model cables were fabricated and their performance under high voltage was measured in pressurized, subcooled and boiling LN$_2$.

2. Design Considerations of LN$_2$ Cooled HTS Power Cables with No Solid Insulation

There are several benefits of implementing LN$_2$ cooled HTS power cables with no solid insulation for medium voltage applications compared to the traditionally utilized lapped-tape insulation design. These benefits include simpler and quicker manufacturing process for long length HTS power cables, potential to reduce the size of the cryogenic cooling plant required for the HTS cable route, ability to utilize prefabricated HTS conductor, retention of dielectric integrity after electrical fault, and reduced hotspots/thermal gradients in HTS section due to the enhanced heat transfer.

Lapped-tape insulation requires multiple layers of the lapped-tape to be helically wrapped on top of one another along the entire length of the HTS conductor. This process needs to ensure that each helical layer is offset to one another to ensure the butt gaps, which are part of the design, do not overlap from one layer to the next. This process also needs to prevent any damage to the lapped-tape or the HTS conductor to ensure optimal performance of the HTS power cable. Any defects during the HTS cable manufacturing process can only be identified once the HTS power cable is installed and cooled to the operating temperature. Replacing the cable at that stage is costly if defects are identified and the dielectric integrity is not as expected. Eliminating the solid lapped-tape insulation and using the cryogen as the sole dielectric medium simplifies the HTS cable manufacturing process and enables the possibility of factory acceptance testing. As the performance of no solid insulation design is a function of the dielectric strength of the cryogen surrounding the HTS conductor, it may be possible to perform factory acceptance testing at room temperature using a gas with similar dielectric properties as liquid nitrogen. This allows for greater consumer confidence for HTS cable technology.
While there has been development with HTS tape efficiency, there has also been development with HTS conductor technology such as CORC® HTS conductors, which are capable of operating at 5-10 kA whilst only having an outer diameter between 3-7 mm [11]. The size of these conductors may allow for smaller cryostats to be utilized which reduces the overall volume of cryogen needed for the cable route. The ability to utilize commercially available HTS conductors as part of the HTS power cable design is advantageous to reduce the manufacturing and lead time of HTS power cables. This should help to make HTS power cables a more attractive and feasible option to industry.

When designing an LN₂ cooled HTS power cables with no solid insulation, the achievable voltage rating is a function of the physical and electrical properties of the HTS conductor, cryostat, insulator spacers and LN₂. For a single phase LN₂ cooled HTS power cables with no solid insulation, the electric field within the cryostat can be derived from the coaxial electric field equation [12]. To ensure the HTS conductor remains concentric to the cryostat at ground potential, insulator spacers are required. As part of our previous work on the S-GIL, various insulator spacer configurations have been investigated along with the relative diameters of the HTS conductor and the cryostat selected. Based on our previous studies, a 12.7 mm diameter HTS conductor and a cryostat (at ground potential) with inner diameter of 39 mm were selected for model cables. These parameters ensure the optimized electric field based on the coaxial equation [13]. Our previous work on gaseous helium cooled HTS power cables demonstrated that a simple design that used tubular insulators ensure the conductor remains concentric to the cryostat. The use of tubular spacers also promotes large openings to facilitate the circulation of the cryogen. 1-m long model cables were fabricated to measure the dielectric response of the HTS conductor and cryostat configuration with and without insulator spacers (Figure 1).

![Figure 1](image_url)

Figure 1. (a) No-spacer HTS cable experimental setup (b) bundled spacers HTS cable experimental setup (c) no-spacer HTS cable configuration cross-section (d) bundled spacers HTS cable configuration cross-section

For the HTS power cables design shown in Figure 1, the dielectric behavior is a function of the dielectric strength of LN₂. For the design shown in Figure 1 (a & c) the maximum withstand voltage is a function of the intrinsic dielectric strength of LN₂. The introduction of the insulator spacers (Figure 1(b & d)) results in a reduction of the maximum withstand voltage as the mechanism of electrical breakdown changes from intrinsic breakdown through the LN₂ to surface flashover occurring along the outer wall of the insulator spacer. For a LN₂ cooled HTS power cables with no solid insulation, the limiting voltage rating is expected to be as a result of surface flashover occurring along the insulator.
spacers. The insulator spacer design shown in Figure 1 is one potential design so it is also important to measure the intrinsic case to know the maximum possible voltage for given dimensions of the HTS conductor and the cryostat.

LN$_2$ power cables that have been previously demonstrated for the electrical power grid applications used pressurized and subcooled liquid nitrogen. Pressurizing and subcooling the LN$_2$ allows for a larger permissible temperature gradient (63-80 K) without the occurrence of bubbles. The dielectric strength of liquid nitrogen has been reported to be between 12 and 50 kV/mm at pressure levels between 200 kPa and 500 kPa) at 77 K when bubble formation has been prevented [14-17]. However, the dielectric integrity is disrupted with the presence of bubbles, and the dielectric strength is significantly reduced when bubbles are present [15]. At atmospheric pressure, liquid nitrogen boils at 77 K, and pressurizing and subcooling suppresses bubble formation and increases the dielectric strength of the LN$_2$. For example, the boiling point increases by 20 K when pressurized to 0.5 MPa [18]. Based on these facts, the experimental setup to characterize the dielectric strength of the 1-m long model cables in both atmospheric pressure and pressurized LN$_2$ was established.

3. Measurements in Pressurized Liquid Nitrogen

3.1. Experimental Setup and Results

For testing the dielectric performance of the solid-insulation-free LN$_2$ cooled HTS cable in pressurized LN$_2$, a stainless-steel piping system for the pressure vessel was arranged. The pressure vessel utilizes a 10 inch Conflat flange with six pipe connections for: (i) LN$_2$ inlet, (ii) LN$_2$ outlet, (iii) gas inlet, (iv) gas outlet, (v) gas pressure gauge, and (vi) extra outlet that can be used for safety if needed. In addition, a relief valve was connected to the gas in/outlet pipe to release excessive pressure when built up. Furthermore, a needle valve was inserted in the gas in/outlet connection to stop the liquid to go up in the gas pipe. A schematic of the experimental set up is shown in Figure 2, along with the associated pipe work required to achieve pressurization.

Regarding test cable preparation, a cable was prepared with 6 polyethylene (PE) bundled tubes, with outer diameter of 12.7 mm, were wrapped around the conductor, with outer diameter of 12.7 mm. Kapton tape was used at discrete locations along the polyethylene tubes to ensure contacts between the conductor and polyethylene tubes to reduce the potential of electric field enhancement at the insulator/conductor interface. The conductor with attached polyethylene tubes was installed within a 39 mm copper tube, which acts as the cable cryostat at ground potential, as shown in Figure 1(b). The tubes surrounding the conductor ensure the position of the HTS conductor at the center of the cryostat. The cable was attached to the power lead which makes the high voltage connection through the bushing, and the copper tube was connected to the lower side of the top plate flange to make the ground connection. Afterward, the vessel was sealed tightly. Due to concerns that the air inside the vessel could contain some moisture, which turns into ice when cooled down and causes surface flashover at a lower voltage levels, the vessel was filled with dry gaseous nitrogen (GN$_2$) at 2 MPa at room temperature. GN$_2$ helped to remove the moisture and checked if there are any leaks. Then, the GN$_2$ was flushed out and evacuated, which helped also in removing any other impurities.

Before the high voltage experiments at 77 K, room temperature experiments were performed with GN$_2$ at 0.5 MPa. The S-GIL design has not been tested with GN$_2$ before, and the experiments were conducted to generate the baseline data to compare with the results of LN$_2$ measurements. Accordingly, the results for LN$_2$ can be judged against GN$_2$ as the insulation medium. Three measurements were taken with GN$_2$ to minimize sample degradation before the measurements in LN$_2$. The results on GN$_2$ insulated cable showed that for the 6 polyethylene (PE) bundled tube design, the maximum withstand voltage before surface flashover occurred is 35.9 kV with an average of 32.3 kV (rms, 60 Hz). The results are as expected based on our previous measurements on GHe cooled cables and the relative dielectric strengths of GHe and GN$_2$.

For the experiments on model cables in LN$_2$, the pressure vessel needed to be filled with LN$_2$ without any contamination. The vessel was first filled with GN$_2$ at 0.4 MPa, at room temperature to ensure the pressure within the vessel would be above atmospheric pressure at 77 K. Then, the pressure vessel was immersed into the external LN$_2$ bath in a cryostat. The slight positive pressure ensures that the air does not enter the vessel during the LN$_2$ filling process. The hose connected to the LN$_2$ dewar was also flushed of any air. The pressure vessel was then filled with LN2 until LN2 was coming out from the LN2 outlet port. This condition replicated what would be achieved in a boiling LN2 bath.
The pressure vessel was connected to a 100 kV AC (rms), 5 kVA transformer and the voltage was ramped up at approximately at 600 V/s (rms) until breakdown occurred. For the experiments in boiling LN₂ (at 0.1 MPa, 77 K), the 5 measurements performed yielded a maximum of 45.2 kV (rms) and an average of 39.8 kV (rms). Preventing bubble formation was achieved in the pressurized LN₂ (to 0.2 MPa) experiments by immersing the pressure vessel/experimental chamber in the outer open LN₂ cryostat at 77 K. The LN₂ in the pressure vessel has an elevated boiling point of ~80 K but is kept at 77 K by the LN₂ in the outer cryostat, thus maintaining the LN₂ in the inner vessel in pressurized and subcooled state to prevent bubbles.

In the experiments performed in pressurized LN₂ (0.2 MPa, 77 K), the breakdown occurred external to the pressure vessel due to the limited standoff/clearances among the HV connection on the top of the bushing and metal gas lines. The highest voltage reached breakdown outside the pressure vessel was 55 kV (rms, 60 Hz), suggesting that the cable would have reached higher voltages if the experimental limitations were not encountered. This result also implies that the withstand voltage of the model cable shown in Figure 1(a) would also exceed 55 kV in pressurized LN2. As breakdown values were recorded on the model cable when the experiment setup had boiling LN2, there was the potential to perform measurements on model cable without insulator spacers in a LN2 bath. As pressurization of the experimental setup was not required, a simpler experimental setup was utilized which consisted of the model cable being connected to the top plate via the HV bushing.

The same procedure of installing the experiment setup within the cryostat and applying the voltage to the model cable was followed as previously described. When the model cable without any insulator spacer was measured, the breakdown occurred externally to the experimental setup at approximately 55 kV. This result was as expected as this model cable should have superior performance than the model cables with insulator spacers. For verification the experiment with the model cable with insulator spacers was performed with the same experiment setup. Surprisingly, the breakdown also occurred externally.
from the experiment setup at approximately 55 kV. This result was approximately 10-15 kV higher than what was recorded with the original experimental setup.

4. Discussion
After completing the tests of the 6 PE bundled HTS cable sample in boiling and pressurized LN$_2$ using the first experimental setup, the sample was disassembled to analyze the problem that caused the variation in experimental data between the experimental setups. It was observed that the cable was clean without any charring or burn marks indicating the absence of surface flashover on the PE tubes. Removal of the bushing from the top plate showed pitting on the rod of the high voltage feedthrough (Figure 3). This suggests the limitation of the first experiment setup was due to the nitrogen gas forming near the bushing and intrinsic breakdown was occurring between the bushing feedthrough and the top plate.

For the case of 0.1 MPa, LN$_2$ vapor was trapped under the top plate and caused the breakdown to occur under the bushing where the dielectric strength is less than the cable dielectric strength. When the pressure was increased for the 0.2 MPa, the vapor/gas dielectric strength increased. The breakdown did not happen at that location nor on the cable, but it happened outside the vessel due to that now becoming the path of least resistance.

![Figure 3. Pitting on the current lead part extended under the bushing](image)

Given the configuration of the experimental setup and the associated problems, there are potential modifications which can be made to improve the voltage withstand capability of the circuit to enable characterization of the model cables at higher voltages. Firstly, the limiting factor is caused from installing the 10 inch diameter pressure vessel within a cryostat with inner diameter of 12 inches. The 6 metal support bars which suspend the pressure vessel in the cryostat transition between LN$_2$ and air. As air has relatively poor dielectric strength the breakdown occurs between the high voltage bushing and the support rods in air. Increasing the gap distance between the support rods by utilizing a larger cryostat would be the simplest method to increase the voltage rating of the experimental setup.

Regarding the first experimental setup shown in Figure 2(a) the nitrogen bubble formation could be resolved by changing the locations of the filling lines. One potential solution is to install the pressure port horizontally instead of vertically which would ensure if bubble formation was to occur it would not happen at the bushing. Horizontally installing the pressure vessel would require modification of how the model cables are installed within the pressure to ensure the cable is still suspended in the center of the cryostat and the stress sphere (at voltage potential) does not come in contact with the pressure vessel wall at ground potential.

While ultimately the experiments showed that improvements are required in the experimental setup, it demonstrated that voltage withstand capability in excess of 55 kV is expected for the given cable and cryostat parameters selected. This in turn demonstrates the potential of LN$_2$ cooled HTS cables with no solid insulation to be utilized for low to medium voltage applications.

5. Conclusion
LN$_2$ was used as the cryogen and insulation medium in S-GIL, instead of gas, to examine the dielectric strength limits for the insulation system of the bundled spacer tubes S-GIL design. The results showed
that there exists a direct relationship between the dielectric strength of the insulation medium and the performance of the HTS cable. S-GIL performance increases with the increase of dielectric strength of the insulation medium which is the cryogen used. The solid-insulation-free liquid cooled HTS design has the potential to be used for applications that use LN$_2$ or LH$_2$. Electric transportation applications will benefit from such cables. The absence of solid insulation offers better heat transfer, minimal degradation during a breakdown event, and easier manufacturing.

6. References

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