

# Novel Design Concept and Demonstration of a Superconducting Gas Insulated Transmission Line

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**Abstract**— A new and novel design concept for superconducting cables that uses the gaseous cryogen as the dielectric medium is presented. This novel design addresses the challenges in developing a dielectric design of a superconducting cable that is cooled by a gaseous cryogen such as gaseous helium (GHe). This design has the added benefit of improving thermal aspects and for DC applications should reduce the possibility of space charge accumulation. The paper provides an overview of design criteria which is necessary to successfully implement this design. A proof of concept experiment was also developed to demonstrate how the voltage rating of such a design is dependent on the dielectric strength of the cryogen being used. The new design has the potential to offer a solution for high power density superconducting medium voltage DC cables that are cooled with gaseous helium and operate in the temperature range of 5-80 K.

**Index Terms**— Dielectric design, Gas-cooled HTS power cables, helium-hydrogen mixture, medium voltage DC, superconducting gas insulated line

## I. INTRODUCTION

IT is envisioned that High Temperature Superconducting (HTS) power cables could replace conventional cables in applications where space and weight are critical design criteria [1]. HTS power cables for generic utility applications are expected to operate in 65-75 K temperature range in pressurized and subcooled liquid nitrogen (LN<sub>2</sub>). In situations where significantly higher power densities (both volumetric and gravimetric) are required, it is necessary to operate HTS cables at temperatures lower than the LN<sub>2</sub> range. In some specialized applications with multiple superconducting devices cooled with a single stream of cryogen, it is necessary to set the operating temperature of some devices significantly below 77 K to accomplish system level optimization [1]. Gaseous helium (GHe) circulation has been demonstrated as a viable option for cooling HTS power cables [2-4]. GHe has a lower dielectric strength compared to LN<sub>2</sub>, thus limiting the voltage rating of power cables [5, 6]. Efforts have been underway at Florida State

University's Center for Advanced Power Systems (FSU-CAPS) to address the dielectric challenges and find solutions to mitigate this limitation of GHe. One of the promising solutions devised was to add small mole fractions of Hydrogen to GHe to enhance the dielectric strength of the gas. It was shown that a 4 mol% H<sub>2</sub> and 96 mol% He mixture possesses about 80% higher AC and DC breakdown strength compared to pure GHe at various pressure levels at 77 K [7, 8].

Whilst the addition of hydrogen to GHe improved the dielectric properties of the coolant, it should be noted that typically a GHe cooled HTS cable is limited to voltages substantially below the partial discharge inception voltage (PDIV) of the insulation system consisting of a solid insulation and GHe. The most common dielectric design for HTS cables is lapped tape insulation. The lapped tape is helically wrapped around the HTS cable to provide the insulation between HTS cable and an outer shield layer, which is kept at ground potential. During the wrapping of the lapped tape, butt gaps are introduced to avoid excessive mechanical stresses to the HTS tapes during the thermal cycling between room temperature and the operating cryogenic temperature. The butt gaps remain present after the HTS cable has been cooled to the cryogenic operating temperature to allow for mechanical flexibility. However, the butt gaps also result in PDIV occurring at a significantly lower voltage than the intrinsic breakdown strength of the lapped tape material would suggest. Partial discharge (PD) occurs in the butt gaps as it is filled with the gaseous cryogen of the cable, which typically has a lower permittivity than the tape material and creates a local enhancement of the electric field [9]. Once PD begins in the butt gap it can be sustained causing deterioration of the lapped tape and lower the life of the cable system [10]. Therefore, a cable must operate below its PDIV to prevent irreversible damage to the lapped tape insulation.

To take advantage of the higher dielectric strength of H<sub>2</sub>-GHe mixtures and to eliminate the need for unfavorable solid dielectric lapped insulation, an innovative gas insulated HTS

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cable design is being proposed. This is the first time that an HTS cable design is presented with a gaseous cryogen functioning as both the dielectric medium and coolant.

Regardless of the cryogen used, the elimination of the solid dielectric medium on the cable will help in improving the heat transfer between the cable and cryogenic fluid flow and improves the thermal aspects of the cable, particularly in situation where the cable is operated close to its power ratings or during a quench. It also reduces the pressure drop along the cable. This new design also offers a significant benefit in HTS DC cables by reducing the possibility of space charge accumulation because the cryogen is continuously circulated through the cable system; accumulation of space charge is a significant problem in superconducting DC cables that operate at cryogenic temperatures. This new idea of using the cryogen as a dielectric is similar to room temperature gas insulated transmission lines (GIL) which utilize the superior dielectric properties of SF<sub>6</sub> [11,12]. It should be noted that the pressurized helium gas at cryogenic temperatures results in a gas density almost as high as SF<sub>6</sub> at typical GIL pressure levels.

This paper presents the main design factors that need to be considered when implementing a superconducting gas insulated cable (S-GIL) along with the design and results of the proof of concept experiments conducted in GHe and 4 mol% H<sub>2</sub>–GHe mixture. For simplicity only a single phase S-GIL will be discussed, although there is the possibility to expand this setup to have multiple cables within the same cryostat.

## II. S-GIL DESIGN CONSIDERATIONS

When designing an S-GIL there are many variables which can affect the maximum voltage rating of the cable. These variables include the electric field profile within the cryostat and the dielectric strength of the cryogen used.

### A. Electric Field within the Cryostat

The electric field within the cryostat is governed by the spacer design, the diameter of the HTS cable and inner diameter of the cryostat. In S-GIL design, the cryostat wall is at ground potential. Hence one of the most important design aspects is to ensure that the HTS cable does not come in contact with or get close to the cryostat wall. An ideal S-GIL design has the HTS cable concentrically located at the center of the cryostat and surrounded by the cryogen. The maximum electric field ( $E_{max}$ ) occurs on the surface of the conductor and can be characterized by the co-axial field equation [13]:

$$E_{max} = \frac{V}{r_s \times \ln\left(\frac{r_c}{r_s}\right)} \quad (1)$$

Where,  $E_{max}$  – maximum electric field,  $V$  – applied voltage,  $r_s$  – radius of the superconducting cable,  $r_c$  – inner radius of the cryostat. For a fixed inner diameter of the cryostat the maximum electric field can be varied by changing the radius of the superconducting cable. It should be noted that this is not a practical design as the voltage rating of the cable can be significantly reduced if the cable shifts from the center of the cryostat. Therefore it is necessary for the S-GIL design to include spacers, which ensure the HTS cable does not shift from

the axis of the cryostat during installation and operation. The inclusion of the spacers in the S-GIL design has the possibility to create a local enhancement of the electric field where the spacer makes contact with the HTS cable. Furthermore, there could be tracking along the surface of the spacer, leading to a flashover. To investigate this phenomenon, a 2D axisymmetric electric field finite element model was created. In this model a spacer with thickness of 2 mm with a pitch angle of 10° was used to connect between the HTS cable and the inner wall of a cryostat. The permittivity of the spacer was set to be the same as G10, a commonly used insulation material at cryogenic temperatures. The inner diameter of the cryostat was set to 39 mm which is one of the standard sizes for cryostats built for liquid natural gas (LNG). The radius of the HTS cable was adjusted between 4.5 and 14.5 mm. Varying the radius of the HTS cable results in the change of the effective gap distance between the HTS cable and the inner wall of the cryostat. This meant that the length of the spacer is varied between 28 and 85 mm, which was determined to be realistic sizes for a spacer. The result of the electric field analysis can be seen in Fig. 1 for the case of an HTS cable with a radius of 7.5 mm and a voltage of 1 kV.

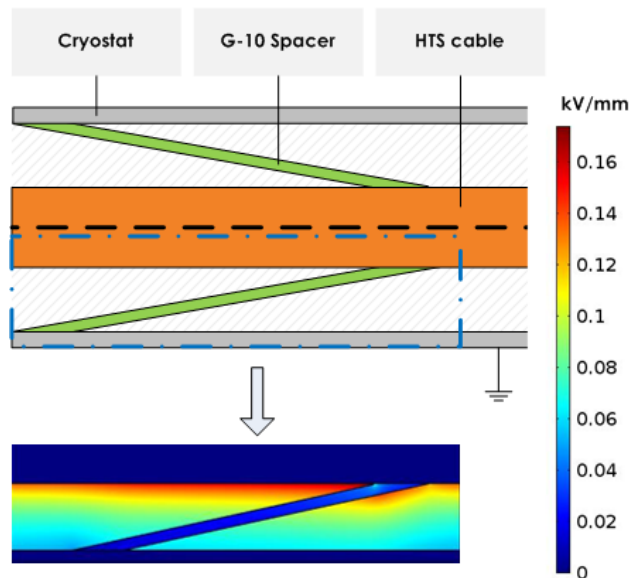


Fig. 1. Electric field (kV/mm) of a spacer in helium using 2D axisymmetric finite element model

Fig. 1 indicates that there is a local enhancement of the electric field at the interface between the HTS cable and the spacer. A curvature with radius of 0.1 mm was introduced at the corner where spacer and cable are connected in order to reduce local peak in electric field in this region, which was applied to all of the electric field models developed. A comparative study was conducted by comparing the maximum electric field at different HTS cable radii of the ideal S-GIL design characterized by (1) and the maximum electric field measured by the FEM electric field models. The results of this study are shown in Fig. 2.

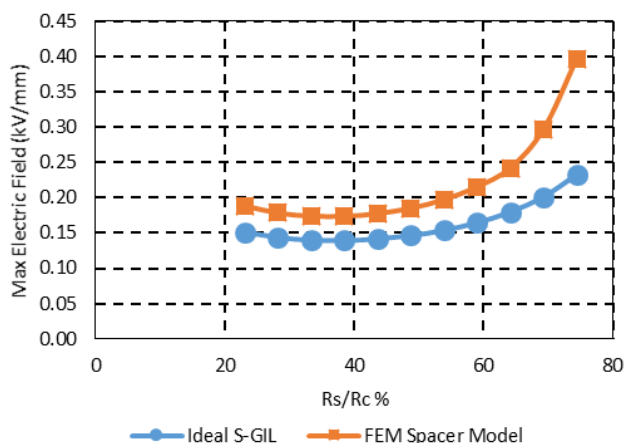


Fig. 2. Maximum electric field at different HTS cable radii of the ideal S-GIL design and the maximum electric field measured by the FEM electric field models

It can be seen from Fig. 2 that as the size of the HTS cable increases the effect of the spacer with regards to maximum electric field also increases. It should be noted that further optimization of the spacer design will help to reduce the maximum electric field to be comparable with the ideal S-GIL design. The FEM models developed only considered the electric field of the spacer and did not take into consideration of the other design factors. Additional design factors that need to be considered are: creepage distance, mechanical strength, sufficient openings for cryogen circulation, flexibility to allow the cable to be pulled into the cryostat and material selection.

Design of the spacers also needs to ensure that no flashover occurs along the surface of the spacer. As mentioned above, the heat load of an HTS cable is an important factor in determining the size of the cooling system, therefore the proposed spacer design should not restrict the flow of the cryogen over the surface of the HTS cable. The spacer design should not cause any damage to the surface of the HTS tape while the cable is being pulled into the cryostat. If the surface of the HTS tape is damaged during this process, the cable's superconductive property will deteriorate. Finally, the material selection for the spacers will have to take into account, besides the dielectric properties, the brittleness at cryogenic temperatures, thermal expansion coefficient, and its ability to withstand thermal cycling.

### B. Cryogen Used

The use of the H<sub>2</sub>-GHe mixture with superior dielectric properties compared to pure GHe results in an HTS cable with higher voltage rating. While it is envisioned that a gaseous cryogen will be used, the design would also be suitable for LN<sub>2</sub> cables. A proof of concept experiment was designed and conducted to show how the dielectric rating of an S-GIL varies depending on the cryogen used. 4 mol% H<sub>2</sub> and GHe mixture as well as pure GHe were the two gases selected. AC breakdown tests were performed at room temperature and 77 K.

A 1 m model cable fabricated consisted a solid copper former with a diameter of 15.9 mm. 10 HTS tapes with width of 4.8 mm and thickness of 0.2 mm were helically wrapped onto the former with a pitch angle of 25° and soldered at both

ends. The effective diameter of the cable after soldering on the HTS tapes was 16.3 mm. To ensure that the measurements being recorded was electrical breakdown through the cryogen and not surface flashover, stress cones made from Mylar were included at each end of the model cable. A layer of carbon paper was added between cable and stress cone to smooth the electric field at the terminations and assist in the wrapping of the stress cone. The size and shapes of the stress cones were verified by completing a 2D axisymmetric electric field FEM model. To ensure that the cable remained in the center of the cryostat a pair of collar clamps were manufactured out of G10. The collar clamp provided the required mechanical strength to hold the cable in place whilst allowing for the cryogen to enter within the cryostat. The collar clamp design had a groove machined in the base to allow for the cryostat to be supported in. For simplicity, the acting cryostat in this experiment was a copper tube with inner diameter of 41 mm, which closely matches with inner diameter of commercially available LNG cryostats. A schematic layout of the fabricated S-GIL for the proof of concept experiments is shown in Fig. 3.

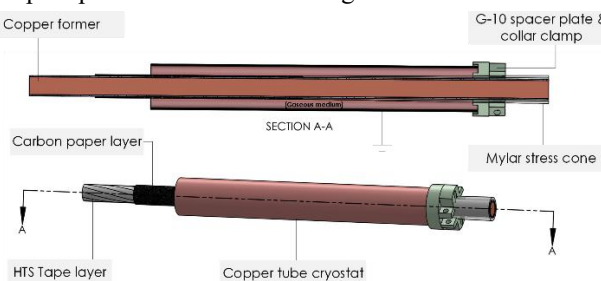


Fig. 3. The layout of the S-GIL used in the proof of concept experiments.

The cable was installed within a pressure vessel. A ground wire was soldered onto the cryostat and connect to the top plate of the pressure vessel which was set to ground potential. The cable was connected to a high voltage bushing, which is mounted on the top plate. A 25 mm stress sphere was connected to the end of the cable to reduce the electric field at the cable termination. The complete experiment assembly can be seen in Fig. 4. Great care was given in establishing a pure GHe atmosphere inside the pressure vessel.

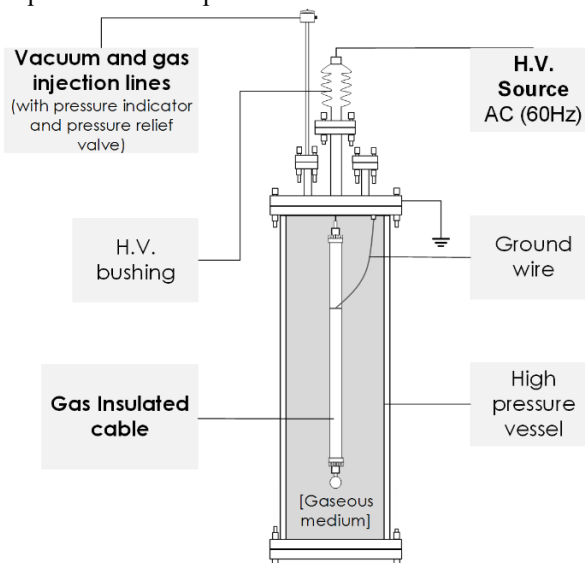


Fig. 4. Experiment arrangement used for the proof of concept of S-GIL.

The high voltage bushing of the pressure vessel was connected to a 100 kV AC transformer. The ramp rate of the transformer was set to 300-500 V/s to ensure a high reproducibility of the measurements. Five AC breakdown measurements were performed at each 2.0, 1.5, 1.0 and 0.5 MPa. Sufficient wait time between two successive measurements was built into the measuring protocol to ensure a high reliability of data. Once all of the measurements had been performed in GHe the pressure was reduced and a dry scroll pump in conjunction with a turbomolecular pump allowed for a vacuum of  $10^{-8}$  MPa to be achieved. The pressure vessel was then filled with 2.0 MPa of the 4 mol% H<sub>2</sub> mixture at room temperature. Five AC breakdown measurements were performed at 2.0, 1.5, 1.0 and 0.5 MPa respectively.

On completion of the room temperature measurements the pressure vessel was immersed in a cryostat filled with LN<sub>2</sub>. By immersing the pressure vessel in LN<sub>2</sub> it ensured that all of the measurements were taken at 77 K. The same measuring procedure which was outlined for the room temperature case was followed for the measurements at 77 K.

The results of the AC breakdown measurements of pure GHe and 4 mol% H<sub>2</sub> balanced with helium at room temperature and 77 K can be seen in Figs. 5 and 6 respectively. In Figs. 5 and 6, the error bars indicate the maximum and minimum breakdown voltages obtained at each pressure level.

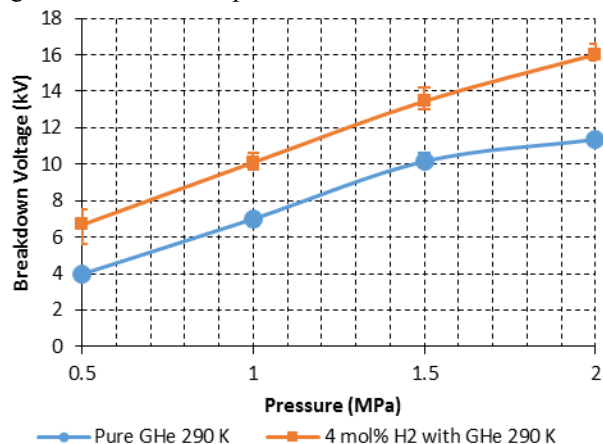


Fig. 5. AC (RMS) breakdown voltage as a function of pressure for pure GHe, 4 mol% H<sub>2</sub> in GHe at 290 K.

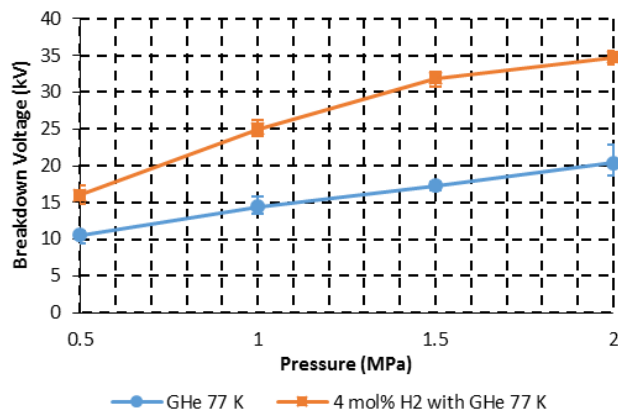


Fig. 6. AC (RMS) breakdown voltage as a function of pressure for pure GHe, 4 mol% H<sub>2</sub> in GHe at 77 K.

### III. DISCUSSION

Using a gaseous cryogen as both the coolant and the dielectric of a HTS cable is a promising way to improve the rating of GHe cooled HTS power cables. The S-GIL design requires further development, but the study shows how variables such as conductor radius and spacer design are pivotal in determining the voltage rating of such cables. With further optimization of the spacer design there should be a reduction in the local enhancement of electric field. As the spacer design is optimized additional variables such as creepage distance, mechanical strength, sufficient openings for cryogen circulation, flexibility to allow the cable to be pulled into the cryostat and material selection will all be explored.

The proof of concept experiments completed on the 1 m model cable demonstrated two important ideas. The first was that for the S-GIL design, a relationship can be established between breakdown voltage data obtained at room temperature and at 77 K. There currently is not a way to test the rating of HTS cables at room temperature before cooling to cryogenics temperature because of the risk of damaging the lapped tape insulation. The S-GIL would also lend itself for factory testing at room temperature before it is shipped and connected for service. The second and more important idea is that the voltage rating of the cable is dependent on the cryogen used. An 80% increase in breakdown strength was observed by using the 4 mol% H<sub>2</sub> mixture instead of pure GHe as a cryogen for S-GIL model cable. This is the expected result as the previous studies have shown about 80% increase in dielectric strength when using the 4 mol% H<sub>2</sub> mixture instead of pure GHe [7]. Further increase in the voltage rating is expected with gas mixtures with higher H<sub>2</sub> mol%.

### IV. CONCLUSION

A proof of concept design, fabrication, and experimental results of superconducting gas insulated transmission line for medium voltage applications is presented. This is a new design concept for gas cooled superconducting cables in which the cryogen acts as the sole dielectric medium is presented. The experimental data suggests that the design concept is suitable for other cryogenic power cables and will have applications where very high power density is needed for naval and aviation applications. The design concept will also be useful for current leads and short runs of power cables for high energy physics and fusion science applications that generally operate at low temperatures in helium environment.

### REFERENCES

- [1] S.V. Pamidi, C.H. Kim, & L. Graber. "Gaseous Helium Cooled Superconducting Power Cables". In Christopher M. Rey (Ed.), *Superconductors in the power grid: Materials and applications* (38 pages). Cambridge, UK: Woodhead Publishing Ltd. 2015.
- [2] J. H. Lim, S. H. Sohn, H. S. Ryoo, H. O. Choi, H. S. Yang, D. L. Kim, et al., "Performance Test of 100 m HTS Power Cable System," *Applied Superconductivity*, IEEE Transactions on, vol. 19, pp. 1710-1713, 2009.
- [3] J. P. Stovall, J. A. Demko, P. W. Fisher, M. J. Gouge, J. W. Lue, U. K. Sinha, et al., "Installation and operation of the Southwire 30-meter high-

- temperature superconducting power cable," *Applied Superconductivity, IEEE Transactions on*, vol. 11, pp. 2467-2472, 2001.
- [4] Superconducting Power Cables: Technology watch 2009. EPRI, Palo Alto, CA: 2009. 1017792
- [5] S. Woo-Ju, H. Jae-Sang, S. Jae-Kyu, L. Jong-Geon, and L. Bang-Wook, "Breakdown characteristics of liquid nitrogen for transmission-class superconducting electric equipment," in *Condition Monitoring and Diagnosis (CMD), 2012 International Conference on*, 2012, pp. 766-769.
- [6] H. Rodrigo, K. Dongsoo, L. Graber, B. Trociewitz, and S. Pamidi, "AC Flashover Voltages Along Epoxy Surfaces in Gaseous Helium Compared to Liquid Nitrogen and Transformer Oil," *Applied Superconductivity, IEEE Transactions on*, vol. 24, pp. 1-6, 2014.
- [7] L. Graber, W. J. Kim, P. Cheetham, C. H. Kim, H. Rodrigo, and S. V. Pamidi, "Dielectric Properties of Cryogenic Gas Mixtures Containing Helium, Neon, and Hydrogen," *IOP Conference Series: Materials Science and Engineering*, vol. 102, p. 012018, 2015.
- [8] P. Cheetham, W. J. Kim, C. H. Kim, L. Graber, H. Rodrigo, and S. V. Pamidi, "Enhancement of Dielectric Strength of Cryogenic Gaseous Helium by Addition of Small Mol% Hydrogen", *Applied Superconductivity Conference 2016, submitted*.
- [9] M. Kosaki, "Research and development of electrical insulation of superconducting cables by extruded polymers," *Electrical Insulation Magazine, IEEE*, vol. 12, pp. 17-24, 1996.
- [10] F. Krahenbuhl, B. Bernstein, M. Danikas, J. Densley, K. Kadotani, M. Kahle, et al., "Properties of electrical insulating materials at cryogenic temperatures: A literature review," *Electrical Insulation Magazine, IEEE*, vol. 10, pp. 10-22, 1994.
- [11] Itaka, K.; Ikeda, G., "Dielectric Characteristics of Compressed Gas Insulated Cables," in *Power Apparatus and Systems, IEEE Transactions on*, vol. PAS-89, no.8, pp.1986-1994, Nov. 1970.
- [12] Zhijie Jia; Ping Liu; Jianming Li; Lin Yang, "Flashover Characteristics Along the Epoxy Resin Insulator under DC Voltage in SF6 Gas," in *Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM), 2012 International Conference on*, vol., no., pp.338-342, 5-6 March 2012.
- [13] R. Kories, H. Schmidt-Walter, "Taschenbuch der Elektrotechnik," 3rd Ed., Verlag Harri Deutsch, 1998.