PAPER • OPEN ACCESS

Effect of Non-Uniformity of Electric Field on Breakdown Strength of Cryogenic Gaseous Insulation Media for Superconducting Power Applications

To cite this article: S. Telikapalli et al 2020 IOP Conf. Ser.: Mater. Sci. Eng. 756 012006

View the article online for updates and enhancements.

You may also like

- Liquid Nitrogen Cooled Superconducting Power Cable with No Solid Insulation A Al-Taie, S Telikapalli, P Cheetham et al.
- <u>Understanding Surface Flashover in</u> <u>Helium Gas Cooled High Temperature</u> <u>Superconducting Devices</u> A Al-Taie, P Cheetham, C H Kim et al.
- <u>How Turbulence Enables Core-collapse</u> <u>Supernova Explosions</u> Quintin A. Mabanta and Jeremiah W. Murphy





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 13.58.150.59 on 02/05/2024 at 18:32

Effect of Non-Uniformity of Electric Field on Breakdown Strength of Cryogenic Gaseous Insulation Media for **Superconducting Power Applications**

S. Telikapalli^{a,b}, M. Kvitkovicova^{a,b}, P. Cheetham^b, C. Park^c, C.H. Kim^b, L. Graber^c, S. Pamidi^{a,b}

^a FAMU-FSU College of Engineering, Department of Electrical & Computer Engineering, Tallahassee, FL, 32310, USA

^bCenter for Advanced Power Systems, Florida State University, Tallahassee, FL, 32310, USA

^c Georgia Institute of Technology College of Engineering, Department of Electrical & Computer Engineering, Atlanta, GA, 30332, USA st18b@my.fsu.edu

Abstract:

A new experimental set up for measuring the breakdown strength of gas media in weakly nonuniform electric field at cryogenic temperatures and high pressures is described. Measure of breakdown strength of helium gas at 77 K and 293 K in a non-uniform electric field with a field efficiency factor 62.5% are presented. The results suggest that the breakdown strength in weakly non-uniform electric field relate to that of uniform electric field by the field efficiency factor, η . This relationship holds good for both 293 K and 77 K data. This observation expands our previously reported systematics of dielectric strength in uniform electric field to the weakly nonuniform electric field conditions, which is important for designing HTS power applications. The established relationship eliminates the need for costly experiments for measuring the dielectric strength at a specific operating temperature and pressure and in the required non-uniformity of the electric field.

1. Introduction

High temperature superconductors offer a novel solution to meet the increasing demand for electrical power in the urban areas creating bottlenecks [1]. High temperature superconducting (HTS) devices offer significantly high power densities compared to conventional conductor technology. In HTS applications such as electric ships, electric aircraft, and high energy physics, where power density is important, the typical operating temperatures are in the range of 4 - 40 K. Hence, liquid nitrogen (LN2), the typical cryogen used in HTS applications cannot be used as it only allows operation between 63-80 K. Helium gas (GHe) is being considered due to its wide operating range (4-80 K). Helium gas is preferred over hydrogen gas which has a similar operating temperature (20-80 K) because of its lower condensation temperature, inert and non-flammable nature. The drawback of using GHe in terrestrial power grid applications is that the operating voltage is reduced significantly due to its lower dielectric strength compared to LN2. The problem of low dielectric strength of GHe can partly be overcome by adding a small mol% of H2 gas to GHe. It was demonstrated that the dielectric strength of a He-H2 gas mixture is proportional to the mole fraction of hydrogen [2]. The relationship between the composition

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1

and the dielectric strength of various gas mixtures was studied by modeling using Boltzmann analysis [3]-[7]. To further improve the prospect of helium gas cooled HTS power cables operating at medium to high voltage levels, a first of a kind superconducting gas insulated cable (SGIL) where the circulating cryogen acts as the sole dielectric was demonstrated for different gas mixtures [8]-[11]. However, the increase observed in the inherent breakdown strength of a gas mixture does not fully translate into the corresponding increase in the dielectric performance of the SGIL. One of the suspected factors causing this inconsistency is non-uniformity of electric field in SGIL. The reported enhancements in the intrinsic dielectric strength of gas mixtures were based on the measurements in uniform electric field emulated using Bruce profile electrodes with a gap distance ranging from 1-2 mm. However, in the SGIL the electric field profile is a function of the diameter of the HTS conductor and the inner diameter of the cryostat. This geometry will cause a weak non-uniformity in the electric field typically represented as the field efficiency factor (η) [12]. The relationship between η and breakdown strength is understood for room temperature applications [12], [13]. To test if this relation is valid for cryogenic temperatures and high pressures experimental investigations of the dielectric strength of gas media at cryogenic temperatures at various pressure levels are necessary. Additionally, the electric field profile of HTS power devices depend on the design and it is useful to have a fundamental understanding of the effect of weak non-uniformity on the dielectric strength and if it is dependent of the gas composition. Without the established relationship between the non-uniformity of electric field and the dielectric strength of a gas media, the relative performance of various designs of HTS power device such as SGIL cannot be modeled. Fabrication and experimental evaluation of various designs is costly.

The focus of this study is to establish an experimental setup to measure the dielectric strength of gases in a defined weakly non-uniform electric field and compare it with the results of uniform electric field at room temperature and cryogenic temperatures. A setup with η of 62.5 % was fabricated keeping the dimensions of the electrodes similar to those used in the uniform electric field experiments. Experiments were performed on helium gas at several pressures.

2. Methodology

2.1. Uniform electric field

For a uniform field, breakdown voltage, V_{bu} , can be sufficiently approximated as E/d where E is the dielectric strength of the insulating material uniformly spread between 2 electrodes separated by gap distance d

$$V_{bn} = E_{max} d\eta \tag{1}$$

Where,

$$\eta = \frac{E_{average}}{E_{max}} \tag{2}$$

 η is 1 for uniform electric fields. In a uniform field, every point in the field is equally stressed and the probability of breakdown is the same at every point. Uniform field systems are very ideal and hard to realize in practice due to system geometries and inherent electric field gradient they produce. The difficulty of maintaining the uniformity of the field increases significantly for higher gap distances[13]. In our experiments, to emulate uniform electric field, Bruce profile electrodes with a radius of 12.5 mm were used as shown in Figure 1. The electric profile is maintained for small gap distances of up to 4 mm with this set of electrodes. It is difficult to maintain the uniformity of the field in the edges will curve thus creating a drop in η . High voltage source (HV) is connected to the top electrode through a bushing rated for up to 300 psi while the bottom electrode is connected to common ground of the supply via the cryostat [2]. Gauge blocks were used to set a desired gap distance between the electrodes. The setup is designed to keep the gap distance consistent for varying temperatures.



Figure 1: Experimental setup for breakdown measurements in uniform field

2.2. Weakly Non-uniform electric field

Equation (1) is also applicable for weakly non-uniform electric fields but, for weakly non-uniform fields η varies between 0 and less than 1 depending on the conductor geometry [14]. Table 1 shows the relation between η and radii of the conductors for different conductor configurations

	U	
Geometrical configuration	Maximum electric field	Field efficiency factor (η)
Parallel plates	$\frac{v}{r}$	1
Parallel plates		
Concentric cylinders	$\frac{v}{r_i ln\left(\frac{r_o}{r_i}\right)}$	$\frac{r_o - r_i}{r_i ln(\frac{r_o}{r_i})}$
concentric spheres (Figure same as concentric cylinders)	$\frac{Vr_o}{r_o(r_o - r_o)}$	$\frac{R_o}{r_c}$
		11

Table 1: Field factors for different conductor geometries reproduced from [13]

Table 1 shows that for increased dielectric strength in weakly non-uniform fields, increasing the gap distance is not always desirable. Figure 2 shows the breakdown strength for different inner radius configurations for a given outer radius using the relation for a coaxial system shown in Table 1. Maximum dielectric strength can be obtained when





Figure 2: Conductor radii vs breakdown voltage relation for coaxial systems reproduced from [12]

and the maximum field efficiency obtainable is 58% [12]. To design a coaxial electric field experimental setup that is compatible with cryogenic temperatures without using any insulating spacers to obtain similar η is complicated and is non-reliable for temperature variations. Hence a hemispherical experimental setup was used to obtain the desired η . Keeping with dimensions of the electrodes previously used, a spherical electrode with a radius of 12.5 mm was used. From Table 1, to get a similar η , the radius of outer hemisphere must be 21.5 mm but an electrode with a 20 mm radius was used as shown in Figure 3 to get a η of 62.5%. This ensures that breakdown is not affected by corona discharges as shown in Figure 2.

Figure 4 shows the results of finite element analysis performed using 2d-axisymmetric COMSOL to ensure there is no field enhancement at the edges and to verify the electric profile is as needed. The spherical electrode is given a nominal test voltage of 1 kV and the hemispherical electrode is grounded. The setup is surrounded by helium gas with a relative permittivity of 1. The maximum field is observed on the surface of the conductor with a value of 0.2 kV/mm, this is similar to the situation in the SGIL cable studied previously, which has a maximum field of 0.2 kV/mm with insulating tubular spacers [8]. An enhancement was found near the edges and it was found that a fillet alone would not suffice to reduce its effects, thus an extra depth of 10 mm was given to give a sufficient fillet. A 10% enhancement was found which given the gap distance increase caused by the fillet was tolerable. The drawbacks of this setup are the slight difference in the η compared to that of an SGIL, the large gap distance necessary to provide the necessary field gradient to get desired non-uniformity and the optimistic breakdown strength predicted by this setup.



(a)

(b)

Figure 3: A schematic (a) and a photograph (b) of the electrode arrangement for the breakdown experiments in weakly non-uniform electric field.





Figure 3b shows the assembled experimental setup mounted on the top plate of the pressure vessel used for the measurements. High voltage connection from the supply is connected to the top spherical electrode through a bushing rated for 300 psi and the setup was connected to a common ground by metal to metal connection (bottom hemispherical electrode to the threaded rod supports from the top-plate). To keep the spherical electrode at the proper height from the base of the hemisphere, 4 identical G-10 pieces were cut to precise length. The test setup was sealed inside a pressure vessel to test the dielectric strength for different gases at different pressure levels.

2.3. Experimental procedure

The pressure vessel is cleaned with alcohol and dry cloth to ensure there is no residual water vapor and dirt particles before sealing. To ensure the purity of gas in the pressure vessel, flush and evacuation cycles were conducted with nitrogen gas first to remove air and other impurities and later with industrial-grade helium (99.8% pure). Between the successive flushing cycles, the pressure vessel was evacuated to 2.2e-7 MPa in between these cycles using a dry-scroll pump. After the flushing cycles, the pressure vessel was filled with ultra-pure GHe (99.9999% pure) to 2 MPa at room temperature. The first ten measurements were considered as seasoning of the electrodes and were not used for the data. This is performed to ensure that the electrodes are free of any imperfections which may cause localized field enhancement.

Fifteen measurements were performed at each pressure level. A Glassman unit PS/SH2—R160j18 with a ramp rate of 0.3 kV/s was used as the high voltage source. DC voltage was ramped up until a breakdown. A two-minute wait time is included in the measurement protocol between successive measurements to ensure thermal equilibrium is attained inside the pressure vessel. The measurements were repeated for different pressure levels as required. Breakdown measurements were performed at room temperature, which was maintained at 293 ± 1 K. For the measurements at 77 K, the pressure vessel was completely immersed in a bath of LN2.

3. Experimental data

The dielectric strength measurements of helium were performed at room temperature for 4 pressure levels in both uniform and weakly non-uniform electric fields. Figure 5 shows the experimental data of the dielectric strength of helium at room temperature in kV/mm in uniform and weakly non-uniform electric fields. An additional curve is included that is the dielectric strength in non-uniform electric field divided by the field efficiency factor, η , of 62.5% according to (4). The data obtained at room temperature is consistent with values predicted using(4).

$$v_{uniform} = \frac{v_{non-uniform}}{FEF} \tag{4}$$

IOP Publishing

Figure 6 shows the experimental data of the dielectric strength of helium at 77 K in kV/mm in uniform and weakly non-uniform electric fields. A comparison of the data in Figures 5 and 6 shows that the dielectric strength at 77 K is significantly higher than that at room temperature. This is as expected considering the higher gas density at 77 K [13]. Due to the larger gap distance used in the experiments in non-uniform field, the breakdown voltage value was high at 2 MPa and electrical breakdown occurred outside the pressure vessel and thus the data for 2 MPa could not be obtained.

It was previously demonstrated that the breakdown strength of gases scales with density and is independent of operating temperature [15]. Figure 7 demonstrates the dielectric strength of helium in kV/mm at 293 K and 77 K at equivalent densities, listed in Table 2.

Pressure at RT	Breakdown voltage	Pressure at 77 K	Breakdown voltage	
MPa	kV/mm	MPa	kV/mm	
2	2.2	0.503	1.9	
1.5	1.8	0.4	1.7	
1	1.2	0.267	1.3	
0.5	0.6	0.107	0.6	

Table 2: Equivalent density comparison

The scattering/pitting in the hemispherical electrode after performing the breakdown measurements was found to be uniformly distributed. This validates the proper centering of the electrodes and uniform gap distance throughout varying temperatures.



Figure 5: Dielectric strength of helium in kV/mm at room temperature for different pressure levels



Figure 6: Dielectric strength of helium in kV/mm at 77 K for different pressure levels



Figure 7: Comparison of breakdown voltages of helium gas at 293 K and 77 K at equivalent densities

IOP Publishing

4. Discussion:

The experimental set up established for conducting breakdown measurements in gas media in a weakly non-uniform electric field at cryogenic temperatures resulted in useful measurements. The dielectric strength in weakly non-uniform electric field is significantly lower than that in uniform electric field, as expected. The absence of any insulating spacers in the experimental setup prevented space charge accumulation and the associated uncertainties in the measurement data. The linearity in the dielectric strength data with pressure suggests that the gap distance was maintained consistent over varying temperatures and pressures.

The close match between the experimental data in uniform electric field and the data set in nonuniform electric field normalized with η shows that the field efficiency factor could be used to estimate the dielectric strength in non-uniform electric field conditions from uniform field data. This observation is useful in the design of HTS devices and estimated dielectric strength of gas media under non-uniform electric field and cryogenic temperatures without having to perform time-consuming measurements. The results also suggest that there is no fundamental difference in the dielectric behavior of gas media at room temperature and at cryogenic temperatures. The observations extend our previous understanding and assessment of the dielectric behavior of gas media that the temperature does not have a noticeable effect on the dielectric strength after accounting for the density of the gas [13].

5. Conclusions:

An experimental set up for measuring the breakdown strength of gas media at cryogenic temperatures and high pressures was established. The set up was used to measure the breakdown strength of helium gas at 77 K and 293 K in a weakly non-uniform electric field with a field efficiency factor 62.5%. The field efficiency factor is in the same range as encountered in a superconducting gas insulated line. The measured breakdown strength in weakly non-uniform electric field, when normalized by the field efficiency factor of 62.5% match with that in uniform electric field for both the 293 k and 77 K measurements. The identical relationship between the dielectric strength behavior in uniform and weakly non-uniform electric field at both 77 K and 293 K suggest that the temperature does not have any noticeable influence on the relationship. This expands our previously reported systematics of dielectric strength in uniform electric field at a broad range of temperatures and pressures which suggested that it scales with density and is independent of temperature and pressure of a gas medium to weakly non-uniform electric fields. This is an important conclusion that allows estimation of the dielectric strength of a gas medium for any application using the field efficiency factor, the operating temperature, and pressure from the data in uniform electric field at any temperature and pressure. This eliminated the need for costly experiments to measure the dielectric strength at the operating temperature and pressure and electrode geometry necessary to emulate the required non-uniformity of the electric field.

References:

- [1] A. P. Malozemoff, "The power grid and the impact of high-temperature superconductor technology: An overview," *Superconductors in the Power Grid: Materials and Applications*, pp. 1–28, 2015.
- [2] 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. Ser. Mater. Sci. Eng.*, vol. 278, no. 1, 2017.
- [3] 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. Ser. Mater. Sci. Eng.*, vol. 278, p. 012040, Dec. 2017.
- [4] C. Park, L. Graber, P. Cheetham, J. G. Viquez, C. H. Kim, and S. Pamidi, "A versatile modeling technique for predicting dielectric strength improvements in gas mixtures for superconducting applications," *IEEE Transactions on Dielectrics and Electrical Insulation*,

vol. 24, no. 5. pp. 2755–2764, 2017.

- [5] C. Park, S. Pamidi, and L. Graber, "Boltzmann Analysis of Cryogenic \$\text{He}\$ \$\\text{H}_{\text{2}}\$ Gas Mixtures as Dielectric Media for High-Temperature Superconducting Power Devices," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–6, Jun. 2017.
- [6] C. Park, L. Graber, and S. Pamidi, "The dielectric properties of gaseous cryogen mixtures of He, H 2, Ne, and N 2 in a temperature range of 50–80 K at pressures up to 2.0 MPa," J. Appl. Phys., vol. 121, no. 8, p. 083304, Feb. 2017.
- [7] C. Park, J. Wei, P. Cheetham, C. H. Kim, S. Pamidi, and L. Graber, "The influence of temperature on the dielectric strength of gaseous cryogens," *Proc. IEEE Int. Conf. Prop. Appl. Dielectr. Mater.*, vol. 2018-May, pp. 164–167, 2018.
- [8] P. Cheetham, J. Wagner, T. Stamm, C. H. Kim, L. Graber, and S. Pamidi, "Electric field analysis of insulating spacers for a superconducting gas-insulated transmission line," *Proc. IEEE Int. Conf. Prop. Appl. Dielectr. Mater.*, vol. 2018-May, pp. 185–189, 2018.
- [9] P. Cheetham, J. Viquez, L. Graber, C. H. Kim, H. Rodrigo, and S. Pamidi, "Novel Design Concept and Demonstration of a Superconducting Gas-Insulated Transmission Line," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–5, 2016.
- [10] P. Cheetham, C. H. Kim, and L. Graber, "Optimization of a Superconducting Gas-Insulated Transmission Line."
- [11] P. Cheetham, C. H. Kim, L. Graber, and S. Pamidi, "Practical Considerations for the Design of a Superconducting Gas-Insulated Transmission Line for Shipboard Applications," *ieee Electr. Sh. Tech. Symp.*, 2017.
- [12] E. Kuffel, W. S. Zaengl, and J. Kuffel, "High Voltage Engineering Fundamentals," *Electr. Eng.*, p. 539, 2000.
- [13] Naidu, High Volatage Engineering, vol. 16, no. 6. 1996.
- [14] R. Arora and W. Mosch, *High Voltage and Electrical Insulation Engineering*. 2011.
- [15] A. Al-taie, C. Park, P. Cheetham, C. H. Kim, and L. Graber, "A New Representation of Paschen's Law Suitable for Variable Temperature Power Applications."