

# Effect of high voltage electrical breakdown on critical current of High Temperature Superconducting tapes

P Cheetham<sup>1,2</sup>, Z Zhang<sup>1</sup>, M Kvitkovicova<sup>1</sup>, J Wagner<sup>1,2</sup>, C H Kim<sup>1</sup>, L Graber<sup>3</sup>, and S V Pamidi<sup>1,2</sup>

<sup>1</sup>Center for Advanced Power Systems, Florida State University, Tallahassee, FL

<sup>2</sup>Department of Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL

<sup>3</sup>Georgia Institute of Technology, Atlanta, GA

Email: Cheetham@caps.fsu.edu

**Abstract.** Effects of high voltage electrical impulse events on the critical current of 2G HTS tapes are studied experimentally to develop an understanding on the potential damage that could occur if superconducting cables undergo electrical breakdown. The need for understanding the degradation is discussed in the context of the superconducting gas insulated lines (S-GIL), a novel design concept for superconducting cables. Since the S-GIL uses the gaseous cryogen as the sole insulation system which does not degrade in an electrical breakdown event, it is essential that the superconducting tapes themselves stay undamaged for the HTS cable system as a whole to be operational after electrical breakdown. Critical current of 2G HTS tapes were measured before and after subjecting them to electrical impulses at various voltage levels. It is shown that the extent of degradation depends on the number and voltage level of the impulses. The results of degradation of critical current are discussed in terms of the total energy released in an impulse event.

## 1. Introduction

High temperature superconductors (HTS) are being developed for use in a variety of applications in the medical, electrical power, transportation, high-energy physics, fusion, and defense sectors [1]. While some of these applications require a low operating voltage such as HTS magnets used in magnetic resonance imaging (MRI), HTS technology in electric power applications operate at significantly higher voltages [2], [3]. HTS devices operating at high voltages need to use dielectric materials and designs that are capable of withstanding the voltages without failure. If electrical breakdown does occur there is the possibility of damage occurring to the dielectric system. Hence a significant design effort goes into designing the dielectric aspects of HTS devices [4]–[6]. In the event of an electric breakdown there is potential for superconducting wire/tape to be damaged in addition to the insulation. After an electrical breakdown, a solid insulation material, such as polypropylene laminated paper (PPLP) used in HTS cables and other devices gets permanently damaged and renders the HTS device inoperable at its nominal voltage [7]. Liquid dielectric media such as liquid nitrogen recovers from the breakdown incident when the vapor generated in the incident condenses back to liquid [7]. For a gaseous dielectric material, such as helium gas, the dielectric properties after an electrical breakdown incident has occurred remain unaltered. There is no change in the physical state and absence of chemical reaction [7].



Therefore, HTS devices that use helium as the sole dielectric medium maintain the dielectric integrity following a breakdown incident and facilitate its normal operation without the need for a repair or replacement if the superconducting component – a wire, cable, or a coil – itself is undamaged. However, there is a possibility that the thermal energy in the electrical discharge and mechanical stresses associated with a breakdown incident could lead to some damage to the fragile superconducting elements. Therefore, it is important in the design of a gas cooled HTS device that consideration is given to the understanding of the extent of potential damage and degradation of the critical current ( $I_c$ ) of the HTS tape caused by one or multiple electrical breakdown events.

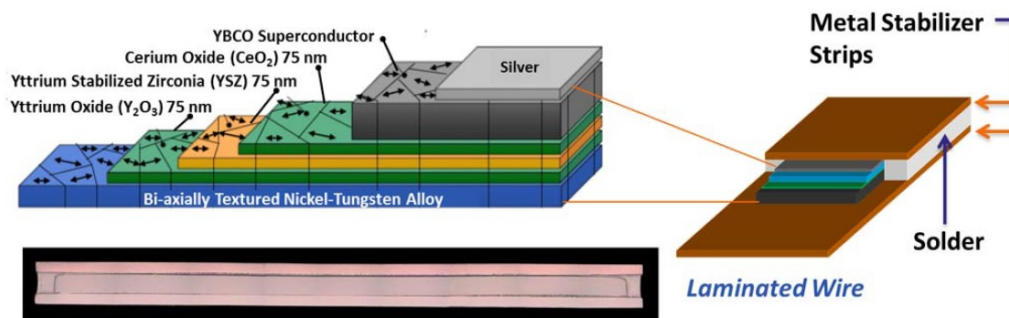
Florida State University's Center for Advanced Power Systems (FSU-CAPS) has been investigating a novel medium voltage gaseous helium (GHe) cooled power cable design which utilizes GHe as both the cryogen and dielectric medium for the cable [8]. This design is referred to as a Superconducting Gas-Insulated Transmission Line (S-GIL) due to its resemblance to a Gas Insulated Transmission Line (GIL) that operates at room temperature and utilizes sulfur hexafluoride ( $\text{SF}_6$ ) gas as the dielectric medium. One of the potential benefits of this cable design is that the dielectric system of the S-GIL tolerates an electrical breakdown and the cable operates normally after cooling back to its operating temperature assuming that the superconducting part of the cable survives the event. This would be a significant advancement from current HTS cable technology where the solid dielectric insulation requires replacement after an electrical breakdown event. The potential for the S-GIL to self-heal under certain conditions would be a useful feature that enhances the resiliency and lifetime of the HTS cable, giving greater confidence to users looking for dependable HTS cable technology.

To investigate the ability of a S-GIL to operate successfully following an electrical breakdown event, it is necessary to examine both the HTS tapes and the S-GIL as a whole to assess the extent of degradation caused by an electrical breakdown event. This paper describes a study aimed at understanding the ability of single tapes of second generation (2G) HTS to withstand an electrical breakdown event and the extent of degradation, if any, in their carrying capability represented by their critical current. The paper describes the type of 2G HTS tapes used in the study and also are planned to be used in the construction of a model S-GIL. The paper also comments on the sections of the S-GIL where potential electrical breakdown is expected to occur. A description of the experiments used to subject the HTS tapes to electrical breakdown, and the procedure used to measure critical current of the tapes before and after multiple electrical breakdown event to track the degradation. The measurements involved subjecting the tapes for repeated lightning impulse events with gradually increasing voltage levels until the superconducting layer was completely destroyed. The results of the effect of the lightning impulse events at various voltage levels on the critical current of the tapes are discussed.

## 2. Structure of HTS Tape

2G HTS, regardless of the variations of manufacturing technology consist of multiple layers of thin ceramic between the bottom metal substrate and the top superconducting layer [9]–[11]. Typically, the HTS tapes have a thin layer of silver on the outside, which acts as a protective coating. Among the various types of 2G HTS, laminated version of tapes have the most robust mechanical structure. The 2G HTS - Type 8501 that was used to perform the investigation on the effect of electrical breakdown events on the critical current,  $I_c$  is copper laminated with a total thickness of 0.17-0.21 mm [12]. The tapes used are formed using rolling assisted biaxially textured substrates (RABiTS) [11]. A stabilizing layer is typically added to both to the top and bottom of the HTS tape to give greater mechanical and electrical properties to the HTS tape (Figure 1). The majority of the cross section of a HTS tape is in fact the stabilizer and the substrate, with only between 1-2% of the cross-section is actually occupied by the superconducting material (REBCO).

Previous studies reported to determine the effects of electrical breakdown on the critical current HTS also were performed on 2G HTS tapes [13], [14]. One of the conclusions made from these studies was that the material selected for the stabilizer affects the level of degradation to the superconducting layer. Copper, stainless steel and brass have all been used as stabilizing materials with each material having certain electrical and mechanical benefits over the other. The results of the previous research conclude



**Figure 1.** (Schematic illustration of the architecture of AMSC's insert and laminated wire architectures. A micrograph of an actual Amperium wire cross-section is shown in the bottom left [9].

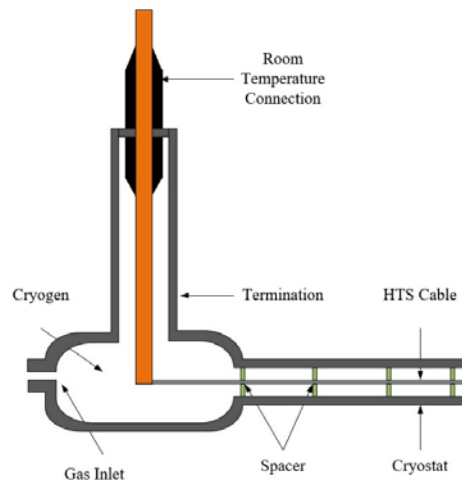
that tapes with stainless steel stabilizer provide greater protection from damage during an electrical breakdown than the tapes with copper stabilizer due to the superior mechanical properties of stainless steel [14]. While this study provides information on the degradation of the superconducting layer after electrical breakdowns has occurred, the authors expressed concern that the energy released during these breakdowns did not accurately reflect the energy which is expected to be released from an electrical breakdown. Significantly higher levels of energy are involved in a breakdown event occurring under actual operating conditions at the rated current and voltage of a HTS device in power applications. Further discussion of the extent of energy release in high voltage impulse or electrical breakdown is provided later in the paper.

### 3. Structure of S-GIL

As mentioned above the S-GIL is a novel HTS power cable design which utilizes gaseous helium as the coolant and as the sole dielectric medium. It is envisioned that the S-GIL will operate in the medium voltage range between 10-20 kV. The S-GIL comprises of several key components including the superconducting cable, cryostat, cryogen, spacers, and terminations as shown in Figure 2. The schematic of the S-GIL is for a single phase superconducting cable installed in a cryostat. The cryostat is at ground potential. Spacers are required to ensure that the superconducting cable does not come in contact with the grounded cryostat.

The electric field distribution within the cryostat is determined by the inner diameter of the cryostat, diameter of the cable, and the size and shape of the spacers. Electrical breakdown between the superconducting cable and cryostat can occur as either intrinsic breakdown through the cryogenic gas or due to the surface flashover along the face of the spacer. If this does occur, the resulting damage from the electrical breakdown should not directly come in contact with a HTS tape. Instead it is expected that the breakdown would occur on one of the copper tapes which is wrapped on the outmost layer of the superconducting cable as the stabilizer layer or shield layer. The copper tapes provide additional mechanical protection to the HTS tapes whilst being on the same voltage potential.

Consideration also needs to be given to the potential scenarios which could lead to electrical breakdown occurring within the S-GIL. While the voltage ratings of the S-GIL will be significantly lower than the expected voltage that electrical breakdown would occur at, mechanical failure of a spacer may result in the superconducting cable shifting off axis and electrical breakdown occurring. Spacer failure may occur as a result of repeated thermal cycling between room and cryogenic temperatures that cause significant mechanical stresses. If the failure of the spacer and resulting electrical breakdown occurs below the rated voltage of the S-GIL, the energy released in the electrical breakdown event will not significantly reduce the current carrying capabilities of the S-GIL. In the worst case, individual spacers will need to replace the defective spacer and the superconducting cable would still be able to be



**Figure 2.** A schematic of S-GIL showing the main components (not drawn to scale) [17].

used. This could provide a significant cost reduction in repairing a superconducting cable after an electrical breakdown has occurred. If a failure of the spacer occurs at rated conditions, the energy released by the resulting electrical breakdown could be in the kJ-MJ range depending on the prospective fault current and the protective equipment (how fast is the system de-energized after a fault occurred). Significant damage is expected to occur to the S-GIL, possibly requiring the superconducting cable to be replaced. Replacement of the S-GIL would be dependent on the extent energy absorbed by the copper tape providing a shield to the HTS tapes. If however, the S-GIL is installed in a network with advanced protective equipment which minimizes the magnitude and duration of the fault current, the energy released during the electrical breakdown would be significantly reduced. By utilizing this technology it may be possible to reduce the energy released in the breakdown to be in the Joule range, which the S-GIL should hopefully be able to survive without significant damage occurring. In this scenario the S-GIL would be able to return to normal operation after the fault occurred. A reduction of the critical current of the affected HTS tape is investigated in this experimental work.

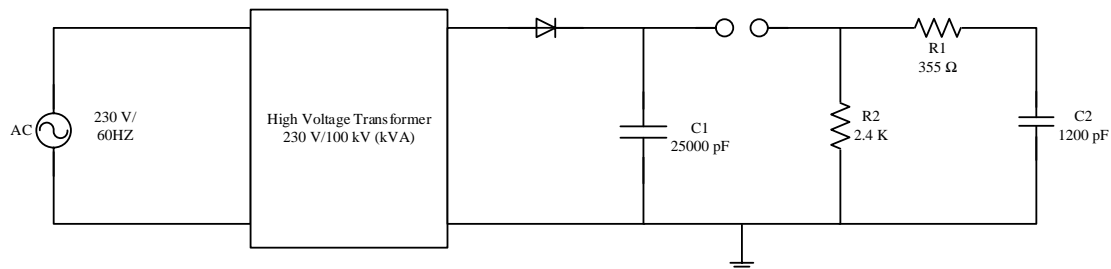
It is expected that the voltage rating of the S-GIL will be determined by the basic insulation level (BIL) measurement, which is used to simulate fault condition that the S-GIL may see while in service. The BIL rating is a function of the radius of the superconducting cable and the cryostat. If an in-service fault occurs which exceeds the BIL of the S-GIL, electrical breakdown will occur. It is not expected that a S-GIL will be able to operate after this has occurred due to the large amount of energy in the kJ (and possibly MJ) range which could be released in the electrical breakdown. Protective equipment such as surge arrestors or superconducting fault current limiters could be utilized to reduce the severity of the fault current experienced by the S-GIL, which in turn reduces the possibility of this occurring.

#### 4. Electrical Breakdown

The amount of energy released during an electrical breakdown is dependent on numerous variables including voltage, current, capacitance, and length of breakdown. As such, it is difficult to determine the exact extent energy released. As stated above, at operating conditions the energy released is expected to be in the kJ range. While an electrical breakdown occurs for a relatively small period of time, the energy released can cause significant and permanent damage to a HTS cable. While significant damage is expected to occur to the S-GIL if electrical breakdown occurs during operating conditions, the energy released during breakdown occurring while performing BIL measurements as part of factory acceptance testing (FAT) is significantly smaller. Electrical breakdown is not expected to occur during FAT, however as mentioned above failure of the spacer will result in reduced dielectric properties of the S-GIL. Currently for superconducting cable applications, FAT can only be performed once the

superconducting cable has been cooled to the cryogenic operating temperature. An additional benefit of the S-GIL is the ability for FAT testing to be completed at room temperature. However, it would also be necessary to complete commissioning testing once the S-GIL is installed at site. There is a small possibility that between these two measurements damage may occur to the spacer during the shipping and installation process which may go unnoticed.

The circuit used to complete BIL measurements is shown in Figure 3.



**Figure 3.** Electrical schematic of BIL/lightning impulse measurement circuit

The resulting impulse waveform from the circuit in Figure 3 has been defined by IEEE STDS 4 as standard lightning impulse with a double-exponential wave shape [15]. The amount of energy released during the impulse is dependent on the operating voltage and energy stored by capacitor [16]:

$$W = \frac{1}{2} C_1 (V_{0max})^2 \quad (1)$$

The energy released by this circuit is at least an order of magnitude less than what is expected to be seen when an electrical breakdown occurs at rated conditions. The previous investigation completed by Kang et al. focused on the degradation of the critical current of HTS tape after a single lighting impulse was performed onto the HTS tape [14]. The HTS tapes used in this study while manufactured by a similar manufacturing process to the tapes used in this study, but of a different type making it difficult to compare. While the exact parameters of the impulse circuit are not given, it is expected that the energy released during each of the impulses would be only a few hundred joules. Even with such a relatively low energy released during each impulse, Kang et al. reported a degradation of the critical current between 5-25% after an 80 kV impulse was performed on the HTS tape [14]. The study reported here focused on determining the amount of energy required to reduce the critical current of a HTS tape to normal state with current carrying capacity of a few amps.

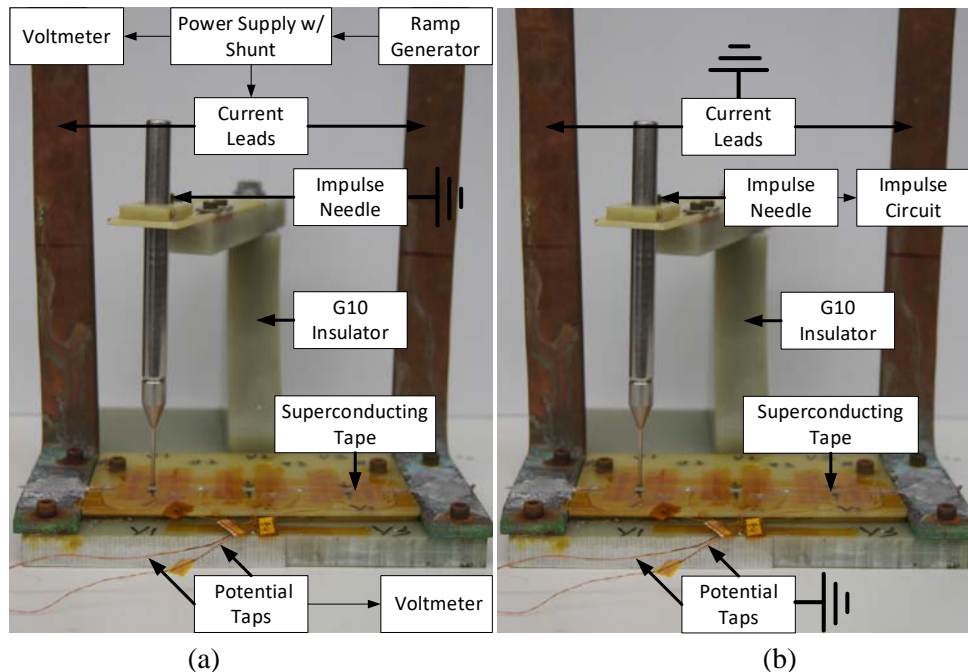
## 5. Electrical Breakdown Measurements

As mentioned above the, 2G HTS tape of Type 8501 was used to determine if the energy released by performing repeated lighting impulse measurements tape would lead to a degradation of the superconducting layer. The measurements represent the worst case scenario, where electrical breakdown occurred directly onto the HTS tape. To ensure the degradation was only a result of the lighting impulses, and consistency of the critical current measurements, a sample holder for the experiments was designed and fabricated which allowed for both the impulse and critical current measurements to be completed without having to remove the HTS tape from the fixture between the impulse events. Figure 4 (a) depicts the experimental setup for measuring critical current of the tapes, which depicts the HTS tape soldered onto two current leads. Voltage taps were soldered onto the HTS tape to measure the transition from superconducting to normal state. Critical current of the tapes is defined using the standard criteria of  $1\mu\text{V}/\text{cm}$ . The ramp generator was used to select the ramp rate of the current during the critical current measurements and to allow extraction of the  $n$  value of the HTS tape. The measurements tracked the variation of critical current and the  $n$ -value of the tapes following the application of impulses.

Figure 4 (b) depicts the experimental setup used for the impulse application. A needle with diameter of 2 mm is connected to the impulse circuit depicted in Figure 3. The gap distance between the needle and HTS tape was fixed at 1 mm using a gauge block set. The current leads and potential taps were



grounded. For both the impulse and critical current measurements, the experiments were conducted by immersing the sample holder in a bath of liquid nitrogen (LN2). It was ensured that during the experiments the LN2 level was above the impulse needle.



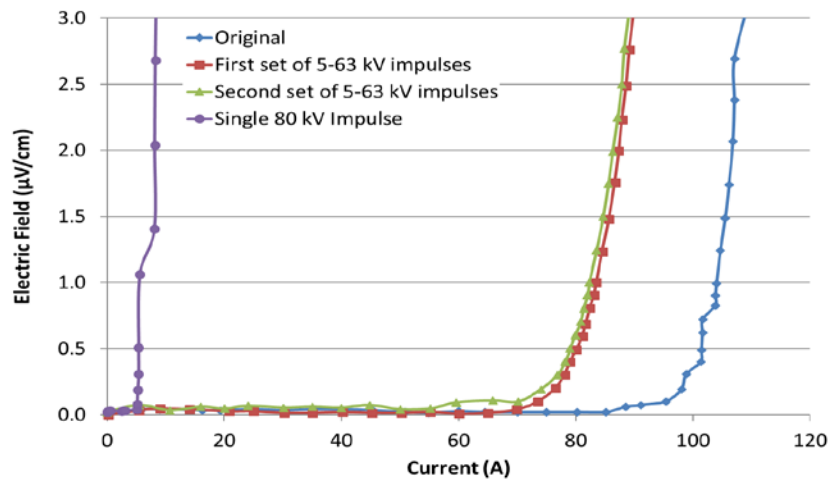
**Figure 4.** (a) critical current experiment setup (b) lightning impulse experiment setup

Before subjecting the sample to electrical impulse events, the initial critical current value is measured on the HTS tape to get a baseline value. Five impulse events were applied to the tape at approximately 63 kV on the HTS tape, with approximately 50 J of energy released per breakdown. A critical current measurement of the HTS tape was then performed following the impulse application. The tape was then subjected to an additional set of five impulses at the same 63 kV level followed by a critical current measurement. Finally, a single 120 kV impulse was applied on the HTS tape (maximum available voltage of the impulse circuit used), which released approximately 186 J of energy in the electrical breakdown. A critical current measurement followed the 120 kV impulse.

A summary of the impulse events and the associated critical current values are listed in Table 1. The extent of the degradation of the critical current of the HTS tape due to the impulses is shown in Figure 5.

**Table 1.** Summary of critical current and lightning impulse measurement data

Measurement	Average Impulse Voltage $C_1$ (kV)	Critical Current (A)	Average Energy Released/breakdown (J)	Average Voltage recorded on Impulse Capacitor $C_2$ (kV)
Original critical current	N/A	104	N/A	N/A
Critical current after 5 impulses	62.5	83.9	48.4	48.1
Critical current after additional 5 impulses	63.3	82.3	50.0	48.8
Critical current after max rated impulse	122	5.58	186.1	79.44



**Figure 5.** Voltage-current traces of critical current measurements of the HTS tape before and after the various lightning impulse cycles.

From Table 1 and Figure 5 it is clear that the critical current of the HTS tape was degraded from the original 104 A to approximately 5 A after the total of 11 lightning impulse events. It appears that the application of the second set of 5 impulses at 63 kV did not have a significant impact on reducing the critical current. However, these measurements may have caused degradation of the stabilizing layer which allowed for the single impulse measurement at 122 kV to drastically lower the critical current to 5 A. In total approximately 750 J of energy was released onto the HTS tape from the application of the lightning impulses. Further studies are necessary to determine if the cumulative effect of multiple impulses is equivalent to a single impulse that would release the same total amount of energy. It would be of interest to track how the nature of and location of degradation of the superconducting layer progresses.

The total amount of energy released by the impulses in the above tests is lower than the amount of energy expected to be released if an electrical breakdown occurs in S-GIL while in service. The experiment completed demonstrates a worse-case scenario where the electrical breakdown occurring directly onto the HTS tape, and future studies should also consider lightning impulse being performed on model superconducting cables. This would provide a greater relevance in trying to generate the conditions experienced during the operation of the S-GIL.

## 6. Conclusion

The extent of degradation of critical current of 2G HTS tapes depends on the voltage level of the electrical impulse event and the associated amount of energy released. It was shown that individual superconducting tapes do degrade in terms of critical current after multiple electrical impulses. It is however, important to realize that in a S-GIL or regular HTS cables, the superconducting tapes are part of the whole cable and are mechanically in robust structure. Thus the extent of damage is expected to be minimal under the impulse voltage levels that single HTS tapes might show some degradation in. The results reported here, however, demonstrate that it is necessary to study the degradation of HTS cables in high voltage electrical impulse events to ensure the development of designs that prevent any damage to the superconducting components of electrical power cables. We plan to conduct future studies on various configurations of HTS cables with the goal of arriving at a robust design that will tolerate electrical breakdown without any degradation in their performance.

## 7. Acknowledgements

This project was funded by the United States Office of Naval Research through grants N00014-14-1-0346 and N00014-16-1-2282. One of the authors, Martina Kvitkovicova, has been supported by the FREEDM program as an undergraduate research assistant.

## 8. References

- [1] S. Pamidi, C. H. Kim, and L. Graber, "High-temperature superconducting (HTS) power cables cooled by helium gas," in *Superconductors in the Power Grid: Materials and Applications*, 2015, pp. 225–260.
- [2] A. P. Malozemoff, J. Yuan, and C. M. Rey, "High-temperature superconducting (HTS) AC cables for power grid applications," in *Superconductors in the Power Grid*, Elsevier, 2015, pp. 133–188.
- [3] 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.
- [4] M. Hazeyama, T. Kobayashi, N. Hayakawa, S. Honjo, T. Masuda, and H. Okubo, "Partial discharge inception characteristics under butt gap condition in liquid nitrogen/PPLP® composite insulation system for high temperature superconducting cable," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 6, pp. 939–944, 2002.
- [5] H. Suzuki, T. Takahashi, T. Okamoto, S. Akita, and Y. Ozawa, "Electrical insulation characteristics of cold dielectric high temperature superconducting cable," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 6, pp. 952–957, 2002.
- [6] P. Cheetham, W. Kim, C. H. Kim, S. V. Pamidi, L. Graber, and H. Rodrigo, "Use of partial discharge inception voltage measurements to design a gaseous helium cooled high temperature superconducting power cable," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 1, pp. 191–199, 2017.
- [7] Naidu, *High Voltage Engineering*, vol. 16, no. 6. 1996.
- [8] 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.
- [9] M. W. Rupich *et al.*, "Second generation wire development at AMSC," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 3–7, 2013.
- [10] X. Li *et al.*, "The Development of Second Generation HTS Wire at American Superconductor," vol. 19, no. 3, pp. 3231–3235, 2009.
- [11] M. W. Rupich, "Second-generation (2G) coated high-temperature superconducting cables and wires for power grid applications," in *Superconductors in the Power Grid*, Elsevier, 2015, pp. 97–130.
- [12] AMSC, "Amperium Copper Laminated Wire," 2014. [Online]. Available: <http://www.amsc.com/documents/copper-laminated-amperium153-wire-data-sheet>.
- [13] J. Kim, Y. Kyu, M. Onyou, L. Seungmin, B. Hongseok, and H. Kang, "Deterioration Characteristics of 2G HTS Tapes with Respect to Electrical Breakdown for Designing a High-Voltage Superconducting Apparatus," *J. Supercond. Nov. Magn.*, 2016.
- [14] J. O. Kang, O. Lee, S. Bang, J. Kim, H. Lee, and J. Hong, "Degradation Characteristics of Superconducting Wires With Respect to Electrical Breakdown Tests," vol. 25, no. 3, pp. 3–6, 2015.
- [15] IEEE, "IEEE Std 4-2013 (Revision of IEEE Std 4-1995) IEEE Standard for High-Voltage Testing Techniques," *IEEE Std 4-2013 (Revision of IEEE Std 4-1995)*. pp. 1–213, 2013.
- [16] E. Kuffel, W. S. Zaengl, and J. Kuffel, "High Voltage Engineering - Fundamentals," *Electr. Eng.*, p. 539, 2000.
- [17] 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.