AC Breakdown Voltages of PEEK Insulation Used in Subsea Cable Connections

DOI:
10.1109/ICD59037.2024.10613357

Document Version
Accepted author manuscript

Citation for published version (APA):
Guana Niquinga, D., Liu, Q., Jeschke, M., & Walton, D. (2024). AC Breakdown Voltages of PEEK Insulation Used in Subsea Cable Connections. In *2024 IEEE 5th International Conference on Dielectrics (ICD)* (pp. 1-4). IEEE. https://doi.org/10.1109/ICD59037.2024.10613357

Published in:
2024 IEEE 5th International Conference on Dielectrics (ICD)

AC Breakdown Voltages of PEEK Insulation used in Subsea Cable Connections

Danny Guaña[1*], Qiang Liu[1*], Michael Jeschke[2] and Daniel Walton[2]

[1]Department of Electrical and Electronic Engineering, The University of Manchester, Manchester, UK
[2]Siemens Energy Limited, Ulverston, UK

*qiang.liu@manchester.ac.uk

Abstract—**Subsea cable connectors are crucial components in offshore power delivery systems, commonly using a solid-liquid composite insulation system. Unfortunately, limited literature exists on the electrical characterisation of the insulation material polyether ether ketone (PEEK), despite extensive research on liquid and solid insulation materials in high voltage applications. This paper investigates the AC breakdown strength of PEEK immersed in a mineral oil at 20 °C. The results are statistically analysed using both 2-parameter and 3-parameter Weibull distributions, resulting in characteristic breakdown strenghts of 30.79 kV/mm and 30.40 kV/mm, respectively. Additionally, the location of each breakdown event was identified using a self-developed image processing procedure.**

Keywords—PEEK, subsea cable, breakdown voltage, breakdown strength, mineral oil.

I. INTRODUCTION

Undoubtedly, one of the main obstacles of subsea engineering lies in providing electrical power to and from underwater installations. The resources are situated offshore, reaching depths up to 3000 meters, experiencing pressures of up to 300 bars, and contending with conductive, corrosive water, along with temperature variations [1, 2]. In this context, subsea connectors emerge as one of the most critical components in offshore power delivery systems, as they must efficiently operate in harsh underwater environments. Indeed, research studies indicated that connectors are responsible for many, if not most, unsuccessful subsea projects [1]. Therefore, the electrical insulation of such connectors plays a pivotal role in their design and development.

Conventionally, insulation design of subsea connectors uses a solid insulator along with a mineral oil (MO) environment, primarily owing to its cost-effectiveness and outstanding dielectric properties. The introduction of the dielectric liquids helps to watertight the pins and sockets and seal them from seawater [3, 4]. Furthermore, dielectric liquids also contribute to maintaining a balanced pressure between the inside and outside of the devices. Nevertheless, allowing a dielectric liquid to permeate a solid material could result in volume expansion, reducing the mechanical strength, causing delamination of composite structures, and decreasing the electrical breakdown strength [2]. Similarly, chemical components in a solid insulator such as plasticizers, hardening agents and stabilisers might desorb and diffuse into the dielectric liquid, prompting a reduction in the intrinsic breakdown strength of the liquid [2]. Therefore, ensuring excellent material compatibility is vital to achieve a reliable insulation design.

The overall design of subsea cable connectors involves a multidisciplinary approach where the choice of the materials is the key. In addition to the dielectric property, other properties including high impact strength, low mould shrinkage, low water absorption, high compressive strength and nonflammability need to be considered. In this case, the thermoplastic polymer polyether ether ketone (PEEK) stands out as an exceptional choice for subsea cable applications due to its excellent mechanical strength (110 MPa) [5], low water absorption (0.5%) [5], superior resistance to heat (T_g = 145 °C) and chemical corrosion [5, 6].

Regrettably, despite the extensive research dedicated to exploring the electrical performance of liquid and solid composite insulation systems, there is lack of literature addressing the electrical characterisation of the PEEK insulation material, for applications of higher voltage ratings. Therefore, it is essential to investigate the breakdown phenomena of PEEK samples immersed in mineral oil under AC stress, which would provide a useful reference for the design and production of underwater/subsea connectors. This comprehension will serve as the foundation for improved performance and safety of subsea equipment, essential for the advancement of the offshore industry.

This paper focuses on the electrical characterisation of PEEK when immersed in a mineral oil, serving as the primary insulation system in subsea cable connectors. A breakdown voltage measurement system, coupled with a temperature control unit is adopted to maintain the solid-liquid insulation system at 20 °C during the experiments. The results are statistically analysed using 2-parameter and 3-parameter Weibull distribution methods. Furthermore, the location of each breakdown event is also studied utilising a self-developed MATLAB code.

II. EXPERIMENTAL DESCRIPTIONS

A. *Experimental Setup*

The experimental setup from [7] has been adopted to perform breakdown voltage measurements. As shown in Fig. 1, it comprises a voltage control system, a temperature control system, and a polycarbonate transparent test cell containing the electrode assembly and the sample. The voltage control system includes a PC, an audio amplifier, a step-up transformer, a 0.5 MΩ current limiting resistor and a capacitive voltage divider.

The primary voltage is sourced from a NI USB-6229 data acquisition device (DAQ), which has the capability of producing sinusoidal waveforms up to ± 10 V. The DAQ output is boosted by a 4000-Watt audio amplifier, which subsequently feeds the primary winding of the single-phase transformer with an output voltage up to 80 kV. In the event of a breakdown, an overcurrent relay together with the current limiting resistor will protect the system from potential high

979-8-3503-0897-6/24/$31.00 ©2024 IEEE

energy damage. In addition, voltage readings are captured utilising a 20 GS/s oscilloscope connected to a capacitive voltage divider with a 10,000:1 ratio.

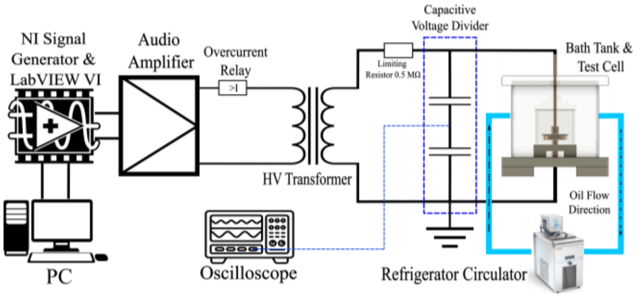

Fig. 1 Schematic of the experimental setup for breakdown voltage measurements [7].

B. Test Cell and Electrodes Assembly

The solid-liquid composite insulation system was contained in a 1.3 L transparent Polycarbonate cubic cell. The insulation system is tested utilising a pair of cylindrical electrodes made of copper with a diameter of 25 mm and an edge curvature radius of 3 mm as per IEC 60243-1 [8].

C. Test Samples and Procedures

A total of 20 samples with a thickness of 1.0 mm were subjected to breakdown tests. The test procedure is summarised as follows:

1) A PEEK sample (with $\varepsilon_r = 3.2$) is immersed in mineral oil (with $\varepsilon_r = 2.2$) and placed between the cylindrical electrodes.
2) The test cell is positioned at the centre of the bath tank, and the chamber temperature is regulated to 20 ºC. Temperature monitoring is conducted using type K thermocouples.
3) A 50 Hz, AC voltage ramp is applied at a rate of 2000 V/s as in [8]. The breakdown voltage and location are recorded.
4) Both the PEEK sample and surrounding mineral oil are replaced after each breakdown event.

D. Breakdown Location Identification

Breakdown in solid dielectrics results in a narrow conducting channel puncturing the sample under investigation and leaving a carbon deposit on the electrode surface [9]. This phenomenon enables the development of a program that analyses the region of interest (ROI) and estimates the location of the carbonised area with respect to the centre of the electrode.

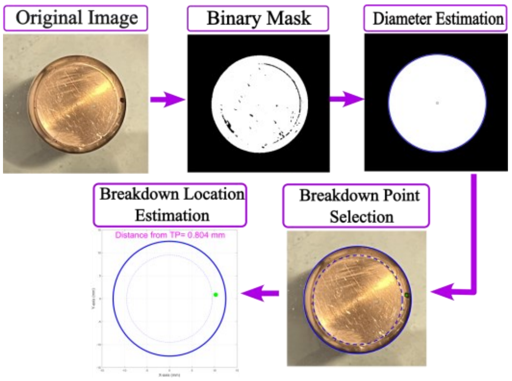

Fig. 2 Post-breakdown image processing for indentifying the breakdown location and its distance from the triple point (TP) junction.

A high-quality post-breakdown photo is loaded in MATLAB, prompting the user to select the ROI as shown in Fig. 2. The code converts the cropped image to the HSV colour space, facilitating the identification and tracking of objects based on their saturation and intensity characteristics. By selecting an appropriate threshold, the program effectively distinguishes the area occupied by the electrode from the background. A binary mask is then created based on a threshold in the saturation channel. The next step involves reducing and filtering noise within the electrode area to achieve an accurate delineation of the ROI. This step ensures that the mask precisely outlines the target without including irrelevant details. Finally, the centre and dimensions of the electrode are determined. The coordinates of the breakdown location are then identified and the distance to triple point (TP) junction was calculated.

III. RESULTS AND DISCUSSIONS

A. AC Breakdown of PEEK at 20 °C

AC breakdown voltage (BDV) and breakdown strength (BDS) results of PEEK immersed in mineral oil at 20 °C are presented in Fig. 3. Each measurement was conducted with a brand-new PEEK sample and clean mineral oil, thus, avoiding potential cumulative effect. The sequential plot demonstrates that BDV fluctuates in the range of 27.26 kV to 34.32 kV without showing a monotonically increasing or reducing trend.

The values of breakdown strength are calculated by dividing each BDV result by the thickness of PEEK which is measured with a high precision bench thickness gauge with resolution of 0.001 mm. Similarly, the values of BDS range from 26.70 to 33.77 kV/mm with an average of 29.88 kV/mm, as shown in Fig. 3. A statistical analysis of the results is summarised in TABLE I. The coefficient of variation (CV) is 0.065, which denotes a level of dispersion less than 10% around the mean. This robust consistency supports the feasibility and reliability of the experimental procedure.

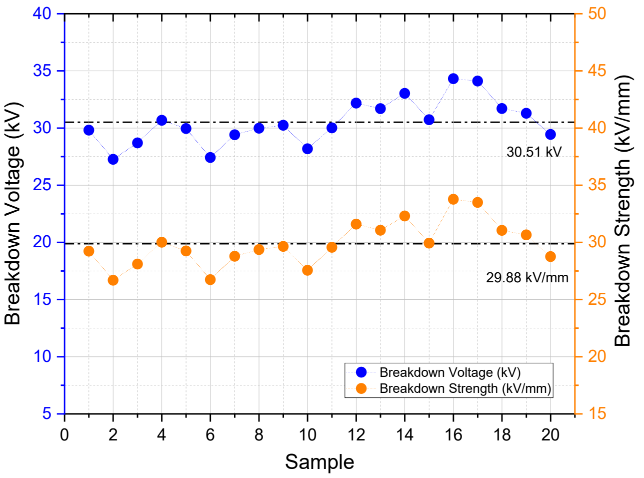

Fig. 3 Breakdown voltage measurements at 20 °C for PEEK samples immersed in mineral oil.

TABLE I. NORMAL DISTRIBUTION ANALYSIS OF BREAKDOWN STRENGTH OF PEEK IMMERSED IN MINERAL OIL

Temperature (°C)	**Breakdown Strength (kV/mm)**		**Coefficient of Variation (CV)**
	Mean (μ)	***STD (σ)***	
20	29.88	1.96	0.065

B. *Statistical Analysis of BDS: 2-parameter Weibull Fit*

The Weibull method is probably considered the most common distribution function in the reliability analysis reporting strength and length of life of materials. The major advantage of Weibull analysis lies in its capability to provide accurate failure analysis and predictions, even with small sample sizes. As per [10], a robust data set is comprised of at least ten specimens. The present study addresses this requirement by doubling the number of samples.

The two-parameter Weibull fit along with 95% confidence bands is illustrated in Fig. 4. The corresponding Weibull distribution parameters are shown in TABLE II. . Overall, the regression line shows a strong fit for the BDS measurements which is further supported by its corresponding R^2 value (0.98). All the experimental points fall within the 95% confidence intervals and scatter around the line. Nevertheless, a thorough examination of the data set suggests that, despite the excellent fit demonstrated by the 2-parameter Weibull approach, the trend may not strictly follow a straight line but rather a concave curve bending downwards. This type of trend is not uncommon and has also been observed across multiple experiments investigating the BDS of solid insulators, as in [11, 12].

TABLE II. WEIBULL DISTRIBUTION ANALYSIS OF BREAKDOWN STRENGTH OF PEEK IMMERSED IN MINERAL OIL

Number of Parameters	**Weibull Distribution Parameters**			**50%**	**1%**	**R^2**
	Scale (α) (kV/mm)	***Shape (β)***	***Location (ɣ) (kV/mm)***			
2-Parameter	30.79	15.89	-	30.09	23.05	0.98
3-Parameter	4.55	2.23	25.85	29.71	26.43	0.99

C. *Statistical Analysis of BDS: 3-parameter Weibull Fit*

The 3-parameter Weibull approach introduces an additional term "ɣ", referred to as location parameter. As implied by its name, this parameter defines the location of the distribution function along the abscissa, providing an estimate of the lowest BDS at which failure might be observed i.e., when $F(x) = 0\%$ [13]. Fig. 5 shows the 3-parameter Weibull distribution plot for PEEK at 20 °C.

The initial notable feature is that the points now scatter around the fitting line without displaying any obvious outliers. The location parameter adjusts the regression line to match the actual trend of the dataset, preventing the emergence of isolated points. Regarding the probability estimations, the 3-parameter method shows a characteristic BDS of 30.04 kV/mm, which is close to that of the 2-parameter approach.

However, from an insulation design perspective, the more crucial aspect is the failure probability at very low values, indicating a high survival rate. The three-parameter approach enables the estimation of location parameter, representing the withstand strength. In theory, the results demonstrate that the insulation system will maintain a 100% survival rate at electric field strengths lower than 25.85 kV/mm. According to [13], the criterion adopted for determining whether the three parameter distribution is "better" than the two parameter approach is that the coefficient R^2 should be larger. Based on the results given in TABLE II. , both 2-parameter and 3-parameter approaches show high R^2 values.

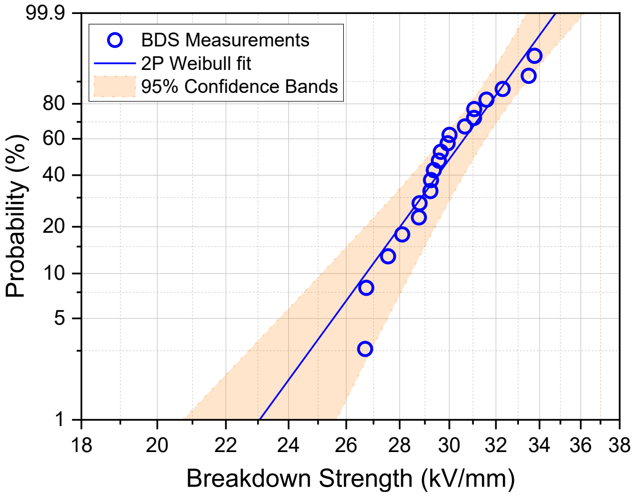

Fig. 4 2-Parameter weibull distribution plot for breakdown strength of PEEK immersed in mineral oil at 20 °C.

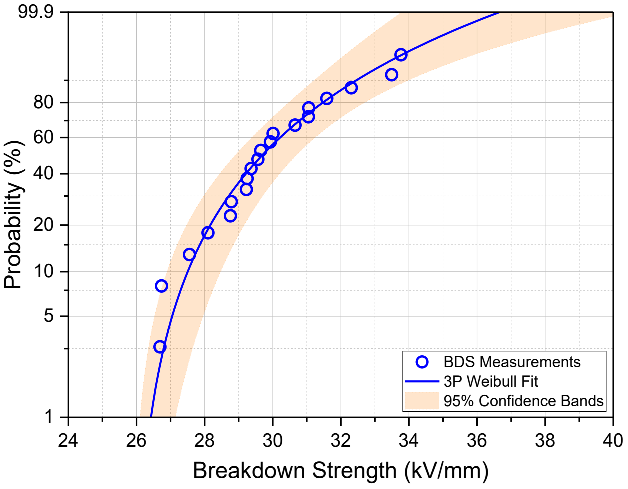

Fig. 5 3-Parameter weibull distribution plot for breakdown strength of PEEK immersed in mineral oil at 20 °C.

D. *Location of breakdown events*

Breakdown in solid dielectrics leads to the formation of a narrow conducting channel that punctures the sample under investigation [9]. In this study, all breakdowns for the solid-liquid insulation system were catastrophic and irreversible in the sense that it involved the local melting and carbonization of the dielectric material at the breakdown location.

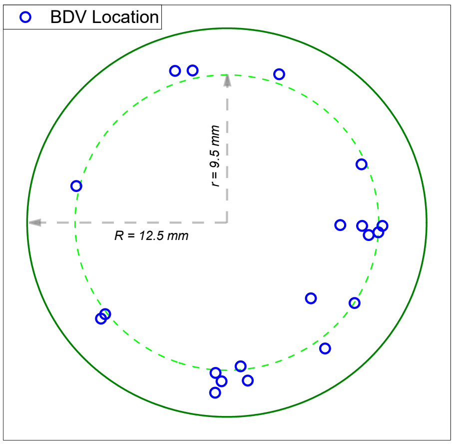

Fig. 6 Breakdown locations of PEEK samples immersed in mineral oil. (R = external diameter, r = internal diameter).

Fig. 6 shows the location of each breakdown event recorded during this investigation. The findings reveal that 14 samples, constituting 70% of the occurrences, occur at the edge of the electrodes in the vicinity of the triple point (TP) where the sample, liquid, and electrode intersect. Besides, the breakdown spot was found, on average, at a distance of 0.68 mm from the inner electrode circumference labelled as "*r*" in Fig. 6. This suggests that the maximum local electric field does not strictly occur at the TP.

IV. Conclusions

This investigation evaluates the AC breakdown properties of PEEK and mineral oil composite materials as the primary insulation system for subsea cable connectors. The analysis of breakdown voltage and breakdown strength at 20 °C was conducted and the results were statistically analysed using both a 2-parameter and a 3-parameter Weibull distribution. The results indicated that both methods establish a robust correlation between the dataset and the regression line, revealing a characteristic breakdown strength of approximately 30 kV/mm, irrespective of the chosen Weibull approach. An advantage of using 3-parameter approach is the ability to estimate the withstand strength with a theoretical 100% survival rate, facilitated by the location parameter. For the insulation system tested in this paper, the location parameter is 25.85 kV/mm.

The investigation also recorded the locations of breakdown events showing that 70% of the events occurred in the vicinity of the TP. These findings can inform future research for optimising insulation design of subsea connectors used in offshore industry. Further work would involve the investigation of PEEK samples immersed in other dielectric liquids e.g. biodegradable liquids.

Acknowledgement

This work was supported by a joint PhD studentship from the Engineering and Physical Sciences Research Council (EPSRC), Industrial Cooperative Awards in Science and Technology, and Siemens Energy, UK. All data supporting this study are provided in full in the 'Results' section of this paper.

References

[1] W. Song and W. Cui, "An Overview of Underwater Connectors," *Journal of Marine Science and Engineering,* vol. 9, no. 8, p. 813, 2021. [Online]. Available: https://www.mdpi.com/2077-1312/9/8/813.

[2] C. Lesaint, J. H⊘lto, H. H. Sæternes, and M. H. G. Ese, "Compatibility of liquid and solid insulation materials for high voltage subsea connectors," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 26, no. 4, pp. 1139-1145, 2019, doi: 10.1109/TDEI.2019.007907.

[3] F. Rémouit, P. Ruiz-Minguela, and J. Engström, "Review of Electrical Connectors for Underwater Applications," *IEEE Journal of Oceanic Engineering,* vol. 43, no. 4, pp. 1037-1047, 2018, doi: 10.1109/JOE.2017.2745598.

[4] T. Hazel, H. H. Baerd, J. J. Legeay, and J. J. Bremnes, "Taking Power Distribution Under the Sea: Design, Manufacture, and Assembly of a Subsea Electrical Distribution System," *IEEE Industry Applications Magazine,* vol. 19, no. 5, pp. 58-67, 2013, doi: 10.1109/MIAS.2012.2215648.

[5] V. R. Sastri, "8 – High-Temperature Engineering Thermoplastics: Polysulfones, Polyimides, Polysulfides, Polyketones, Liquid Crystalline Polymers, and Fluoropolymers," 2014.

[6] K. J. Bigham, "POWERING MOTOR PERFORMANCE: AN INTRODUCTION TO PEEK EXTRUSIONS," 2017.

[7] D. Guana, Q. Liu, M. Jeschke, and D. Walton, "Effect of Temperature on Breakdown Voltage of Silicone Rubber Insulation Used in Subsea Cable Connectors," in *2023 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 15-19 Oct. 2023 2023, pp. 1-4, doi: 10.1109/CEIDP51414.2023.10410467.

[8] *Electric strength of insulating materials — Test methods Part 1:Tests at power frequencies*, B. S. Institution, 2013.

[9] L. A. Dissado and J. C. Fothergill, *Electrical Degradation and Breakdown in Polymers*. London, UK: The Institution of Engineering and Technology, 1992.

[10] *IEC 62539:2007 Guide for the statistical analysis of electrical insulation breakdown data*, IEC, 2007.

[11] G. Raju, A. Katebian, and S. Z. Jafri, "Breakdown voltages of polymers in the temperature range 23/spl deg/-250/spl deg/C," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 10, no. 1, pp. 117-127, 2003, doi: 10.1109/TDEI.2003.1176573.

[12] S. U. Haq and G. G. Raju, "DC breakdown characteristics of high temperature polymer films," *IEEE transactions on dielectrics and electrical insulation,* vol. 13, no. 4, pp. 917-926, 2006, doi: 10.1109/TDEI.2006.1667753.

[13] R. B. Abernethy, J. Breneman, C. Medlin, and G. L. Reinman, "Weibull analysis handbook," Pratt and Whitney West Palm beach fl Government Products DIV, 1983.