IOP Conference Series: Materials Science and Engineering

Cryogenic testing of a 25 kV RIS bushing

To cite this article: Stefan Fink *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1240** 012148

Cryogenic testing of a 25 kV RIS bushing

Stefan Fink, Uwe Fuhrmann and Volker Zwecker

Institut für Technische Physik, KIT - Campus Nord, Hermann-von-Helmholtz-Platz 1,
76344 Eggenstein-Leopoldshafen, Germany

Corresponding author: fink@kit.edu

Abstract. High voltage bushings for cryogenic current or voltage leads must master safely the special thermal stress in addition to the high voltage requirements. Resin impregnated synthetic (RIS) bushings have proven their usability for room temperature high voltage application since few years. Such paper free bushings are less hygroscopic than paper based bushings, which can be an advantage for components exposed to cryogenic temperatures on one side and to air conditions on the other. A conventional 25 kV, 2 kA room temperature RIS bushing was assembled to an open bath cryostat and subjected to five thermal cycles. High voltage tests were successfully performed under cryogenic conditions. No degradation of the bushing was found after the thermo-mechanical stress of the fast cool downs and one fast warm up. This paper focuses on the thermal tests.

1. Introduction

The present investigation is performed in the framework of the "Faculist" study for a 420 kV superconducting fault current limiter (Fault current limiter study). For this application the bushings are intended to be subjected partially to cryogenic conditions within a liquid nitrogen bath cryostat exceeding the standards for conventional outdoor applications, which are limited to temperatures down to -40 °C [1] or -70 °C [2]. The market for such cryogenic bushings is relatively small and therefore commercial bushings explicitly declared for cryogenic use [3] are difficult to obtain.

One strategy to acquire cryogenic high voltage bushings is to develop and build special solutions, e.g. in case of high voltage labs [4] [5] or for fusion magnets current leads [6]. Another solution is to check if conventional bushings are able to meet the requirements under cryogenic conditions. Resin impregnated paper (RIP) bushings are dry bushings, whose main insulation consists of a crepe paper cylinder impregnated with a curable resin. The RIP technology is a common technique for conventional power engineering and has also proven its usability under cryogenic conditions [7] [8].

A disadvantage of RIP bushings are failures caused by moisture ingress [9]. Hence, hydrophobic alternatives are preferred considering potentially permanent wet conditions of specific locations on the airside of cryogenic bushings. A hydrophobic alternative is a dry paperless resin impregnated synthetic (RIS) bushing. This paper describes cryogenic tests of an oil to outdoor RIS bushing, which is commercial available. For the cryogenic tests the "oil side" was immersed in liquid nitrogen.

2. Test sample and setup

The RIS sample was the transformer bushing STARIS Sia 25-2000 E5,34 (figure 1). The total length is 1401 mm. Other dimensions are specified in [10]. Its highest phase to phase voltage for equipment is 25 kV. The rated current is 2 kA. The specified ambient temperature is -30 °C up to 50 °C.

The procurement was focused on the acquisition costs because it was uncertain if the bushing can survive even one single cool down. Hence a medium voltage bushing was ordered. Only few aspects were considered for the selection of this bushing:

- Three different lengths on the "oil side" are offered by the manufacturer based on different current transformer lengths. The longest current transformer length was selected, which was not used for current transformer application but for a sufficient long temperature grading profile.
- An outdoor type silicon insulator was selected for the room temperature side because the amount of icing and condensation was unknown.
- The manufacturer should be able to deliver RIS bushings for high voltage levels and RIP high voltage bushings of this manufacturer were successfully operated under cryogenic conditions with an internal pressure of at least 0.2 MPa (gauge).

The manufacturer performed high voltage tests according to a standard for power apparatus bushings [11].

After delivery the high voltage tests of KIT were performed initially at room temperature conditions outside the cryostat (figure 1). For further tests, the bushing was clamped on a steel lid with a diameter of 650 mm (figure 2). Pt100 temperature sensors were installed at heights corresponding to the maximum (LN2_max_level) and minimum (LN2_min_level) liquid nitrogen level foreseen for high voltage operation. Another Pt100 sensor was installed at the height of the bottom insulator end of the bushing (bushing_bottom). The lid was mounted on top of a cryostat with a diameter of 400 mm (figure 3). This setup was an open cryostat version because the used lid does not allow tight fixation for evacuation. The used RIS bushing is not specified for overpressure operation.

Figure 1. RIS bushing.

Figure 2. Temperature sensor positions for RIS bushing assembled on lid.

Figure 3. Schering bridge test with bushing and lid assembled on the cryostat.

The test tap was remained grounded during the cryogenic tests in order to avoid internal icing. Thermal insulation was affixed on metal surfaces of the bushing in order to reduce thermal losses.

3. Tests

Five thermal cycles were performed. Each thermal cycle comprised at least one filling period with liquid nitrogen for a cool down from room temperature to liquid nitrogen temperature (77 K, 0.1 MPa absolute) and a subsequent warm up to room temperature. Only one day of testing under cryogenic conditions was foreseen for thermal cycle number one. Hence only one filling with liquid nitrogen was performed. More thermal stress was generated during the other four thermal cycles with tests on more than one day. For these cycles every further test day required a refill in order to obtain a liquid nitrogen level necessary for high voltage tests. Figure 4 shows temperatures within the cryostat during thermal cycle number 4 for the initial days. Figure 5 shows the cool down process from room temperature only. For this cool down warm nitrogen gas was blown in the inner chamber of the cryostat for 25 min in order to reduce the amount of ice generation. Then the liquid nitrogen shield was filled for 26 min. During this period the uppermost sensor (LN2_max_level) indicated the lowest temperature values because the liquid nitrogen shield is in the upper region of the cryostat. After the shield is filled up with liquid nitrogen, the nitrogen gas injection for the inner chamber was stopped. Then the liquid nitrogen supply for the inner cryostat chamber was connected and the liquid nitrogen filling was started. As soon as liquid nitrogen reached the insulator part of the bushing the filling was interrupted for 10 min and then continued. The duration between starting filling of the liquid nitrogen shield and indication of 77 K for the top sensor was 1 h 38 min.

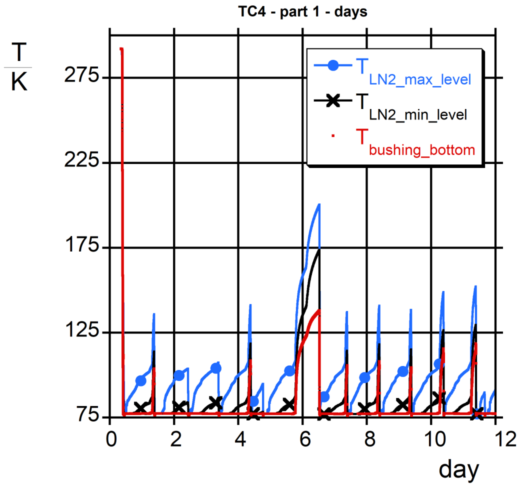

Figure 4. Temperature measurement for the first 12 days of thermal cycle 4. The 3 temperature sensors were located at the rated maximum and minimum level of liquid nitrogen for high voltage operation, and at the level of bottom end of the insulator part of the bushing.

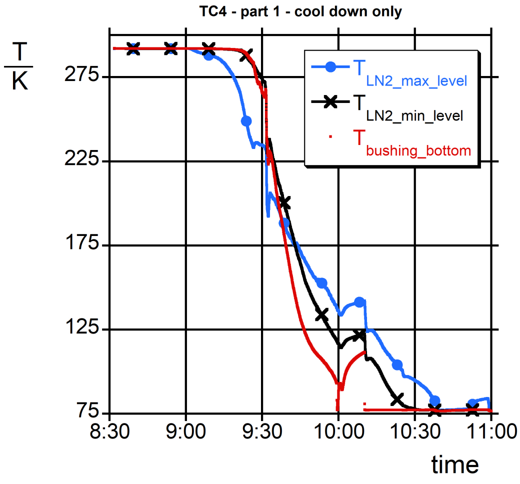

Figure 5. Temperature measurement vs. daytime for initial cool down process of thermal cycle 4.

Warm up took few days for the thermal cycles 1 to 4. A faster warm up was intended for thermal cycle number 5. Therefore the bushing tests for thermal cycle 5 were performed in a cabin with access to a crane. For this fast warm up the cryostat lid was lifted from the filled cryostat in a way that the bushing was dragged out of liquid nitrogen within 2 min. Additionally, warm air was blown on the surface of the bushing in order to speed up the warm up process.

A total sum of 37 “cold days” is obtained counting for each thermal cycles the days from the first filling with liquid nitrogen to the last filling with liquid nitrogen before warm up to room temperature. In these sum the days without filling (because no high voltage tests are done on these days) are included.

The longest thermal cycle was number 4 with 24 running days from first filling to last filling with liquid nitrogen.

Partial discharge tests under AC conditions were performed before and after critical thermal or electrical experiments. This test should provide information which stress mode was the reason for failure in case of bushing destruction. RMS voltage value of 32 kV was selected in case of cryogenic operation or for testing in air outside the cryostat. The value was reduced to 16 kV (only thermal cycle 1) or 25 kV in case of room temperature operation with the bushing mounted on the cryostat. The cabin with crane access was not shielded which led to overlaying with a high disturbance band around 90 pC. The final partial discharge test with the bushing out of cryostat showed a charge below 1 pC. This result is considered as acceptable indicating no severe degradation.

Schering bridge measurements were usually performed after the routine partial discharge tests for status monitoring of capacitance and dissipation factor. Figure 6 shows the measured capacitance and figure 7 the dissipation factor for the tests during thermal cycle 1 to 5. There is a clear relationship depending on the test condition for the measured capacitance as well as for the dissipation factor. The bushing had a capacitance around 710 pF under room temperature conditions outside the cryostat. Assembly in the cryostat increased the capacitance to values around 730 pF, which can be explained by the increase of stray capacitance to the cryostat wall. After cool down the capacitance decreased to values around 680 pF although liquid nitrogen has a permittivity of 1.41 and not 1.0 like air or nitrogen gas. This behavior can be explained by decrease of the permittivity of the insulator material of the bushing. The dissipation factor for room temperature was measured between 0.250% and 0.289% whereas the dissipation factor was between 0.466% and 0.519% for cryogenic conditions.

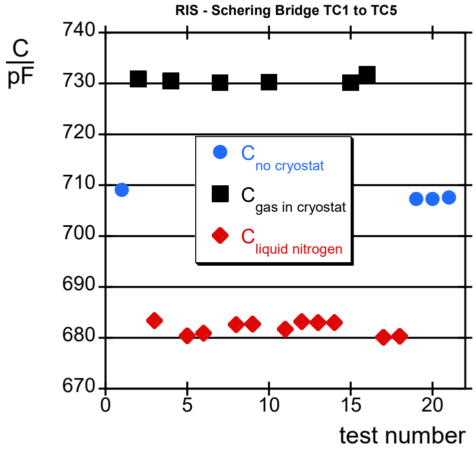

Figure 6. Capacitance vs. chronological test number arranged according to test condition, i.e. under room temperature condition either outside cryostat or with warm gas in cryostat or under cryogenic conditions with liquid nitrogen.

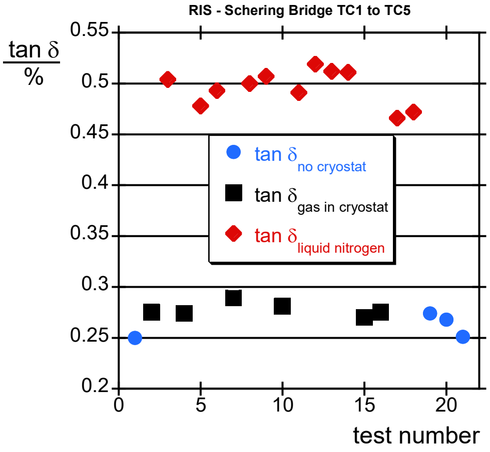

Figure 7. Dissipation factor (tan δ) vs. test number arranged according to test condition.

During cool down for thermal cycle 5 it should be investigated if stationary temperature distribution can be reached within a single 8 h shift in case of no current operation. Nitrogen gas flashing was started at 9:02. Filling with liquid nitrogen started at 9:50 and was stopped at 11:22. Figure 8 shows temperature data and Schering bridge results.

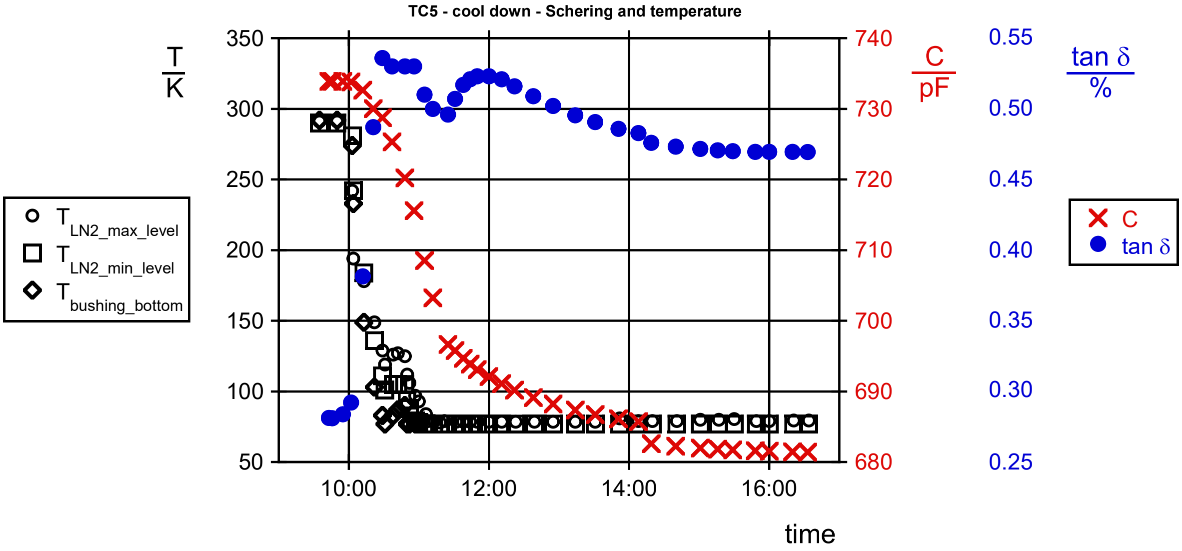

Figure 8. Temperatures (T), capacitance (C) and dissipation factor (tan δ) measurement vs. time during a single 8 h shift starting with warm nitrogen gas flow at nine o'clock. Liquid nitrogen filling was stopped at 11:22.

The capacitance was strictly monotonically decreasing after starting the cool down process. The dissipation factor had two local maxima at 10:29 and around 12:00. Then the dissipation factor was strictly monotonically decreasing. Between 16:00 and 16:33 the capacitance decreased for 0.16‰ and the dissipation factor for 0.32‰ only. It can therefore be concluded that concerning cool down a quasi-static temperature distribution of this RIS bushing can be achieved within a single 8 h shift.

Surface temperature on the air side of the bushing (figure 9) was investigated with a thermal imaging camera (figure 10) under air temperature of 20.5 °C. Simple thermal insulation based on synthetic rubber was sufficient to avoid icing or low temperatures on the high voltage connection above the bushing.

Figure 9. Optical imaging of the air side of the bushing.

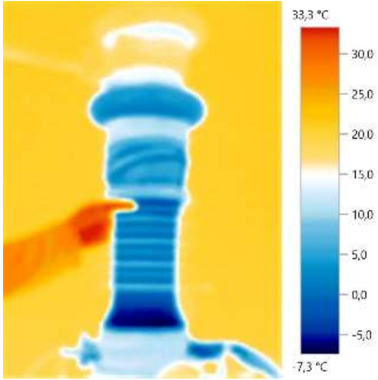

Figure 10. Thermal imaging of the air side of the bushing with temperature legend between -7.3 °C and 33.3 °C.

A more detailed view on the silicon region shows that for warm-temperate indoor application the sheds interrupt the ice path resulting in a limitation of the icing to the vertical surface only. This characteristic is advantageous concerning flashover sensitivity.

No mechanical degradation was found by visual inspection. Leak testing was performed at KIT before first and after last voltage test (figure 11). For the incoming inspection, leaks were found at the clamping piece of the top flange and on the air release screw of the mounting flange. A break of 17 days was taken between lifting the bushing out of the cryostat and the second leak test. Leak rate was above $3 * 10^{-4}$ hPa l / s on the air release screw. A leak rate of $\leq 2.8 * 10^{-9}$ hPa l / s was found for the clamping piece, which means that it can be considered as tight.

Figure 11. Leak test after fifth thermal cycle with evacuated tube around the insulator side which had been cooled with liquid nitrogen.

Several AC, DC and impulse tests were performed under cryogenic conditions during the 5 thermal cycles which are described in [12].

4. Discussion

A dry type bushing was selected for cryogenic application in order to avoid freezing or liquefaction of the fluid [13]. The paper free RIS bushing type was described as less hygroscopic than the RIP type, which is an advantage in case of long term operation under cryogenic conditions with expected humidity caused by condensation on the surface. The examined RIS bushing comprises a copper rod which causes potentially more mechanical stress to the insulator during cool down compared to versions where a tube or rod with a smaller outer diameter than the inner insulator diameter is fixed on top of the bushing [3] [7]. No degradation can be found after 5 cool downs by visual inspection, leak testing or partial discharge test. A refueling time of 2 h and a removal time of 2 min is expected to be short enough to be representative at least for medium size applications and no shock cool down is required. Indeed for filling with cans it would have been even difficult to cool down the used RIS bushing setup much faster.

Schering bridge measurement on RIS material have shown a capacitance decreasing with temperature and at least one local maximum of dissipation factor between room temperature and 77 K which is a frequently reported behavior of polar materials [14] [15]. The higher dissipation factor for the bushing under cryogenic conditions than at room temperature conditions does not necessarily mean that the insulator material itself has a higher dissipation factor for liquid nitrogen temperature. The insulator was only partially immersed in liquid nitrogen. Also insulator spaces below the liquid nitrogen level were warmed by the copper rod. In addition, the air side insulator material was cooled by the copper rod. Hence the temperatures of relevant portions of the insulator volume were shifted towards the region where higher dissipation factors than at room temperature can be expected leading to an overlaying effect in relation to the dissipation factor reduction by the regions which were around liquid nitrogen temperature.

The disappearing of the leak on the clamping piece may be explained by a blocking of the leakage by water due to condensation which means the waiting time for the leak test after warm up was too short. Nevertheless axial leakage may be an issue for further improvement. The insufficient leak tightness of the air release seal could be fixed by closing the drilling on the steel flange if necessary. For higher pressure applications other flange mounting solutions will be selected which have already proven their cryogenic usability on RIP bushings and which have no air release.

5. Conclusion

The investigated RIS bushing showed no thermo-mechanical degradation after subjection to five thermal cycles between room temperature and 77 K although the bushing contains a copper rod for 2 kA operation. No breakdowns, flashovers or indication of degradation of the electrical insulation occurred during high voltage tests according or related to standards for conventional bushings. Strong icing on the bushing head was avoided with simple indoor thermal insulation. Leakage improvement is expected to be a feasible task for the next RIS bushing version. Unresolved issues are still open concerning research on RIS material properties (e.g. thermal expansion or thermal conductivity) as well as tests relevant for RIS bushing application (e.g. thermal stress by current operation). The results obtained so far rationalize further investigations with this kind of material for cryogenic high voltage applications, e.g. a 420 kV RIS bushing for a current lead of a superconducting fault current limiter.

6. References

[1] IEC std 60137, 2017 p 25
[2] GOST 15150-69, 1971
[3] Fink S and Noe M 2008 A facility for testing the dielectric strength of liquid nitrogen *Int. Conf. on Dielectric Liquids* doi 10.1109/ICDL.2008.4622450
[4] Hill N Blaz M Haake F Hilbert M and Kurrat M 2019 Bushing for a liquid nitrogen cryostat - A novel field grading material *Int. Symp. on High Voltage Engineering* 289-297
[5] Frayssines PE Lesaint O Bonifaci N Denat A Lelaidier S and Devaux F 2002 Prebreakdown phenomena at high voltage in liquid nitrogen and comparison with mineral oil *Trans. on Dielectrics and Electrical Ins*. **9** 899-909
[6] Heller R et al. 2018 Overview of JT-60SA HTS current lead manufacture and testing *Trans. on Appl. Supercond.* **28** 1-5
[7] Fink S and Zwecker V 2019 15 min DC breakdown tests with liquid nitrogen *Int. Conf. on Dielectric Liquids*
[8] Ulbricht A *et al* 2005 The ITER toroidal field model coil project *Fus. Eng. and Design* **73** 189-327
[9] Xu Z Hu W Yin P Xie X Luo X and Wan B 2020 The influence of moisture on the insulation performance of epoxy resin impregnated paper *Int. Conf. on High Voltage Engineering and Application*
[10] STARIS Sia+ 25 – 230 kV *Publ. STARIS 11/2020* HSP Hochspannungsgeräte GmbH
[11] IEEE std C57.19.00-2004, 2005
[12] Fink S and Zwecker V 2021 Cryogenic high voltage testing of a 25 kV RIS bushing *to be published*
[13] Koo J Seong J Hwang J Lee B and Lee S 2012 Design of 154 kV extra-high-voltage prototype SF6 bushing for superconducting electric power applications *Jpn. J. Appl. Phys* **51** 09ME01
[14] Barucci M Bianchini G Gottardi E Peroni I and Ventura G 1999 Dielectric properties of Stycast 1266 over the 0.07-300 K temperature range *Cryogenics* **39** 963-66
[15] Foner S and Schwartz BB 1974 Superconducting machines and devices *Plenum Press* 473