Lightning impulse breakdown voltage of liquid nitrogen under the influence of heating

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Abstract. For application of high voltage superconducting apparatus liquid nitrogen is often not only used as coolant but also for electrical insulation. A temperature increase, e.g. during a quench of a fault current limiter, may cause a considerable decrease of the breakdown voltage within the apparatus. A cryostat was equipped with an adjustable sphere to plate electrode arrangement for the examination of the breakdown and withstand voltages of liquid nitrogen depending on the gap length. The sphere was connected to high voltage and the plate electrode was grounded. Standard lightning impulses till 360 kV were applied to the arrangement. First investigations with a non heatable plane for pressures till 0.3 MPa (absolute) showed no technical relevant gain by pressure increase especially for negative impulses. Hence the dielectric strength of liquid nitrogen in the heated case in comparison to the not heated mode was only examined at 0.1 MPa (absolute). Approximately a doubling of the gap length was necessary in case of a 0.5 kW heating in order to achieve the same 16% breakdown voltage or the same withstand voltage as in the case with no heating.

1. Introduction
The use of liquid nitrogen as electrical insulation within high temperature superconducting power equipment with test or operation voltages higher than 200 kV is still a large effort especially if a possible degradation of the dielectric strength by heating in case of a quench is considered. The FACility for TEsting LIquid Nitrogen ("Fatelini") at the ITP had been already used in prior tests without a heater till alternating voltages (AC) of 200 kVrms and standard lightning impulse (LI) voltages till 370 kV [1].

2. Electrode arrangement
Most hardware components are described in [1]. Firstly, a sphere of 50 mm diameter and a non heatable plane with 300 mm were used. The sphere was arranged above the plane and the distance can be adjusted in steps of millimetres. For the next test series the plane was exchanged by a plate with a heated centre. The total diameter of this plate is 300 mm, too. The diameter of the heater area itself is about 120 mm. The heating power was adjusted to a value between 500 W and 530 W. During initial heating tests with liquid nitrogen in a glass pot it was found that a heating time of 6 s is sufficient to produce gas bubbles under ambient pressure. Unfortunately, the initial heating tests caused a permanent deformation between the heated and the not heated part of the plate. The heated part
remains flat but the unheated part buckles a bit. As a consequence, it is bended in the electrode arrangement in opposite direction as the sphere. Because the thickness of the steel above the heater is only 1.7 mm and the effect is expected to be acceptable compared to the results with a sphere to plane arrangement it was decided not to machine the plate again.

3. Set-up and procedures

3.1. Test set-up

After filling to the rated liquid nitrogen level which can be observed with 2 independent measurement systems the pressure is increased. Then ambient pressure, temperature and humidity was measured and the spark gap distance of the Marx Generator (figure 1) was adjusted. Next, the starting temperature of the liquid nitrogen was measured. During temperature calibration of the oscilloscope the gap distance between sphere and plate electrodes was adjusted and controlled by distance elements.

![Figure 1. Impulse voltage circuit and Fatelini cryostat in an experimental cabin of the Cryogenic High Voltage Lab: cryostat with bushing (right side), high voltage divider (foreground), three-stage Marx Generator (left-middle), and transformer (left side, background).](image)

Then the voltage was ramped up for charging the Marx Generator. The charging process was observed on the primary side of the high voltage transformer and on the secondary side with a capacitor divider. In case of an impulse test with heated liquid nitrogen the heater was started. The heater voltage was observed by an oscilloscope to make sure that the power remains in the defined range. Then the voltage of the high voltage transformer was ramped down and the transformer was separated from the grid by switches. The Marx generator was triggered 6.1 s after starting of the heater to ensure the boiling of liquid nitrogen and the lightning impulse was digitally stored. Then a timer was started to ascertain the minimum waiting interval between 2 tests. During this waiting interval the waveform was analysed and the pressure inside the cryostat was tuned.

3.2. Breakdown test procedure using the non heatable plane

Different test procedures were used depending on the kind of test. For the breakdown test with the non heatable plane a procedure for breakdowns derived from [2] was used.

The test procedure in [2] is briefly described as follows: After selection of the appropriate initial value 5 impulses at each voltage level are performed. The voltage step is 5 kV (or 10 kV). The end of the test is reached after a total sum of 5 breakdowns. For the test to be valid, the test arrangement shall
withstand a minimum of 3 test levels before breakdown occurs. Otherwise the tests are continued at lower levels. Finally, the average is calculated.

In contrast to [2] for the procedure used for Fatelini some changes were made: Firstly, a variable gap length instead of a constant electrode distance was used because the target of the examination is to deliver breakdown values not only for one gap length. Secondly, voltage steps were changed for higher voltages (10 kV step above 150 kV up to 250 kV, 15 kV step above 250 kV) and the number of minimum step sizes before the first breakdown was increased. Furthermore, the waiting interval was increased to at least 2 min in case of no breakdown and to at least 5 min in case of breakdown.

Due to the very time consuming test procedure this method was not used for the tests with the heatable plate.

3.3. Breakdown test procedure using the heatable plate

For better comparison the tests with the heatable plate were performed with and without heating. The test procedure for the heatable plate was derived from [3] for breakdown (i.e., disruptive discharge). The principle of the test method is to make use of the up-and-down method with a certain number of equal voltage applications at a step in case of no breakdown. The number of the equal voltage applications n determines the disruptive discharge probability p according to:

\[ p = 1 - (0.5)^{1/n} \]  

For n = 1 the method delivers the widely used 50% probability and the voltage \( U_{50} \). The 50% probability is academically interesting but not very expressive as basis for a technical design. In contrast a low disruptive discharge probability would be very valuable for technical use but requires n values which would cause a large effort, e.g., for a disruptive discharge probability of 1% the number n is 69. For the breakdown tests with the heatable plate it was decided to select n = 4 and use the results for further withstand tests. With n = 4 the disruptive discharge probability is 16%.

The results are the number of k stress groups applied at the voltage levels \( U_i \). The first level to be taken into account is that at which at least two preceding groups of stresses have been applied. The total number of useful groups is m and the voltage step is dU. According to [3] the following selection was done \( m > 15, \ 0.01 U_{50} \leq dU \leq 0.03 U_{50} \).

\( U_i \) is the voltage at which the disruptive discharge probability is p. In case of \( p = 16 \) the voltage is \( U_{16} \), \( U^* \) is the estimate of \( U_i \). According to [3] the lowest voltage level taken into account should not differ from \( U^* \) more than 2 dU. Instead of just neglect values of test results which are not in agreement with this definition all values were still considered for the tests with Fatelini. In case of appearance of measurements which differ more than 2 dU the number of useful groups has been increased, i.e., more voltage applications were performed to obtain \( m > 15 \).

To clearly indicate that the test procedure is based on [3] but modified, the indication of the voltage derived from n = 4 is \( U_{16} \) instead of \( U_i \). (According to formula (1) for n = 4 the disruptive discharge probability \( p = 0.15910 \). It is not explained in [3] why p is taken as 0.15 instead of 0.16 which would be on the safe side for application, too.)

The minimum waiting interval between 2 voltage applications was 3 min if no breakdown occurred and 5 min if breakdown occurred.

3.4. Withstand tests

Appropriate distances were selected to withstand e.g., 360 kV derived from the voltage values which were delivered from the breakdown tests. The voltage was applied 20 times and the target number of breakdown was 1. The minimum waiting interval was the same as in section 3.3.
4. Results

Firstly, the non heatable plane was used to check the functionality of the facility and to find the technical relevant pressure range for the heating experiments.

Figure 2 and figure 3 show the results of the breakdown tests for both polarities with the non heatable plane at 0.1 MPa (abs.). The series with 8 mm distance of negative polarity contain only 2 breakdowns instead of 5 because no further breakdown appears till the maximum possible test voltage of 360 kV. Both pictures show an increasing of the mean breakdown voltages with the gap length which is linear till 4 mm and slightly decreasing for the longer distances. No polarity effect can be observed.

![Figure 2. Breakdown voltage $U_{b1^+}$ for 1 bar and positive polarity vs. gap length between sphere and non heatable plane. Unfilled circles show single breakdown events. Filled circles show the mean value of all 5 breakdowns at one specific gap length.](image)

![Figure 3. Breakdown voltage $U_{b1^-}$ for 1 bar and negative polarity vs. gap length between sphere and non heatable plane.](image)

Figure 4 shows the mean breakdown voltage vs. gap length depending on pressure and polarity. The pressure was varied in three steps 0.1 MPa, 0.2 MPa, and 0.3 MPa (absolute). The breakdown voltage is increasing with the gap length, namely linearly till a distance of 4 mm for all pressures and both polarities. Increase of the mean breakdown voltages with the pressure is observed for positive polarity only. But the data basis is too small to give a final statement and all mean breakdown values are below a linear increase for increasing pressure.

Derived from the results of figure 4 the gain of the dielectric strength by a pressurised system seems technically not so much important. It was therefore decided to perform further tests at about atmospheric pressure only. A valve which released the nitrogen gas and prevented pollution with air caused a cryostat pressure increase of about 60 hPa in addition to the atmospheric pressure.

Figure 5 shows the result of breakdown tests at 0.1 MPa with the heatable plate according to the up-and-down method with $n = 4$, resulting in a voltage with a disruptive discharge probability of 16%. All tests with heated or unheated plate show an increase of the breakdown voltage for both polarities with an increasing distance of the gap between sphere and heatable plate.
The heating caused a significant reduction of the breakdown strength of liquid nitrogen resulting in about a doubling of the gap length to keep the same voltage as in the unheated tests. Positive polarity shows higher dielectric strength in the unheated case and in the heated case for gap lengths of 10 mm or more, e.g. the difference of the breakdown voltage for the two polarities is at a distance of 10 mm in the heated case 9%.

Table 1 shows the results of withstand voltage tests with the non heatable plane at 0.1 MPa. The tests were performed only for the gap lengths from 8 mm on in steps of 2 mm.

Table 1. Withstand voltage tests with the non heatable plane at 0.1 MPa.

| Gap length | Number of breakdowns for positive polarity | Number of breakdowns for negative polarity |
|------------|------------------------------------------|------------------------------------------|
| 8 mm       | 0 at 300 kV                               | 0 at 280 kV                               |
|            | 3 at 320 kV                               | 4 at 300 kV                               |
| 10 mm      | 1 at 310 kV                               | 1 at 350 kV                               |
| 12 mm      | 0 at 360 kV                               | 1 at 360 kV                               |
| 14 mm      |                                          | 0 at 360 kV                               |
No clear polarity effect was found. No breakdown with the facility limit of 360 kV appeared for positive polarity at 12 mm and for negative polarity at 14 mm.

Table 2 shows the results of withstand voltage tests with the heatable plate at 0.1 MPa. The withstand tests were performed in a way to achieve the most suitable length for 1 breakdown of 20 lightning impulse voltages of 283 kV and 360 kV. 283 kV was selected for a possible later comparison with 200 kV AC which is the present limit of AC supply of the Cryogenic High Voltage Lab of the ITP. For the withstand tests without heating no polarity effect was found and the results are in adequate agreement with the values of table 1.

In contrast to the tests without heating a lower dielectric strength for negative polarity was found in the case with the 500 W heating impulses. In this case with the 500 W heating impulses a doubling of the distance for positive polarity was necessary to achieve about the same dielectric strength as in the unheated case - for negative polarity even more, but a distance increase to 250% was found to be sufficient.

Table 2. Withstand voltage tests with the heatable plate at 0.1 MPa.
20 standard lighting impulses were applied at a specific gap length

| Gap length | Number of breakdowns for positive polarity without heater | Number of breakdowns for positive polarity with heater | Number of breakdowns for negative polarity without heater | Number of breakdowns for negative polarity with heater |
|------------|----------------------------------------------------------|-----------------------------------------------------|--------------------------------------------------------|-----------------------------------------------------|
| 8 mm       | 1 at 283 kV                                              | 1 at 283 kV                                         |                                                        |                                                     |
| 10 mm      | 1 at 360 kV                                              | 1 at 360 kV                                         |                                                        |                                                     |
| 16 mm      | 0 at 283 kV                                              | 7 at 283 kV                                         |                                                        |                                                     |
| 18 mm      | 0 at 283 kV                                              | 11 at 360 kV                                        |                                                        |                                                     |
| 20 mm      | 1 at 360 kV                                              | 11 at 360 kV                                        |                                                        |                                                     |
| 25 mm      | 0 at 360 kV                                              |                                                      |                                                        |                                                     |

5. Conclusion
The test facility “Fatelini” allows the examination of the standard lightning impulse breakdown and withstand voltage of liquid nitrogen on a sphere to plate electrode arrangement under the influence of heating impulses. Initial tests with a non heatable sphere to plane arrangement have shown that a technical relevant increase of the dielectric strength cannot be expected for increasing the ambient pressure to 0.2 MPa or 0.3 MPa (absolute). Hence the tests were only performed at about ambient pressure. Heating caused a decrease of the dielectric strength of liquid nitrogen for all examined gap lengths rsp. voltage values. A multiplication of the electrode distance with the factor 2.5 can be recommended for technical application in case of a similar electrode arrangement and heating energy.

References
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