Superconductivity Centennial Conference

Studies of breakdowns in liquid nitrogen at different pressures between Rogowski electrodes

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Abstract

The usage of superconducting machines in the power grid or other high energy application makes it necessary that the machine can withstand all electrical stresses which can occur during normal operation and at transient overload. To guarantee a sufficient insulation, it is essential to know the properties of the insulating material. For HTS applications liquid nitrogen is a possible cooling and insulation liquid.

In this paper the influence of pressurized liquid nitrogen on the discharge voltage is observed. Therefore, a cryostat was used, that can be pressurized and the discharge voltages at 3 bar abs and 5 bar abs were investigated. The investigations were performed between Rogowski electrodes to guarantee a homogeneous electric field without discharges at the electrode edges. Experiments were done with gap distances up to 7 mm. The liquid nitrogen was stressed with lightning surge voltage of both polarities and AC ramp with a rise of 2000 V/s.

1. Introduction

Due to the high critical temperature of High-Temperature-Superconductors (HTS), liquid nitrogen can be used as coolant for superconducting devices. Often it is also used for electrical insulation. As coolant it is normal that the liquid nitrogen is heated up during normal operation. This heat input can get rather high, if the superconductor quenches. The heat leads to the creation of bubbles [1], [2]. The dielectric constant of gaseous nitrogen ($\varepsilon_r = 1$) is different from that of liquid nitrogen ($\varepsilon_r = 1.44$) [3]. The different dielectric constants result in an enhancement of the electric field in the bubble. In addition, the discharge field strength in the bubble is smaller than in the liquid. Therefore, the insulation properties of the liquid nitrogen diminish [2], [4-6]. To reduce the creation of bubbles, the liquid nitrogen can be pressurized [7-9]. This leads to a higher boiling point of the liquid. If the temperature remains at the lower value while
pressurizing the new boiling point will be above the temperature of the liquid itself and the gas bubbles will condensate faster. Besides bubble creation due to heated up materials, higher electric fields lead to more ionization which manifests itself as heat and could crate bubbles. [10, 11]. Therefore pressurizing also influence discharge behavior in liquid nitrogen without bubbles created by heated materials.

In this study, the discharge voltage of liquid nitrogen is investigated in a homogeneous electric field. The electrodes have a Rogowski shape. This shape avoids discharges at the edges of the electrodes, thus the discharges only occur in the homogeneous field. The pressure of the liquid nitrogen is varied from 3 bar$_{abs}$ to 5 bar$_{abs}$ to measure the influence on the breakdown voltage.

2. Experimental

2.1. Setup

The experiments were performed in a cryostat made of stainless steel. It has an inner diameter of 600 mm and an inner height of 800 mm. The cooling was done with a continuous flow cooling system. The flow rate of liquid nitrogen through the cryostat was 400 g/s at 77 K. The inlet of the liquid was the joint at the bottom of the cryostat (Fig. 1 (a) a). Fig. 1 (b) shows the electrode arrangement. The upper and lower electrodes (b) were mounted via support rods (c) which guaranteed the parallelism of the electrode surfaces to each other. The electrodes had a Rogowski shape at the edges to avoid discharges in this region. The Rogowski electrodes were designed to avoid discharges at the edges for a gap length up to 25 mm. The electrodes were of diameter 108 mm with a homogeneous region between the electrodes being of 40 mm. The gap distance was adjusted via a steel cable and a lifting spindle (Fig. 1 (a) d).

The arrangement was stressed with lightning surge and 50 Hz AC voltage. The lightning surge had a front time of 1.2 µs and a time to half-value of 50 µs. The determination of the discharge voltage was done with the up-and-down method. Thereby the first lightning surge voltage has to be so small that no discharge occurs. Then the voltage was raised in defined steps until a breakdown occurs. For the next test
the voltage was reduced by the defined voltage step. If no discharge occurred, the voltage was raised again. This procedure was done for another 30 tests. Because of the impossibility to measure the impulse crest value if the discharge occurred at the front of the wave, the crest value was calculated using the charging voltage of the capacitors of the impulse generator. Therefore a utilization factor was determined with the results of the measurements without a discharge. This utilization factor is calculated by dividing the impulse crest voltage by the charging voltage. After the measurements the average of the utilization factor was calculated and multiplied with the charging voltage. For the 50% discharge voltage the calculated impulse crest values of the 30 shots were averaged.

Before the start of the measurements the electrodes were conditioned with several lightning surge breakdowns. This is necessary because a rise of the discharge voltage could be observed for unused electrodes [12, 13].

3. Results

Measurements were done at a pressure of 3 bar$_{\text{abs}}$ and 5 bar$_{\text{abs}}$. Fig. 2 shows the results of the measurements. For a gap distance larger than 2 mm a constant value of the electric field strength can be observed for every voltage form. These constant values confirm the homogeneity of the Rogowski electrodes.

![Electric breakdown field strength for 3 bar$_{\text{abs}}$ and 5 bar$_{\text{abs}}$ ambient pressure](image)

The homogeneity of the electrodes is also confirmed with the appearance of the discharge tracks in the homogeneous area of the electrodes (Fig. 3 (a)) and with no visible polarity effect during the measurements with positive and negative lightning surge. The differences between the negative and positive lightning surge tests at 5 bar$_{\text{abs}}$ and the fluctuations at 3 bar$_{\text{abs}}$ are within the scatter of the data.
In Fig. 3 (b) a surface scan of the electrode can be seen. Due to the discharges several melting areas of the electrode surface are visible. The peaks and valleys have a height difference in the range of 20 µm. This roughness does not seem to influence the discharge behavior of the configuration permanently. The constant electric field strength for different gap distances is a good indication for this, because the measurements were done one after another without changing the electrodes or polishing the surface. During a test sequence the discharge voltages fluctuate for a constant electrode configuration. It is assumed that the protrusions on the surfaces, due to the discharges, have an influence on the fluctuations. If a larger protrusion is build due to a discharge, the next discharge voltage will be lower. But the next discharges will occur at this protrusion with a higher probability, so that the surface is melted again and the protrusion will be smoothed. Afterwards the discharge voltage will rise again.

At both pressures the discharge voltages of the test with AC ramp are below the values for the lightning impulse. The reason is that the rise time of the impulse waveform is 1.2 µs. Due to this the applied voltage can reach higher values until the streamer channel has been built up between the electrodes and the discharge occurs. Similar phenomena were observed in oil [14].

The discharge field strengths at 1 mm gap distance for AC voltage at 3 bar$_{abs}$ and 5 bar$_{abs}$ and for positive lightning surge at 3 bar$_{abs}$ are lower than at higher gap distances (Fig. 2). The reason could be particles on the electrodes, which weaken the dielectric strength of the arrangement [15]. Every time before the series of measurements started the particles were visible. In Fig. 4 these particles can be seen, which are assumed to be ice particles that deposit on the lower electrode when no measurements are performed. The source of the particles is not clear yet. Normally the liquid nitrogen cannot get in contact with air so that humidity can condense because of the continuous flow cooling system. Also during the cool down sequence a contact is not possible because first nitrogen gas is pumped through the cryostat to remove the air. During the first measurement the particles disappear so that they do not influence the next measurements. The three measurements, which are mentioned above were the first measurements in a series of measurements. The dissipation of the particles is probably caused by the blasts of the discharges. In any case the particles were not visible any more after the first measurement.
An explanation for the higher discharge field strength for the lightning surge tests at 1 mm gap distance and 5 bar$_{abs}$ can not be given at present.

![Fig. 4. Particles on the electrode surface](image)

Increasing the pressure from 3 bar$_{abs}$ to 5 bar$_{abs}$ leads to an increased discharge field strength. This effect is visible for all used voltage forms. For gap distances above 2 mm the enhancement of the discharge field strength is around 15% for lightning surge and AC tests (Fig. 5).

![Fig. 5. Enhancement of the discharge field strength](image)

At a gap distance of 1 mm the enhancements differ significantly. But this effect arises from the influences on the discharge field strength at 1 mm which are described before. At least for the positive lightning surge these influences enhance each other. The value at 3 bar$_{abs}$ is lower due to the particles on the electrode surface and the value at 5 bar$_{abs}$ is higher than normal. Therefore the quotient of both reaches a very high value in Fig. 5. Compared with literature values for similar arrangements, the measured results show a good agreement. In [16] a coaxial cylindrical electrode arrangement and in [8] a sphere plane arrangement were investigated. The reached enhancements are around 15% and 23%, respectively. The cylindrical electrodes had a rough surface. For cylindrical electrodes with a mirror finish the enhancement decreases, but due to the discharge tracks on the electrodes, used in our work, it is assumed that the comparison of the results for the rough surface for are more reasonable.
It is assumed that the reason for the enhancement of the discharge voltage with raising ambient pressure is the suppression of micro bubbles on the electrode surface. These bubbles will be created by high electric fields on the protrusions on the surface [16]. Because of the dependence of this effect on the electrode surface and unlike the volume it would explain that the enhancement is independent of the gap distance.

4. Conclusion

Measurements in a homogeneous field at ambient pressures of 3 bar$_{\text{abs}}$ and 5 bar$_{\text{abs}}$ were carried out. During the tests no polarization effect with positive and negative lightning surge could be observed and both values are higher than the values for the AC ramp. If the gap is varied, the measured discharge field strengths remain at a constant value. Due to the increase of the pressure the discharge field strength raises about 15% for each voltage form. An explanation is the suppression of the bubble creation at micro protrusions on the electrode surface.

In further work the pressure influence on the discharge voltage has to be investigated when the electrode is heated up and bubbles were actively created. It is assumed that the influence of the pressure on the discharge voltage will be higher if the amount of bubbles between the electrodes is larger.

References

[7] Seok BY, Komatsu H, Kushinaga M, Suehiro J, Hara M. Pressurizing and Sub-cooling Effects on Electrical Breakdown of LN2 in Modeled HTS Coil. IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 8, No. 6, December 2001