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Dielectric measurements on HTS insulation systems for electric power equipment

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Abstract

Since the development of flexible high temperature superconducting multifilament wires superconductive coils were constructed for the application in electric power equipment. The dielectric behaviour of conventional technology is well known, but this experience can only be partially applied to superconducting insulation systems. Some prototypes of cables, power and traction transformers and current limiters were built, but there is not sufficient knowledge about optimum dielectric structures and ageing. This paper gives a view to the criterions for liquid nitrogen as coolant and insulating medium of low temperature insulating systems for electric power equipment and shows the results of dielectric measurements tested with different structures.

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Keywords: Breakdown voltage; Partial discharge; Dielectric measurements; Liquid nitrogen; LN_2

1. Introduction

For the operation of high temperature superconducting (HTS) devices liquid nitrogen (LN_2) is necessary to cool the HTS conductor down to an operating temperature of about 77 K. The superconducting characteristic of ceramic HTS already occurs above 100 K. Depending on the application in electrical power systems and high voltage devices LN_2 is an attractive dielectric liquid for insulation purposes. Some prototypes of cables, power and traction transformers and current limiters were built, but there is not sufficient knowledge about optimum dielectric structures and ageing. Constructionally it is to differentiate between superconducting resources with warm and with cold dielectric. Resources with warm dielectric have a system separation between the HTS parts, which were cooled down on cryogenic temperature and other electrical components. Applications with cold dielectric uses LN_2 as insulating liquid. They are more cost-intensive due to the substantially larger cooling volume.

The aim for the measurements is to test different electrical insulating structures in specified LN_2, to observe the breakdown voltage and partial discharge behaviour.

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2. The insulation medium liquid nitrogen

Analog to conventional power equipment, e.g. transformers or cables, the insulating liquid has to fulfill several functions: insulation, cooling and impregnation. The maximum stress and life span on electrical machines depend on the quality of the used fluids. The necessary criteria, investigations methods and evaluation possibilities for the quality of the insulation liquid have to be developed. For conventional systems this factors and measuring methods are well known and determined in the relevant standards.

To the insulating liquid LN_2 it applies the appropriate criteria to find investigation and preparation methods. A substantial factor for the purity of LN_2 is the proportion, size and composition of particles. Most of this particles are ice crystals. Investigations at electrode configurations showed that the microscopically small ice crystals of a LN_2 enriched with humidity can clump and be formed to larger crystals. In dependency of the electrical field strength the particles can be charged, and they will align themselves in the electrical field. Similarly to the formation of particle bridges in oil it comes to the accumulation of ice particles between the electrodes.

From earlier investigations it is well known that the direct current conductivity of ice decreases below −100 °C strongly and the dielectric constant falls with −196 °C on ≈3. Ice is at very low temperatures an excellent insulator [1].

3. Specification of liquid nitrogen

Three classes of LN_2 were tested, a filtered, a pure and one ice particle enriched. The separation of the particles from the LN_2 may influence the long time behaviour. The filtration procedure is realized with a mechanical sinter glass filter, whereby porosity was selected according to ISO 4793 P16 or 10–16 μm. This porosity should guarantee a particle free LN_2 with an excellent dielectric behaviour. The pure LN_2 was taken direct from the tank of the producer. And the contamination with ice particles was simply done with enriching the LN_2 with air humidity.

4. Breakdown voltage measurements

The LN_2 is filled into a cryogenic test vessel wherein the electrodes are arranged (see Fig. 1). Using an automatic breakdown measuring instrument the test voltage is gained and applied into the cryogenic test vessel. The electrodes were in horizontal position according to EN 60156 valid for insulating liquids. Two spherical brass electrodes with 2.5 mm gap distance were used. A ramp shaped network-frequent alternating voltage (2 kV/s) was applied and the breakdown voltage values were recorded.

For the analysis and representation of the measurement results the two parametric Weibull distribution according to Eq. (1) with the parameters of Table 1 was consulted.

$$F(x) = 1 - e^{-\{(x-x_0)/(x_{63}-x_0)\}^{\delta}}, \quad x_0 = 0 \qquad (1)$$

In Fig. 2 the breakdown probabilities are represented in dependence of breakdown voltage. The evaluation of the measurements showed that the breakdown voltage for the humid LN_2 is 59 kV, for pure LN_2 62 kV and for the filtered LN_2

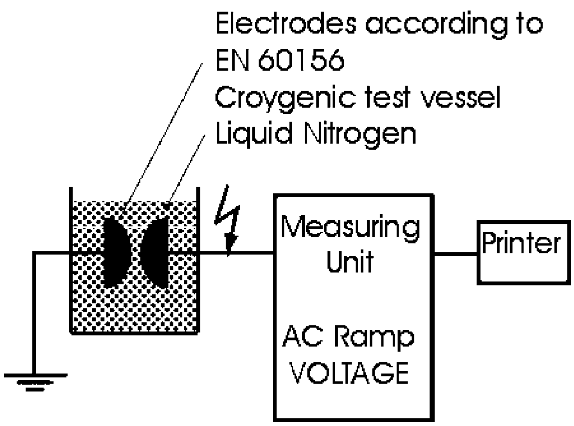

Fig. 1. Block diagram of the measuring circuit.

Table 1
Parameters of Weibull distribution

LN_2 class	x_{63}	δ
Humid	63.49	7.07
Pure	65.12	10.47
Filtered	63.44	10.12

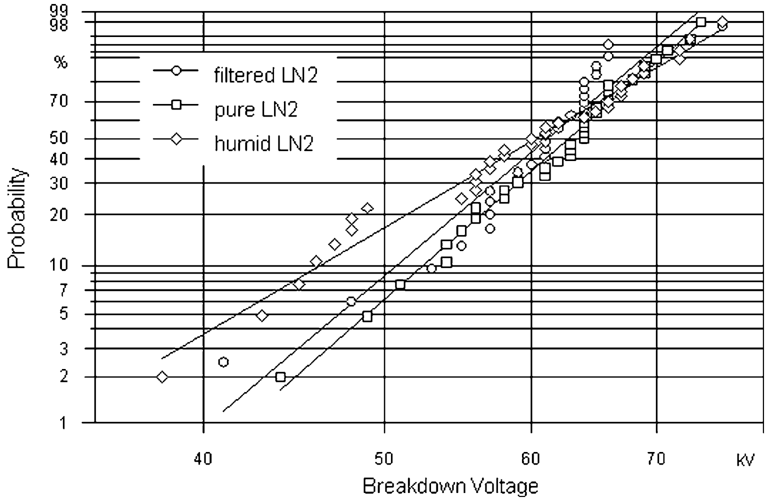

Fig. 2. Breakdown probability of different LN_2 classes.

61 kV. Taking a look to the upward grading of the approximation lines we can see that the grading of the humid line is very low and starting with very deep values. This means that very low but also very high breakdown values can be achieved depending on the flow conditions of the ice particles between the electrodes. This is the reason for a higher variance of distribution for humid LN_2 (9.5%) comparing to the other two classes (6.5%).

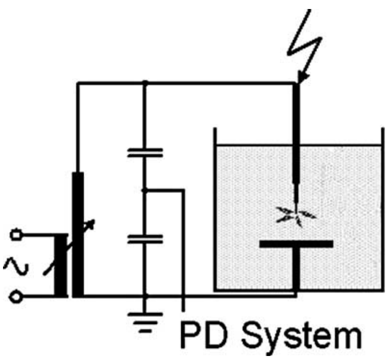

Fig. 3. Partial discharge measuring circuit.

5. Partial discharge measurement

The partial discharge behaviour is an important indicator for the condition of the insulation system of electrical power equipment. Using modern TE systems PD patterns can be taken and evaluated. Often PD monitoring systems are used for quality assurance and quality control during production process and operation period. In Fig. 3 the PD measuring circuit is illustrated. The test circuit according to IEC 270 is built up of a transformer, capacitive divider and the test arrangement in the cryogenic test vessel. The measuring signal of the PD system is coupled out by a quadrupole.

The PD characteristics of a needle to plane electrode arrangement with the three defined LN_2 classes were measured and evaluated by the PD system. In Fig. 4 the PD pattern of the needle to plane electrode arrangement is shown.

Rising the voltage up to the PD inception the basic noise level was under 2 pC for all LN_2 classes. The PD inception voltage in different LN_2 classes and arrangements of the needle position was between 35 and 40 kV. While the pure LN_2 had a constant PD level with an intensity of maximum 4 pC up to the breakdown voltage of 50 kV, the PDs of the humid LN_2 reached an intensity of 40 pC.

The PD impulses appeared in the negative and positive maximum of the sinus, which means that the PDs were external type.

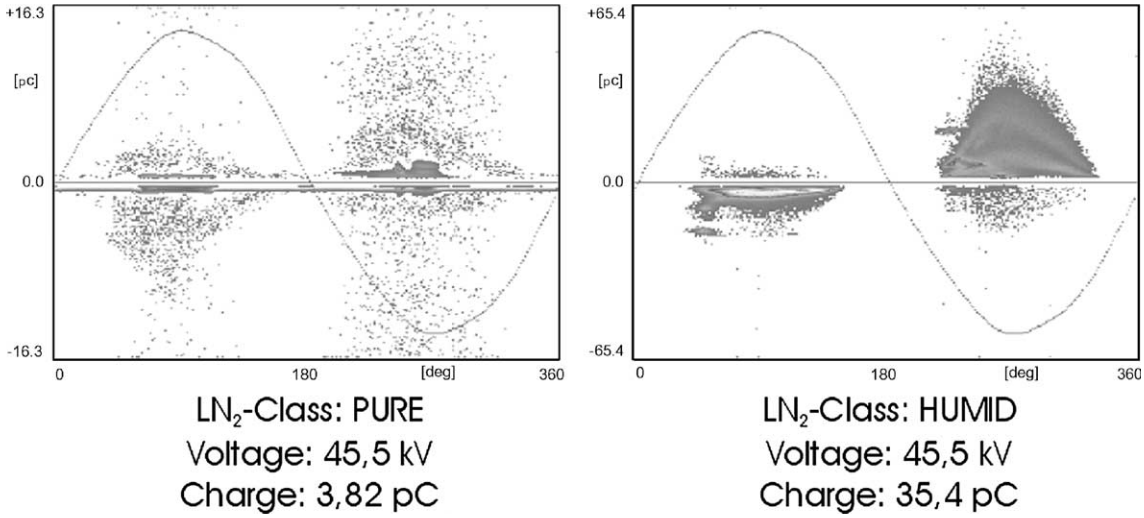

Fig. 4. PD fingerprint of a needle to plane electrode configuration with pure and humid LN_2.

6. Results

Liquid nitrogen can be used as cooling liquid and has excellent dielectric behaviour. The purity or the humidity content of LN_2 subjects similar considerations as valid for oil [2].

The breakdown measurements showed that the purity of the LN_2 can represent a criterion for the firmness of the insulation system and thus a factor of influence to the life span of HTS power equipment respective to the cryogenic insulation systems. The more ice particles in the LN_2 are the lower is the absolute breakdown voltage.

The partial discharge measurements showed that there is an influence of the LN_2 purity on the PD intensity but not to the PD inception voltage. The position and gap distance of an needle plane electrode configuration has no significant influence to the partial discharge inception voltage.

The cooling circuit of a superconducting device has to be sealed hermetically to prevent the purity of the liquid nitrogen and to achieve a long time stability of the dielectric characteristics of the electrical insulation system.

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