INVESTIGATION OF THE TEMPERATURE INFLUENCE ON THE BREAKDOWN VOLTAGE IN GAS INSULATED SYSTEMS UNDER DC VOLTAGE STRESS

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Abstract: During the last years, the technology of HVDC became increasingly important. In comparison to AC applications, the electrical DC field is controlled by the partially temperature-dependent conductivities of the insulating materials. During operation, the current-carrying conductor causes an inhomogeneous temperature distribution both along the insulator and in the gas compartment. To understand the influence of the temperature on the electrical field, both phenomena have to be investigated separately. Thus, this paper describes a method to calculate the breakdown voltage of a gas insulated system with heated electrodes, exclusively with respect to the effects in the gas. Finally, a decrease in the breakdown voltage caused by a lower gas density can be stated. Besides, additional measurements on an experimental test set-up confirm the calculation results.

1 INTRODUCTION

In order to transmit electrical energy over very long distances, the technology of high voltage direct current has become more important. Additionally, the need for space saving installations continues growing over the last years. Thus, gas insulated systems become more attractive for HVDC transmission. Their insulation represents a nearly uniform system in comparison to non-uniform air insulations. Therefore, well-known problems, e.g., surface charge accumulation or particles, are more critical using SF_6 under high pressure.

Reaching the steady state after energizing, the resistive field distribution is controlled by conductivities of epoxy (insulator material) and SF_6. The heating of the inner conductor due to operating and short circuit currents causes an inhomogeneous temperature distribution, influencing the local conductivity. Hence, the electrical field is transformed in a way that the location of the highest field strength is shifted. Consequently, the flashover behaviour of insulators under DC stress differs from the behaviour under AC or impulse voltage stress.

2 OBSERVED EFFECTS

In order to investigate the flashover performance of epoxy resin insulators under both DC voltage stress and inhomogeneous temperature distribution, the influencing factors have to be analysed separately.

Mainly three effects have to be considered:

- Space charge accumulation
- Temperature-dependent conductivity of the insulator
- Inhomogeneous temperature distribution

This paper is focusing on the effects caused by temperature. Before investigating the insulator with its field-inverting properties, the influence of the hot gas flow has to be understood. So the other effects are just described shortly.

2.1 Space charge accumulation

Due to applied DC voltage, the resistive field distribution is determined by the conductivities of the insulating materials. The behaviour of charge carriers at the interface gas / insulator seems to play a key role in understanding the possible decrease of dielectric strength [1]. Recently big efforts in calculating and measuring the surface charge density of spacers under DC stress were made, e. g. [2], [3], [4]. However, the described effects were not yet studied comprehensively in reference to the experimental breakdown voltage.

2.2 Temperature-dependent conductivity of the insulator

As already mentioned before, operating currents lead to an inhomogeneous temperature distribution between conductor and enclosure. Insulators, with their radial extension, experience all temperature levels. Since the conductivities determine the electrical field during DC operation, a special focus has to be set on the properties of the insulators. In the relevant temperature range the surface conductivity of epoxy resin is varying in order of magnitudes [5].

Investigations on cable insulations found the following correlation between DC conductivity and temperature [6]:

$$\kappa = \kappa_0 \cdot exp\left(-\frac{W}{k \cdot T} + \beta \cdot E\right) \qquad (1)$$

where: W = activation energy in J
E = electrical field strength in $kVmm^{-1}$
k = Boltzmann constant in JK^{-1}
β = coefficient in $mmkV^{-1}$
ϑ = temperature in °C
T = absolute temperature in K

For instance the bulk conductivity of the epoxy resin Voltalit in relevant ranges of T and E was in [6] referred as:

$$\kappa = 2 \cdot 10^{-20} \cdot exp\,(0.1 \cdot \vartheta + 0.08 \cdot E)\ \frac{S}{m} \qquad (2)$$

The conductivity of the insulator near the heated conductor is increasing. Hence, the location of the highest field strength is shifted to the enclosure; the distribution of the electrical field is inverted. Therefore it has to be investigated, how strong the influence on the breakdown voltage is.

2.3 Convective gas flow

Joule heating will lead to a certain temperature distribution between conductor and enclosure, as current is flowing in the busbar [7]. The main heat transfer mode is convection among radiation inside the vessel and radiation to the ambience [8]. In the vicinity of the conductor, where the flow velocity is around zero, there is also heat conduction. Even if the main gas flow is turbulent, the temperature distribution in this thin layer is determined by laminar flow [9].

It depends on different parameters, whether the temperature distribution will be homogeneous or inhomogeneous. The system’s boundary conditions determine the behaviour of gas pressure and gas density. In order to predict the breakdown voltage, the correlation between these properties and the dielectric gas strength has to be understood.

The following paragraph will first of all describe possible scenarios with different boundary conditions. Secondly the focus will be set on relevant cases of normal and failure operation.

3 POSSIBLE SCENARIOS OF GAS FLOW

3.1 Overview

With respect to the ideal gas law,

$$p \cdot V = n \cdot R \cdot T \qquad (3)$$

where: p = pressure of the gas
V = volume of the gas
n = number of moles
T = temperature of the gas
R = universal gas constant

it has to be distinguished between an isobaric (at constant pressure) or an isochoric (at constant volume) temperature rise. Furthermore it has to be stated, whether the temperature distribution is homogeneous or inhomogeneous.

The breakdown voltage can be calculated out of the electrical field distribution in the electrode system and the inner dielectric gas strength $E_{di}(x,y)$ as a function of the gas density $\rho(x,y)$ (Table 1).

Table 1: Possible scenarios of gas flow [10]

	isochoric	**isobaric**
homo-geneous	$\rho = \frac{m}{V} = const.$ $E_{di} = const.$	$\rho = \frac{m}{V} \sim \frac{1}{T}$ $E_{di} \sim \frac{1}{T}$
inhomo-geneous	$\rho(x,y) = \frac{p(\bar{T})}{T(x,y) \cdot R}$ $E_{di}(x,y) = E_{di,20°C} \cdot \frac{\rho(x,y)}{\rho_{20°C}}$	$\rho(x,y) = \frac{p}{T(x,y) \cdot R}$ $E_{di}(x,y) = E_{di,20°C} \cdot \frac{\rho(x,y)}{\rho_{20°C}}$

The cases of a homogeneous temperature rise in the complete volume are for the interesting dimensions of inner and outer radius (several centimetres) in a coaxial system not relevant. Thus, only inhomogeneous temperature distributions will be considered in this paper.

Since gas insulated systems are hermetically sealed, every process seems to be isochoric. With respect to this assumption, normal and exceptional cases of operation will be examined below.

3.2 Scenarios of temperature rise

During operation the inner conductor may reach temperatures around 100 °C (maximal temperature of electrical contacts under SF_6: 105 °C [11]) and will heat a bigger gas volume around. According to the rise of the average gas temperature, the gas pressure rises as well.

The convective gas flow with its inhomogeneous temperature distribution is causing differences in the gas density $\rho(x,y)$. It is assumed that the gas density around the hot electrode decreases and becomes the decisive factor for the discharge [10].

In order to calculate the breakdown voltage with the help of the streamer criterion, it is necessary to find out the dielectric gas strength along the possible discharge channel. As stated in Table 1, the distribution of the gas density, e. g. found by FEM calculations, has to be known.

In the case of normal operation (isochoric and inhomogeneous) two factors interfere with each other:

- Lower gas density (locally seen) is resulting in lower dielectric gas strength.
- Higher gas pressure is resulting in higher dielectric gas strength.

Sections 4 and 5 are considering this superposition exemplarily. It has to be discussed, whether the insulation strength of an HV device should be proved at highest expected conductor temperature.

Since the dielectric gas strength strongly depends on the gas density, it can be seen from Table 1 that the isobaric temperature rise is even worse than the isochoric: there is no increase of the gas pressure [10].

With respect to the completeness, two isobaric cases with certainly no relevance during normal operation have to be considered: hot spot and short circuit.

Screw and plug contacts exist between all the single components of a gas insulated system. In the unlikely event of a contact problem, a hot spot could occur.

The caused temperature rise would be strongly locally limited. Thus, a significant rise of the average temperature is not expected, the gas pressure is remaining at a constant level. The distribution of the gas density would be exclusively determined by the distribution of the temperature.

In principle, the short circuit current with a duration less than one second generates an adiabatic heating. Conductor temperatures up to 200 °C [12] may occur and heat up the first millimetres of gas around the conductor. The temperature rise can be considered as isobaric.

The dielectric gas strength in the vicinity of the hot electrode decreases proportional to the gas density, which is exclusively determined by the gas temperature.

Since short circuits and hot spots are not expected situations, further investigations in this paper will focus on the relevant case of normal operation.

4 EXEMPLARY CALCULATIONS

The simplest compartment of gas insulated systems is a coaxial cylinder arrangement. The electrical field distribution $E(x)$ is given by

$$E(x) = \frac{U}{x \cdot ln\frac{r_2}{r_1}} \quad (4)$$

where: U = applied voltage
r_2 = outer radius
r_1 = inner radius

It is possible to calculate the breakdown voltage with the streamer criterion:

$$\int_0^{x_c} \bar{\alpha}(x) = \ln 10^8 \approx 18.42 \quad (5)$$

where [13]:

$$\bar{\alpha}(x) = \frac{28}{kV} \cdot \left[E(x) - E_{di,20°C} \cdot \frac{\rho(x)}{\rho_{20°C}}\right] \quad (6)$$

The critical path length x_c to solve the integral of equation (5) is calculated out of

$$\bar{\alpha}(x) = 0 \quad (7)$$

at a given voltage. If the value of the integral exceeds 18.42, the applied voltage will lead to the breakdown.

The required distribution of the gas density can be calculated with FEM tools, like computational fluid dynamics (CFD). The example is carried out for the isochoric case (filled at 20 °C and 1 bar) of normal operation. Ambient and initial temperature is 20 °C.

The calculation is proceeded for electrode temperatures of 20 °C and 80 °C. After eight hours the temperature distribution with hot electrodes reaches the steady state. The gas pressure is rising from 1 bar to 1.09 bar, while the mean gas density is constant over time (Figure 1).

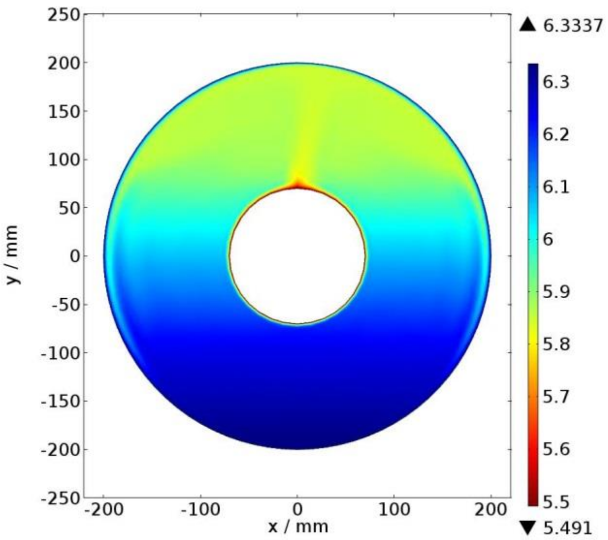

Figure 1: Gas density after 8 hours

The gas density along the line x = 0 is shown in Figure 2.

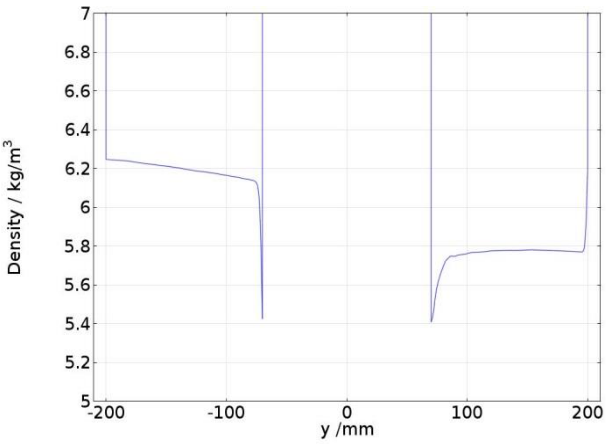

Figure 2: Distribution of gas density along x = 0

Under normal conditions, the density of SF_6 is 6.072 kg / m^3. The calculation results demonstrate the lower density around the heated conductor (down to 5.4 kg / m^3).

The distribution of the gas density in the first ten millimetres can be approximated with polynomial functions. With this, a decrease in the breakdown voltage by 5 … 8 % can be stated (Table 2).

Table 2: Calculation results with technical E_d

Electrode temperature	20 °C	80 °C
Breakdown voltage	503 kV x_c = 3,71 mm	y > 0: 460 kV, x_c = 0,31 mm y < 0: 486 kV, x_c = 1,91 mm

The distribution of the gas density differs over and under the hot electrode significantly. For triggering the discharge, only the field distribution on the first few millimetres is crucial. The mean gas density in the region of the critical path x_c is clearly lower than the density under normal conditions.

Figure 3 shows the density distribution in the region of the critical path length (less than 5 mm). It can be seen, that the density at $y < 0$ is rising very quickly to a normal level around 6 kg / m^3.

The density in the hot gas flow above the electrode is increasing very slowly. Only a short critical path length is necessary, to reach the number of 10^8 charge carrier in order to start the discharge process.

Obviously the discharge will occur in the area of the hot gas flow, where the density is wide-ranging low.

Additionally, it has to be mentioned that the lowest gas density appears in the area of the highest field strength. This combination is advancing discharge mechanisms.

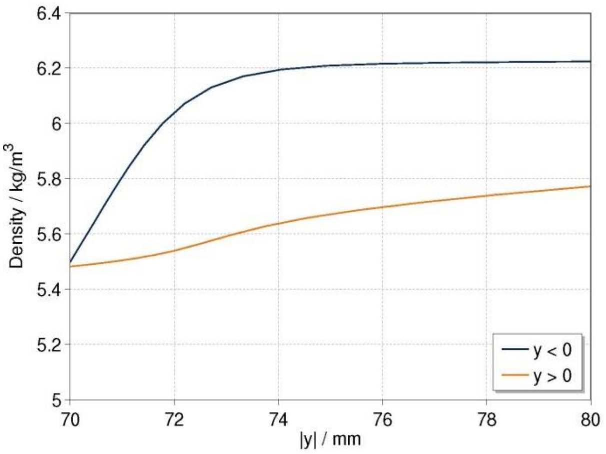

Figure 3: Distribution of gas density in the vicinity of the high voltage electrode along x = 0

This model is calculated in 2D with infinite length. Systems in practice are limited in their volume. It can be assumed, that real gas chambers lead to a higher mean pressure during operation. Thus, the density will not drop so strongly in a wide area. Hence, it is expected, that the breakdown voltage decreases not too significantly.

5 EXPERIMENTAL RESULTS

In order to investigate the flashover performance of epoxy resin insulators under both DC voltage stress and inhomogeneous temperature distribution, a special test vessel with electrodes was designed (Figure 4).

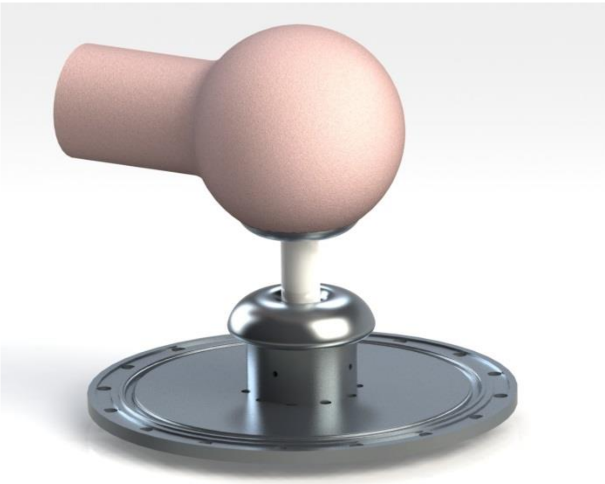

Figure 4: Test setup without enclosure

To learn more about the influence of the hot gas flow, the breakdown voltage was measured without the epoxy resin test specimen. Heating elements heated the electrodes up to ca. 95 °C. Table 3 contains the results in comparison to the non-heated state at 20 °C. A decrease in the breakdown voltage of 5.6 % was measured.

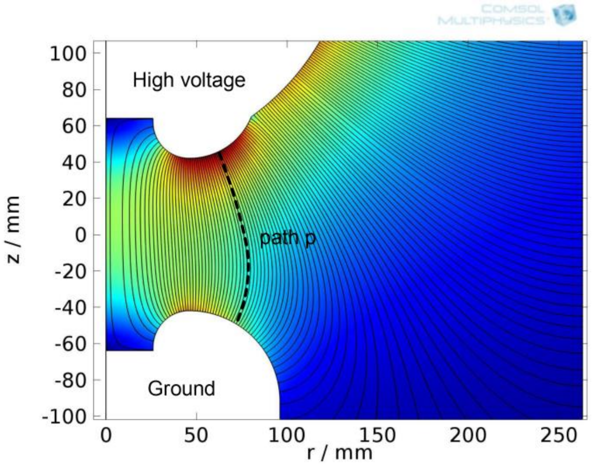

Figure 5: Electrical field strength and lines with the most probable path p for the breakdown

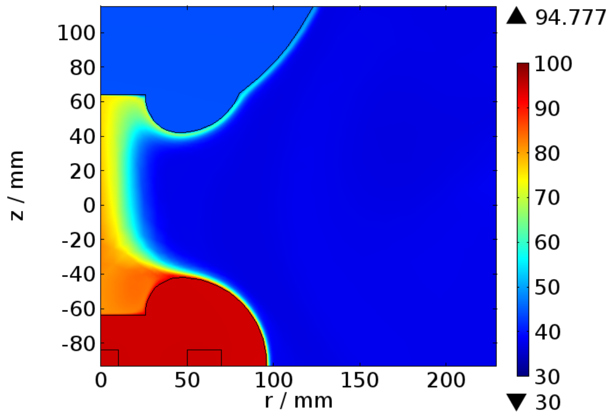

Figure 6: Temperature distribution (CFD) after 9 h

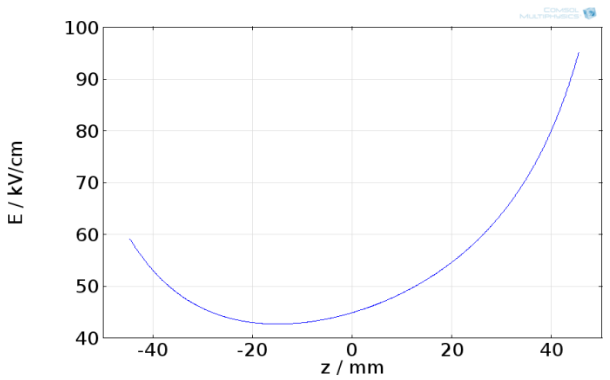

Figure 7: Field strength along path p

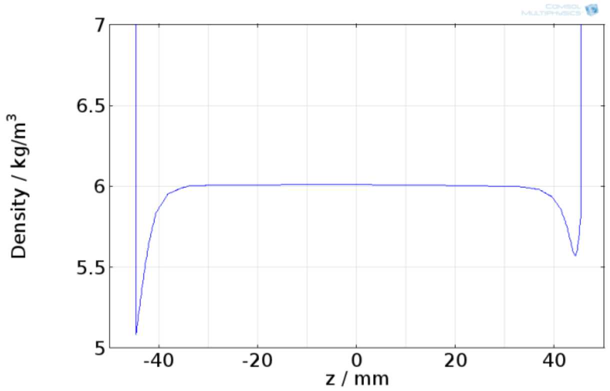

Figure 8: Gas density along path p

Table 3: Breakdown voltage of experimental setup

	Measurement	
Electrode temperature / °C	20	94.8
Breakdown voltage / kV	486	459

Using CFD simulation, it should also be possible to calculate the breakdown voltage.

As described in the exemplary calculations of the coaxial system, two input parameters along the most probable path of the breakdown are necessary:

- Distribution of the electrical field (Figure 5)
- Distribution of the gas density (Figure 6)

Along the path p, the field strength (Figure 7) and the gas density could be illustrated (Figure 8). The first few millimetres of both curves were approximated with polynomial functions, in order to calculate the breakdown voltage.

The degree of homogeneity η could be found by:

$$\eta = \frac{E_m}{E_h} = 0.61 \qquad (8)$$

where: E_m = average strength of the electrical field

E_h = highest strength of the electrical field

Thus, the inner dielectric gas strength E_{di} with respect to the existing electrode roughness could be evaluated as:

$$E_{di} = 83 \frac{kV}{cm} \qquad (9)$$

By applying the streamer criterion eq. (5) on the electrical field and the gas density along path p, the breakdown voltage can be calculated for an electrode temperature of 95 °C (Table 4) and compared with the measurement.

Necessarily, the calculation is proceeded for both possible directions: the discharge starts at the high voltage electrode or at the ground electrode, depending on gas density and field strength. Table **4** shows a much lower breakdown voltage of the discharge starting at the high voltage electrode, what confirms the measurement.

The electrical field strength at the high voltage electrode (y > 0) is so high, that the breakdown is initiating there, although the gas density is not as low as in front of the ground electrode.

In summary, it can be seen, that all possible starting points have to be considered, when coping with heated electrodes. In the described case, a symmetrical field strength could lead to a discharge, starting at the ground electrode.

Table 4: Breakdown voltage of experimental setup: measurement vs. calculation

	Measurement		Calculation	
Electrode temperature / °C	19	95.2	20	94.8
Breakdown voltage (starting at high voltage electrode) / kV	486	459	481	462
Breakdown voltage (starting at ground electrode) / kV	-	-	766	673

The results of measurement and calculation differ from each other only by a maximum of 1 %. So the method of calculating the breakdown voltage is suitable in the context of the applied conditions.

6 CONCLUSION AND OUTLOOK

This paper describes the influence of the hot gas in the vicinity of the conductor on the breakdown voltage. Therefore, different scenarios of gas flow are introduced. The most probable case for normal operation is at the focus of the outlined calculation method.

Necessary input parameters, like the electrical field distribution and the gas density, are extracted from FEM calculations. The breakdown voltage of both the non-operating and the operating (heated) state of the gas insulated system is predicted with the help of the streamer criterion.

Finally, the calculation method of predicting the breakdown voltage with hot electrodes is verified by several measurements on an experimental test setup. The good accordance between calculation and measurement leaves a certain understanding of the influence of the convective gas flow. It opens the possibility to turn towards the other well-known already shortly described effects (see section 2).

Further investigations will cope with the influence of the temperature-dependent conductivity, in order to examine the flashover performance of epoxy resin insulators under both DC stress and an inhomogeneous temperature distribution.

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