The effect of Low Temperature on the Role Played by Electrodes in Vacuum Breakdown

B. Mazurek

Technical University of Wroclaw, Wroclaw, Poland

ABSTRACT

Electrical breakdown requires the creation of plasma in interelectrode space. The electrodes are the source of plasma, but the more important dense plasma is created on the anode. In a system with an insulating spacer, the insulator material is the source of plasma. The cooling of the anode needs more energy for plasma creation. Similarly, cooling of the insulator part where the plasma is created increases the electrical strength.

1. INTRODUCTION

Vacuum is a good thermal and electrical insulator, and therefore, is often used in devices in which the two properties are important, *e.g.* cryo-electrotechnical or space equipment. The influence of low temperature on the vacuum breakdown and vacuum flashover has been frequently discussed in the literature. The results referring to the influence of low temperature on the vacuum breakdown voltage are much the same. The majority of authors agree that the effect of cathode cooling on breakdown voltage is insignificant. However, cooling of the anode considerably increases the electrical strength. There is much disagreement as to the influence of low temperature on the vacuum flashover voltage. The aim of the present paper is to show the mechanism of electrical discharge in vacuum, taking into account the temperature of electrodes. Such a generalization allows us to predict the behavior of the vacuum insulating system, and is of much use in designing such systems.

2. ELECTRICAL DISCHARGE IN VACUUM

The first requirement in the production of plasma in vacuum breakdown is the creation of a gaseous region which can be ionized through the action of the electric field. If the electrode surfaces are considered to be clear, then the source of the plasma must be the electrode material. At technical vacuum levels of 10^{-3} Pa, practical electrode surfaces are always contaminated by sorption products, gas molecules, water, *etc.* This contamination plays an important part in breakdown development, because with increased voltage, desorption around a cathode emitting site occurs. Plasma is created from this gas whose density is directly dependent on the adsorbed layers.

Breakdown, at room temperature, commences with field emission from the cathode. The field emission current brings an amount of energy to the anode surface. As was shown in earlier work [1], Fowler-Nordheim emission current is too small for the creation of anode plasma. the situation changes dramatically at the moment of the creation of the cathode plasma, because a new rich source of electrons exists to contribute to the bombardment of the anode surface. As electrons are ejected from the cathode plasma, positive ions remain near the cathode surface to enhance the local field. Plasma creation is accompanied by a rapid rise in current, and thermal distortion of emission sites takes place. The distortion results in the periodic extinction of the emission current, and thus cathode pulses are observed [2, 3].

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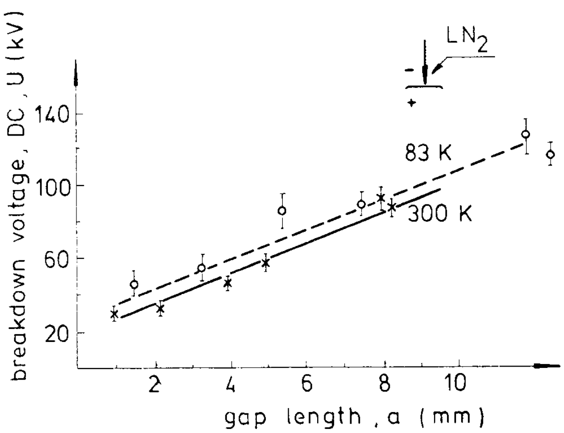

Figure 1.

dc breakdown voltage as a function of the gap length; point cathode temperatures 300 K and 83 K.

From such a picture of breakdown development there arise questions concerning the effects of electrode cooling. Cooling should increase the thickness of adsorbed layers. This, in turn, should increase the density of plasma and result in an incrtease of cathode pulse frequency. The emission centers on the cathode are heated in very short time periods of ~ 5 ns. With such short times, these centers are adiabatically insulated from the rest of the cathode. The expected higher pulse frequency is observed experimentally [3]. Therefore, the influence of the cooling of cathode on the vacuum electrical strength should be of no significance. This has been confirmed by the experimental results, *e.g.* Figure 1 [4].

Different considerations are involved in anode cooling. Once again the contamination layers should increase with cooling. On the application of voltage, Fowler-Nordheim emission from the cathode provides the anode with energy to create desorption, this is in fact what occurs and the anode is cleaned, leaving perhaps some traces of tenacious water molecules. At the moment cathode plasma appears, the emission current rises rapidly, and sufficient energy is supplied to the anode to melt and evaporate the material. The resulting dense anode plasma fills the interelectrode space. If we take into account a critical temperature T_c, at which the vapor pressure is high enough to create a condition for plasma, it is easy to calculate that at 300 K less energy is needed than that required if the anode is cold. The anode temperature could be described [5] by the Equation

$$T = \frac{2q}{\lambda}\sqrt{\frac{\alpha t}{\pi}} \qquad (1)$$

where q is the power density, α the thermal diffusivity, λ the thermal conductivity, and t the time. This is shown in the calculation made for a copper anode where at room temperature the critical power density is $q_{300} = 1.01\times10^7$ W/cm^2, while for an anode cooled with liquid nitrogen to about 80 K it is $q_{80} = 1.19\times10^7$ W/cm^2. It should be noted that power density is proportional to $U\,j$ where U is the applied voltage and j is the current density on the anode. The calculation shows that breakdown on a cooled anode occurs at a higher voltage. This is confirmed experimentally, Figure 2. However, the increase in the voltage needed for breakdown on a cold surface ie slightly less than expected and can be attributed to the accompanying increase in cathode pulse frequency and associated increase in effective current density.

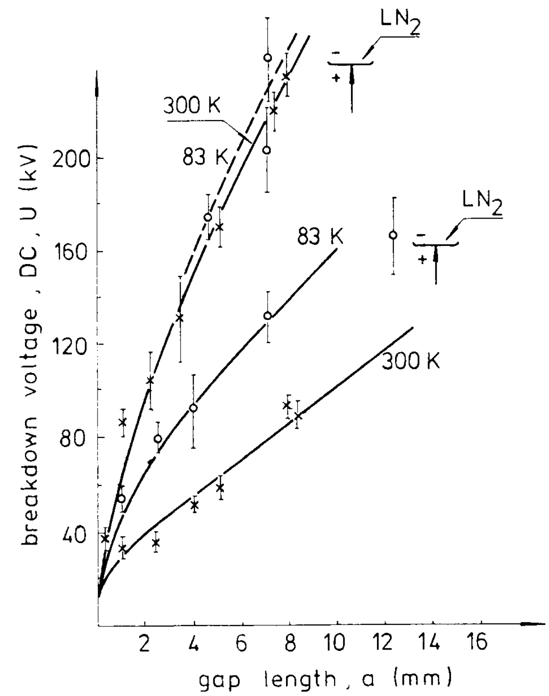

Figure 2.

dc breakdown voltage as a function of the gap length. Parameters: temperature of the plane electrode and polarity.

3. SURFACE FLASHOVER IN VACUUM

It has been shown in the preceding Section that the discharge development in the vacuum, without spacer, requires the creation of anode plasma which fills the interelectrode space. Due to this, the plasma creation from the cold anode needs more energy, and thus results in a higher breakdown voltage.

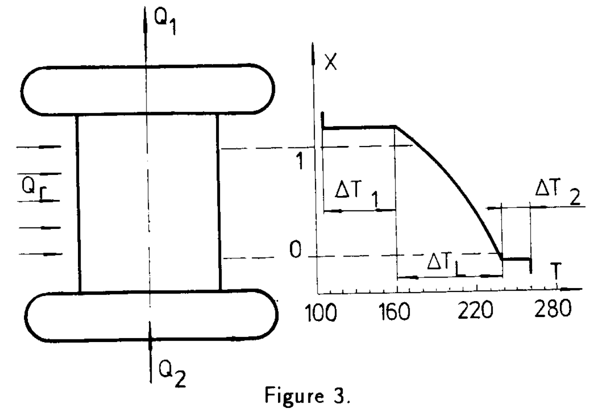

Figure 3.

Temperature distribution in the electrode/insulator system after 2 h of cooling with the influence of radiation on the side surface of the insulator taken into account [7]. Q_1: heat taken out by the cooler, Q_2: heat flowing to the system via a lower electrode lead, Q_r: radiation heat.

The situation changes if an insulator is placed between the electrodes. The decrease of the breakdown strength in the vacuum system with the spacer is caused by the fact that for the creation of insulator plasma less energy is required [6]. In this case the insulator plasma creates the breakdown. It can be expected that not the temperature of electrodes but rather that of the insulator influences the electrical strength.

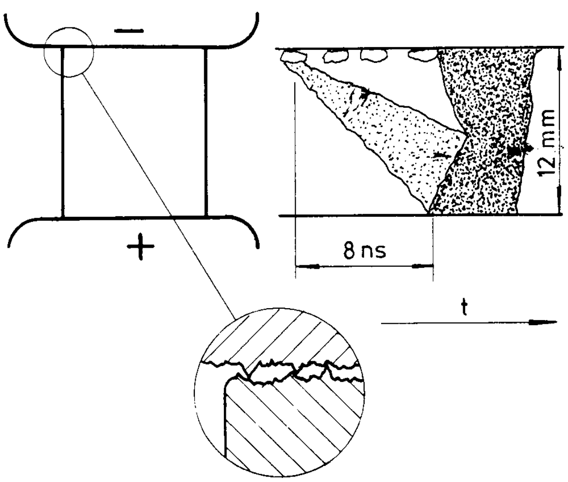

Figure 4.

A streak image of the surface flashover across high-density alumina.

On one-sided cooling of the electrode/insulator system, there occurs the temperature distribution as shown in Figure 3 [7]. It depends on the insulator/anode junction. Also the surface flashover mechanism depends on the electrode/insulator contact, especially from the cathode side (triple junction). With the simplest contact, the flashover is initiated by the plasma in the cathode triple junction, Figure 4 [7], which has also been proved by other authors, *e.g.* [9]. In this case, the cathode cooling brings about the cooling of the part of insulator part near the cathode. Therefore, the plasma creation in the cooled triple junction needs more energy, *i.e.* , higher breakdown voltage. It was proved in [7] that in such a system the cooling of the cathode to 80 K caused the following increments of the breakdown voltage: 20% at dc voltage and about 50% at impulse voltage.

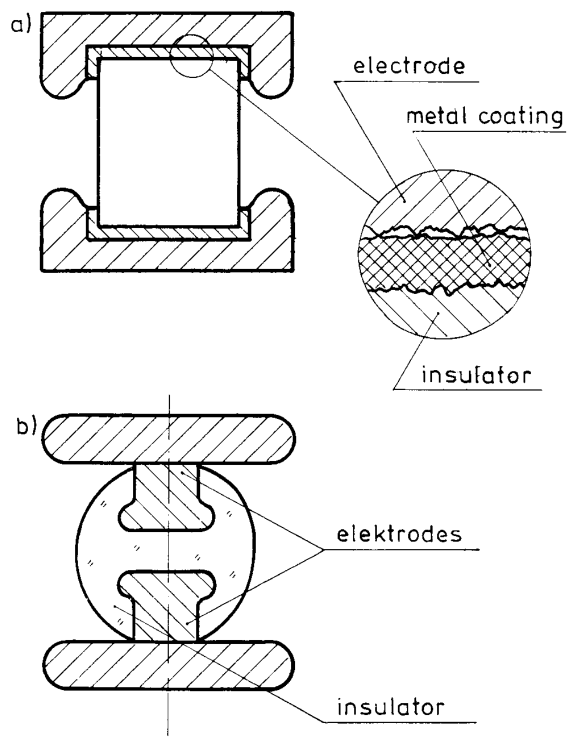

Figure 5.

(a): spacer insulator with metal, coated surface of contact, (b): spacer insulator with electrodes controlling the distribution of electric field.

The above mechanism changes if the triple junction is properly designed in order to eliminate the cathode plasma. This can be achieved by the metal coating of the insulator contact surface and special shaping of the cathode, Figure 5a, or special shaping of the insulator, Figure 5b.

4. CONCLUSIONS

THE electrical breakdown of vacuum insulation systems is connected with plasma creation in the interelectrode space. In vacuum without insulator spacer, the anode is the source of plasma. Therefore, the cooling of the anode increases the breakdown voltage. The influence of the cathode cooling on the breakdown strength is insignificant. Insulator material becomes the source of plasma if placed between the electrodes. The breakdown strength is increased if the part of the insulator in which the plasma is generated is cooled. If the plasma is created in a nonideal cathode triple junction the cooling of the system from the cathode side increases the breakdown strength. Metal coating of the insulator surface in the triple junction and proper design of the cathode shape eliminate cathode plasma creation. In this case the plasma is created at the anode side, and then the cooling from the anode side increases the breakdown strength.

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