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The role of microparticles in initiating the electric breakdown in high–voltage vacuum insulation systems

Władysław Opydo, Dawid Opydo
Poznań University of Technology
60–965 Poznań, ul. Piotrowo 3a, e–mail:Wladyslaw.Opydo@put.poznan.pl

Włodzimierz Bieliński
University of Science and Technology in Bydgoszcz
85–789 Bydgoszcz, ul. Prof. S. Kaliskiego, e–mail: Bielin@utp.edu.pl

The paper presents the hypotheses of initiating mechanisms of the electric breakdown in vacuum insulation systems caused by small material granules, i.e. the microparticles. The microparticles detached from the parent electrode have an electric charge and move in the inter–electrode area due to the electric field. The role of a microparticle in initiating the breakdown in a vacuum insulation system depends to a considerable extent on the microparticle energy at the moment of its impact against the opposite electrode, i.e. on its velocity at the impact time.

The paper presents calculation of the microparticle velocity values at the moment of the impact against the opposite electrode under the conditions existing in practice in the vacuum insulation systems. It was assumed for purposes of the calculation that the microparticles are spherical and made of copper, aluminum or iron, and are subjected to constant electric field. Minimum values of the microparticle velocity necessary to cause plastic deformation of the electrode surface in result of the impact are determined.

(The calculations have been carried out with the computer program developed in C# language on the Visual Studio 2013 environment.)

KEYWORDS: high–voltage vacuum insulation systems, metallic microparticles, electric breakdown

1. Introduction

A material granule located on the high–voltage electrode surface of an insulation system, or on a micro–unevenness of the surface has a certain electric charge due to the voltage applied to the system terminals. In result the electric force acts on it and detaches it from the parent electrode, attracting it to the opposite electrode. Once the force exceeds the adhesion force joining it with the surface, the granule or micro–unevenness is detached from the surface of the insulation system electrode and begins its journey towards the opposite electrode.

The surface of a carefully prepared electrode of the vacuum insulation system should be basically free of larger micro–unevennesses and material granules. Therefore, the phenomenon is limited only to the microparticles of micrometric dimensions.

The effects of microparticle motion in the inter–electrode area and their impacts against opposite electrode surface are basic phenomena for several hypotheses of initiating the electric breakdown in vacuum insulation systems [7, 8, 9]. They depend to a considerable extent on the kinetic energy of the microparticle at the moment of its impact against the opposite electrode. In consequence, they depend on electric field intensity in the system, on its distribution in the inter–electrode area, electric charge of the microparticle, its dimensions (inclusive of the mass) and its velocity at the moment of impact against the opposite electrode.

According to Menon and Srivastava [5] the microparticles occurring in the vacuum insulation systems may be divided into three groups, depending on their velocities at the moment of collision with the electrode:

- microparticles of low velocity, up to about 100 m/s;
- microparticles of medium velocity, from about 100 m/s to the speed of sound in the electrode material, i.e. up to about 4 km/s;
- microparticles of very high velocity.

Kinetic energy of the microparticles of low velocity in the insulation systems is not sufficient for non–elastic collision with the electrode surface. According to Olendzkaja [6] breakdown in an insulation system may be initiated by slow microparticles in result of extension of the discharge existing between the electrode and microparticle to the whole inter–electrode area. Such a discharge may arise once the microparticle approaches the electrode to several micrometers.

Moreover, the microparticle collision with the electrode reverses the polarity of microparticle electric charge. In result of elastic reflection from the electrode, during the second passage or further passages and reflections, the microparticle may accumulate higher energy, sufficient for inelastic collisions with the electrode surface.

The microparticles of medium velocities are distinguished by the velocities exceeding the one that is necessary to cause plastic deformation of the electrode surface. They may lead to electric breakdown caused by the collision with the electrode that may imply:

- formation of a crater and ejection of the electrode material in solid, liquid, or gas form;
- immediate plasma formation.

The craters formed on the cathode surface are good electron emitters in the field emission, due to their sharp edges.

The plasma formed in consequence of microparticle collision is a result of thermal ionization caused by kinetic energy of the microparticle released in the collision area.

The microparticles of very high velocities that occur in practical vacuum insulation systems have the radius below 0.01 μm. In result of their collision with the electrode surface they evaporate and contribute to a certain growth of metal vapour quantity in the vicinity of the surface. Nevertheless, this does not significantly affect the electric strength of the insulation system.

The first hypothesis related to breakdown initiation in vacuum insulation systems caused by the microparticles was formulated by Cranberg [2]. Cranberg assumed that the material nugget detached from the electrode may initiate the breakdown provided that the energy density in the area of the impact against the opposite electrode exceeds a certain critical threshold. However, he did not consider in details the whole mechanism of ionization development leading to the breakdown. Such an addition to the original hypothesis has been made by Slivkov [10] and Germain and Rohrbach [3]. These authors quantitatively analyzed the mechanism and verified it experimentally. It was assumed in both analyses that a charged microparticle of the electrode material, having very small diameter (about 10^{-7} m) and spherical or semi–ellipsoidal shape, accelerates in the electric field, collides with the electrode and evaporates. In the vapours originating this way from the collision area a microdischarge develops that is defined by the Paschen's law. Although the microdischarge may be damped with decreasing vapour pressure, caused by vapour expansion to the inter–electrode area, it may be assumed that the number of generated ions is sufficient to local heating of the electrode surfaces, evoking secondary emission, releasing the absorbed gases and even electrode evaporation. The processes occur in result of interaction of the ions accelerated in the electric field with the electrode surface. In the gases or electrode material vapours released from the electrode material a discharge and breakdown is initiated.

The review of breakdown initiation mechanisms presented above indicates that the type of the mechanism of the breakdown initiated by a charged microparticle depends mainly on its velocity at the time of its collision with the electrode, on its mass and, in consequence, its radius. Fig. 1 schematically presents the velocity ranges of spherical microparticles and approximate ranges of their radii, corresponding to particular breakdown initiation mechanisms [7].

The present paper includes the results of microparticle velocity calculations in the conditions of electrically stressed practical vacuum insulation systems. It was assumed that the calculation is to be carried out for the insulation systems with macroscopically uniform electric field, while the spherical microparticles are made of copper, aluminum, or iron, i.e. of the chemical elements usually used for the parts of the high–voltage insulation systems or being the main components of the materials used for these parts.

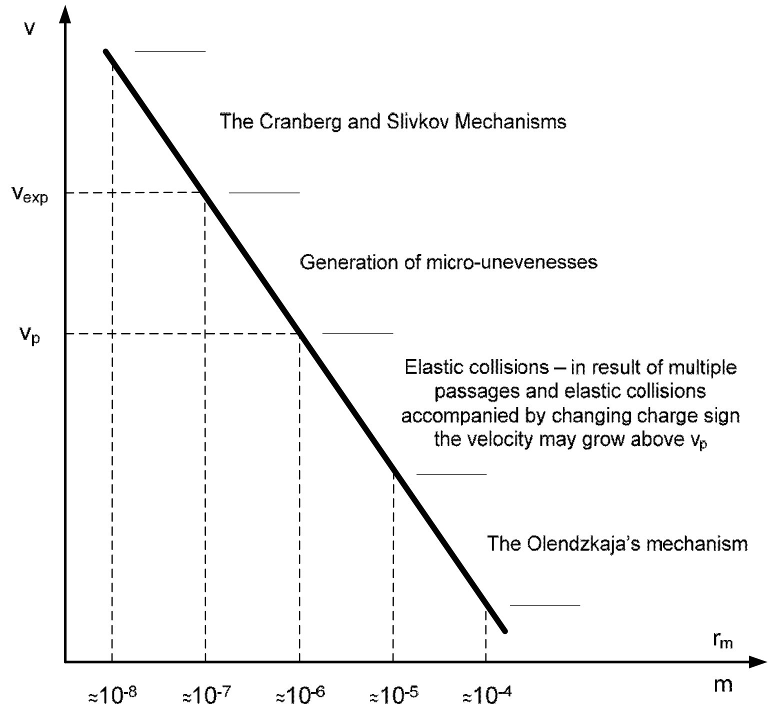

Fig. 1. Schematic presentation of dependence of the velocities of spherical microparticles on the ranges of their radii corresponding to various mechanism of the breakdown initiated by the microparticles in vacuum; v_p – critical velocity necessary to invoke plastic deformation of the electrode surface; v_{exp} – minimum velocity necessary to explosive evaporation; r_m – microparticle radius [7]

For computation purposes a computer program was used that was developed in Visual Studio 2013 in programming language c#.

2. Basic relationships

Microparticle of spherical shape located on planar surface of the electrode has the electric charge [4]

$$Q = \frac{2}{3}\pi^3 \varepsilon_0 r_m^2 E_0 , \tag{1}$$

where: ε_0 – permittivity of free space, r_m – microparticle radius, E_0 – average macroscopic electric field intensity near the electrode surface.

Hence, the microparticle is subjected to electrostatic force detaching it from the electrode surface. When the force exceeds the electrode adhesion force, the microparticle is detached and accelerates towards the opposite electrode. The energetic balance (the energy supplied by electric field to the microparticle becomes its kinetic energy) causes that in the time of collision with the opposite electrode the microparticle velocity is equal to

$$\upsilon = \left(\frac{2QU}{m} \right)^{1/2}, \tag{2}$$

where: Q – microparticle charge, U – voltage at the system terminals, m – microparticle mass.

In case of an insulation system subjected to macroscopically uniform field $E_0 = U/d$ (with d being the inter–electrode gap) substitution of the formula (1) into (2) and $m = (4/3)\pi r_m^3 \delta_m$ (where δ_m is the microparticle material density) gives the following formula determining microparticle velocity at the time of its collision with the opposite electrode:

$$\upsilon = \pi U \left(\frac{\varepsilon_0}{r_m \delta_m d} \right)^{1/2}. \tag{3}$$

In order to cause plastic deformation of electrode material the velocity of the colliding microparticle must exceed the critical velocity of plastic deformation of the material. It is equal to the lowest speed of a part of the material that causes its plastic deformation. It may be calculated from the formula [1]

$$\upsilon_p = \left(\frac{8R_e}{\delta_e} \right)^{1/2} \tag{4}$$

where: R_e – yield point of the electrode material, δ_e – density of the electrode material.

The formulae (3) and (4) enable to formulate the following formula, allowing to determine maximum value of a spherical microparticle radius causing plastic deformation of the electrode material:

$$r_{mk} = \frac{\pi^2 \varepsilon_0 \delta_e U^2}{8R_e \delta_m d} \tag{5}$$

An assumption that the microparticle and the electrode are made of the same material ($\delta_e = \delta_m$), allows to simplify the formula (5) to the form:

$$r_{mk} = \frac{\pi^2 \varepsilon_0 U^2}{8R_e d} \tag{6}$$

3. Results of the calculation

The values of density and yield points of copper, aluminum and iron, used for the calculation purposes, are shown in Table 1.

Table 1. Specification of the material data – values of density and yield points of copper, aluminum and iron

Type of the material	Material density (δ)	Material yield point (R_e)
Copper	8933 kg/m^3	35 MPa
Aluminum	2720 kg/m^3	60 MPa
Iron	7875 kg/m^3	185 MPa

Substitution of the material data specified in Table 1 into the formula (4) enabled to calculate critical velocities of plastic deformation of copper, aluminum and iron. They have the following values: v_{pCu} = 177.0 m/s, v_{pAl} = 420.1 m/s, v_{pFe} = 433.5 m/s.

Formula (3) served for determining the relationships between the speed of a spherical microparticle at the time of its collision with the opposite electrode and its radius. These relationships are presented in Fig. 2.

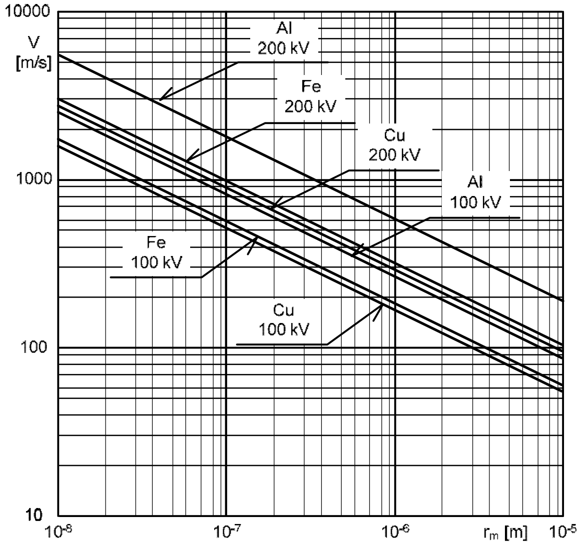

Fig. 2. Relation between the velocities and radii of spherical copper, aluminum and iron microparticles at the time of their impact against the opposite electrode surface, in case of a vacuum insulation system with electrode gap equal to 5 mm, for 100 kV and 200 kV voltage

They were defined for the insulation systems in which the electrodes and microparticles are made of the same material (i.e. copper, aluminum or iron), with the electrode gap equal to 5 mm and the voltage at the system terminals equal to 100 kV and 200 kV.

For purposes of analyzing the breakdown initiation mechanisms in the vacuum insulation systems the relationship between the maximum microparticle radius able to induce plastic deformation of the electrode surface and the voltage at the system terminals is very useful. Such a relationship has been determined with the use of the formula (6) and presented in Fig. 3. It was assumed for purposes of the calculation that the electrode gap is equal to 5 mm and the microparticle and system electrode bombarded by it are made of the same material (i.e. copper, aluminum or iron).

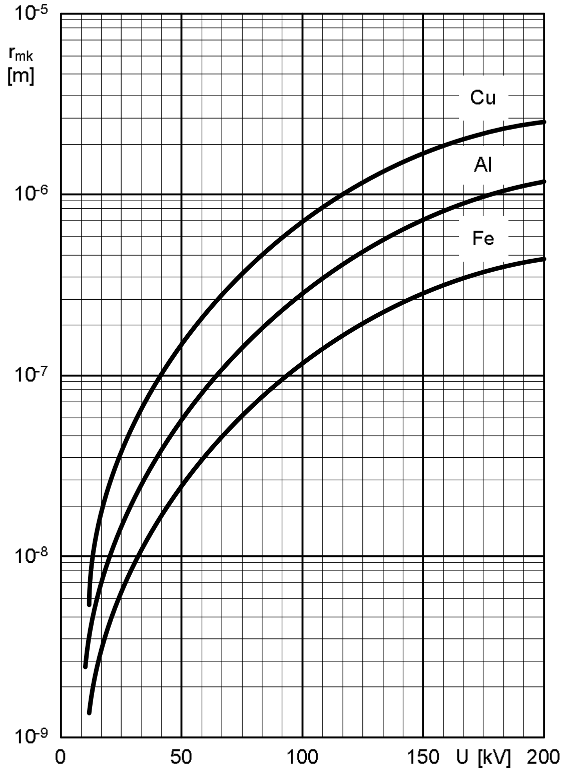

Fig. 3. Relation between maximum radius of a spherical microparticle causing plastic deformation of the electrode surface of a vacuum insulation system and the voltage occurring at the system terminals, both the microparticle and the electrode are made of the same material (i.e. copper, aluminum or iron), with the electrode gap equal to 5 mm

Comparison of the characteristics shown in Fig. 2 to the calculated critical speeds of plastic deformation of the electrode materials shows that in case of voltage of 100 kV the largest copper spherical microparticle able to deform a copper electrode surface has the radius 0.6 μm. The radius of a similar aluminum microparticle in the same conditions is equal about to 0.3 μm, while in case of an iron microparticle in the system provided with iron electrodes is equal about to 0.1 μm.

In case of the voltage 200 kV the largest spherical copper microparticle able to deform the copper electrode surface has the radius of about 3 μm. Radius of an aluminum microparticle exerting a similar effect in the system provided with aluminum electrodes amounts about to 1μm, while in case of an iron microparticle in the system provided with iron electrodes is equal about to 0.5 μm.

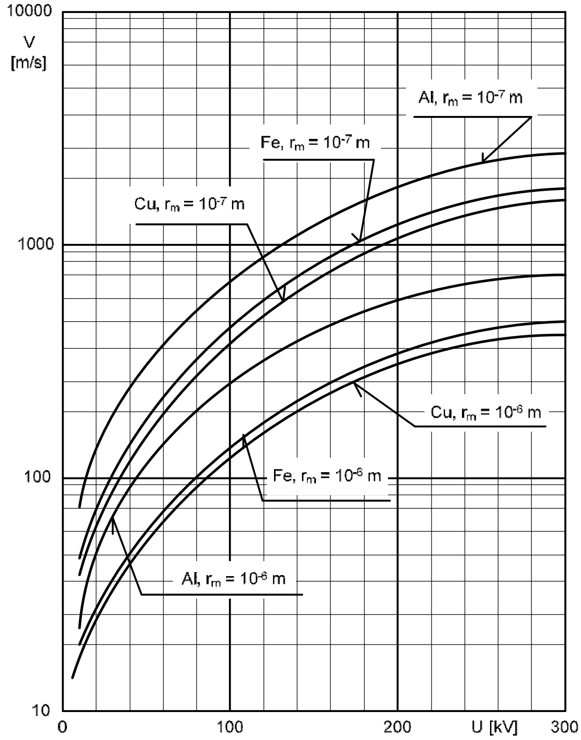

Fig. 4. Relation between the velocities of spherical copper, aluminum and iron microparticles of the radii 10^{-6} m and 10^{-7} m at the time of their impact against the opposite electrode surface and the value of the voltage existing at the terminals of a vacuum insulation system with electrode gap equal to 5 mm

In the next Figure 4 the relations between the velocities of spherical microparticles at the time of their impact against the opposite electrode surface and the voltage at the system terminals are presented. These relations are determined based on the formula (3), assuming that both the electrodes and spherical microparticles (having the radii 10^{-6} m and 10^{-7} m) are made of the same material (i.e. copper, aluminum or iron), with the electrode gap equal to 5 mm. Fig. 4 shows that for the voltage equal about to 70 kV, i.e. the average value of the electric field in the inter–electrode area equal to $E_0 = U/d =$ 14 kV/mm, the spherical microparticles of 10^{-6} m or smaller radius hit the opposite electrode with the velocity exceeding 100 m/s.

4. Conclusions

The paper provides the following conclusions that are important for the analysis of the vacuum high–voltage insulation systems:

1. Critical plastic deformation speed of copper, aluminum and iron, defined as the lowest speed of a material part, necessary to cause its plastic deformation, is equal to 177.0 m/s for copper, 420.1 m/s for aluminum and 433.5 m/s for iron.
2. For the voltage of 100 kV existing at the terminals of a vacuum insulation system with 5 mm inter–electrode gap the largest copper spherical microparticle able to deform a copper electrode surface has the radius about 0.6 μm. The radius of similar aluminum microparticle in the same conditions in the system with aluminum electrodes amounts about to 0.3 μm, while for an iron microparticle in the system provided with iron electrodes it is equal about to 0.1 μm.
3. For the voltage of 200 kV occurring at the terminals of a vacuum insulation system with 5 mm inter–electrode gap the largest copper spherical microparticle able to deform a copper electrode surface has the radius about 3 μm. The radius of similar aluminum microparticle in the same conditions in the system with aluminum electrodes amounts about to 1 μm, while for an iron microparticle in the system provided with iron electrodes it is equal about to 0.5 μm.
4. In case of an insulation system with 5 mm inter–electrode gap and the voltage equal to 70 kV, i.e. for the average value of the electric field in the inter–electrode area equal to $E_0 = U/d = 14$ kV/mm, the spherical microparticles of 10^{-6} m or smaller radius made of copper, aluminum or iron crossing the inter–electrode area hit the opposite electrode with the speed exceeding 100 m/s.

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