CHARGE ACCUMULATION ON SLIGHTLY CONDUCTIVE BARRIER SYSTEMS AND ITS EFFECT ON BREAKDOWN VOLTAGE IN AN AIR INSULATED ROD PLANE ARRANGEMENT

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Abstract. The barrier effect has been known since the 1930's. It is of great importance in the field of high voltage engineering as the breakdown voltage of an electrode arrangement can be increased significantly when dielectric barriers are applied. Nevertheless, an exact and general valid physical model explaining the barrier effect in gaseous, liquid and solid insulation systems is still not known. For gaseous insulation systems, the Marx-Roser model is widely accepted for explaining the barrier effect. The Marx-Roser model explains the barrier effect by a redistribution of the electric field in the gap. This redistribution is due to the space-charge field in front the tip but also due to the surface charge field formed on the barrier. This leads to a higher breakdown voltage of the system. In a recent publication of the authors, it was shown that the surface resistance of the barrier has a huge impact of the breakdown performance of the barrier arrangement. The breakdown voltage of the system decreased when the surface resistance of the barrier was decreased over a value of around 10^7 Ohm.

To investigate this effect, the surface potential due to accumulated surface charges on the barrier surface was measured for three different values of barrier surface resistance. It was shown in the experiments that at lower values of surface resistance, less surface charges are accumulated at the barrier surface. This leads to a decrease of the field reduction effect between high voltage electrode and barrier surface and might result in lower breakdown values of the system.

Keywords: Barrier, conductivity, breakdown voltage, surface charge, space charge, charge accumulation.

1 Introduction

The effect of barrier systems on breakdown performance of electrode systems has been known for a long time. First reports about the barrier effect have been published by E. Marx and H. Roser when they studied air gap discharges in the 1930’s using AC, DC and lightning impulse voltages (LI) [1, 2]. These early publications explain the barrier effect in gases with the redistribution of the electric field in the gap [1-3].

In gaseous insulation systems, the model from Marx and Roser is still used today by many authors to explain the barrier effect. It has also been used as explanation for insulation systems consisting of liquid and solid dielectrics [4, 5]. At present, there are various other hypotheses trying to explain the barrier effect in insulation systems. Inhomogeneous polarization or electro-physical characteristics of the main and barrier materials are suggested in literature [6].

According to [6], the Marx-Roser model can only explain the barrier effect in rather short gas gaps. The theory does not apply for longer gas gaps, liquid dielectrics or solid arrangements. This is explained by the drift velocity and free path length of the charge carriers being too slow or small to form a significant surface charge layer on the barrier within the by the Marx-Roser model required time frame [6]. However, in a recent publication [7] it was shown that the saturation charge levels on dielectric barriers in air can be reached in a few tens of nanoseconds of exposure to positive streamer channels [7]. So according to [7] the Marx-Roser model can also be applied in longer gas gaps like presented in this study.

According to [6], an exact and generally valid physical model explaining the barrier effect is still not known. In a recent publication [8], the influence of the surface conductivity of the barrier on the withstand voltage was investigated. Following the qualitative explanation provided by the Marx-Roser model the value of the surface conductivity of the barrier has a significant influence on the withstand voltage of the whole system.

In [8] and [9], it was shown that the withstand voltage of a single barrier system decreases when the conductivity of the barrier surface increases. A theory to explain this measured effect was proposed in [9]. According to this theory, when a certain conductivity of the barrier is exceeded, the charge at the barrier is distributed faster at the surface due to the smaller resistance and the barrier behaves as a floating electrode.

A dielectric surface can only be charged up to the saturation level [10]. At saturation the amount of accumulated surface charges is so large that the normal component of the electric field is compensated and the surface charging stops. This saturation charge level is strongly dependent on the surface conductivity of a dielectric barrier and according to [1] and [2] may influence the breakdown performance of the system. This effect has to be investigated in further detail.

To investigate this theory the surface charge on the barrier surface has to be measured. In particular, the goal of experiments is to confirm if the accumulated surface charge is reduced for decreased surface resistances, which may finally result in lower field reduction at the electrode and a lower breakdown voltage.

2 Theoretical Background

In Fig 1 results from [8] are presented. In this publication it was shown that with decreasing surface resistance the breakdown voltage of the single barrier system decreased as well.

These results can be explained with two different approaches.
The Marx-Roser model explains the barrier effect with the creation of space charges due to ionization near the electrode tip and accumulation of surface charge on the barrier. In case of positive tip, fast electrons will move towards the positive tip. The remaining slower positive space charges drift in direction of the field and accumulate at the barrier surface. This might result in a reduction of the electric field and consequently in an increase of the breakdown voltage [1, 2, 6]. Because less surface charge is trapped at the barrier surface with the decreasing surface resistance less field due to the surface charge is accumulated at the barrier surface. As a result, the overall electric field in the gap between barrier and high voltage electrode gets higher with decreasing surface resistance.

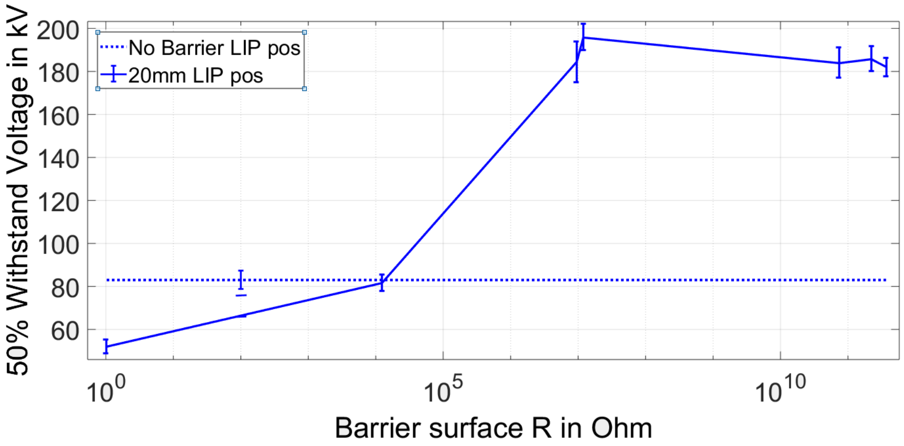

Fig. 1. 50% withstand voltage at positive lightning impulse (LI) stress depending on the surface resistance of the barrier. The dotted lines represent the breakdown voltage of the 80mm gap without barrier. The solid line is for positive LI, data taken from [8]. Note: The experiment shown here has been performed for the same electrode configuration as described in section 3, but with a barrier size of 525x700 mm.

Another approach to explain the results from [8] can be derived from a model introduced in [10]. This model is based on streamer propagation stability field in combination with a saturation charge model of the dielectric surface.
In general, the value of the accumulated surface charge on a dielectric barrier depends on the discharge behavior around the electrode and of the surface conductivity of the barrier. Both factors can have significant impact and make the problem very complex. This complexity can be avoided when only the most extreme case of surface charging is considered. The most extreme case is charging till saturation with a very high (or infinite) surface resistance. In this saturation case, the amount of the surface charge is so large that the normal component of the electric field pointing from the barrier out in the air, E_{nAir}, is zero. As a result no field line ends on the surface anymore. So further charge accumulation at the barrier is not possible and the charging of the barrier surface

stops. This model has been introduced in [10] and experimentally confirmed in [11] and [12].

According to the stability field model [10] the lowest voltage in kV that enables a breakdown of an air gap larger than 40 mm with inhomogeneous electric field can be expressed as [10]:

$$U_{ws} = U_0 + d\,E_{st} \tag{1}$$

where U_{ws} is the withstand voltage, d is the distance between electrodes in mm. E_{st} is the internal field strength in kV/mm along the positive streamer behind its head, and has the same value as the required external field for stable streamer propagation (stability field). A voltage of $U_0 \approx 20\text{-}30$ kV is equivalent to the potential of the streamer head needed to generate a breakdown. The value of E_{st} is in the range of 0,54 kV/mm for positive impulse [10].

Equation (1) can be applied not only for straight gaps between electrodes but also for arrangements where the streamer propagates parallel to dielectric surfaces or has to bypass dielectric barriers like it is present in this study [10]. In such cases, the distance d in (1) represents the clearance between electrodes (the closest connection in air between the rod tip and the grounded plate).

With this model it is possible to roughly calculate the high values of breakdown voltage for high surface resistance cases in Fig 1.

3 Methods

3.1 Experimental Setup

To measure the effect of accumulated surface charges on a barrier, a vertical single barrier arrangement between a high voltage rod electrode and a grounded plate electrode was used The dimensions used were similar as in [8], see Fig 2. The grounded plate electrode is made of copper and measures (height x width) 1100 x 1000 mm. The barrier material and dimensions were a little different as used in [8]. As barrier, a 5 mm PMMA ("Plexi glass ®") plate with dimensions 400 x 600 mm was used. The high voltage rod electrode is made of alumina and has a radius of 7 mm. It is 260 mm long and the tip is rounded with a radius of 3.5 mm. The tip of the high voltage electrode was positioned in the middle of the barrier at a z position of 200 mm and a x position of 300 mm. A 200 mm toroid was used as well to guard the connection of the high voltage electrode.

As gap distance of 80 mm is chosen between the tip of the high voltage electrode and the ground electrode. The barrier is positioned 20 mm in front of the high voltage electrode.

The experiments presented in this paper were conducted with positive lightning impulse voltage. An eight stage 800 kV, 40 kJ Marx generator was used to create 1.2/50µs lightning impulses (LI). The earth current was monitored using a Pearson 6585 current monitor to ensure that there was corona inception at the high voltage electrode during the lightning impulse.

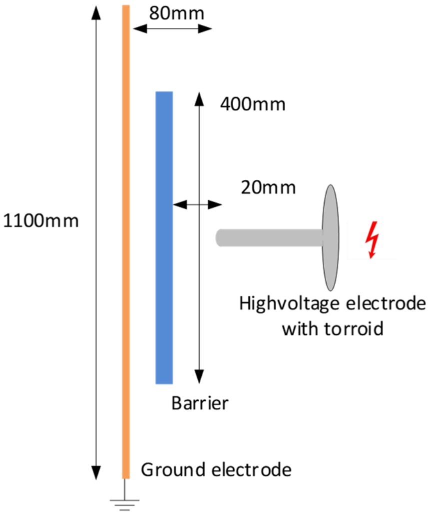

Fig. 2. Dimensions of experimental set up seen from the side with high voltage electrode, 5 mm PMMA barrier and grounded copper plate.

To measure the surface potential of the PMMA barrier, a DC-Stable Electrostatic Voltmeter 341B with a 3450 sensor from Trek was used. This is a high precision electrostatic voltmeter using the principle of a vibrating Kelvin probe. Its principle is to zero the electric field between itself and the measured surface which was placed 2 mm away from the sensor by adjusting its potential [13, 14]. The sensor does not measure surface charge in Coulomb. It measures the result that is due to the surface charges, the electric potential in Volt caused by the charges at the surface. The sensor is mounted on a robot stage which moves the sensor along the barrier in x and z direction to measure the surface potential on the whole surface. After the LI impulse, the barrier and ground plane were moved along a rail system and positioned 2 mm in front of the probe tip. The whole surface potential on the barrier was then scanned using the robot stage resulting in 2D maps of the surface potential distribution of the whole barrier.

For the experiments, the surface resistance of the barrier had to be varied. This was done using a conductive graphite spray. During the measurement series, more and more graphite spray was applied to the surface of the barrier decreasing the surface resistance. The surface resistance of the barrier was measured with a Keithley source meter 2410 before every series of measurement. The source meter can provide up to $U_{DC} = 1.1$ kV and measures a minimal current of 1 pA. Thus, it was possible to measure a surface resistance up to a value of $R = 10^{15}\ \Omega$

3.2 Experimental procedure

The measurements here were based on the saturation charge assumption [10], as explained in section 2. This was necessary as a complete breakdown of the barrier system leads to an unreproducible part- or full discharge of the barrier as the conductive plasma channel formed by the breakdown is a low resistance path to ground. Thus, a positive LI voltage of 80 kV was applied to the high voltage electrode and no breakdown of the system occurred. The applied 80 kV was sufficient to ignite corona discharges at the tip electrode and charge the barrier surface.

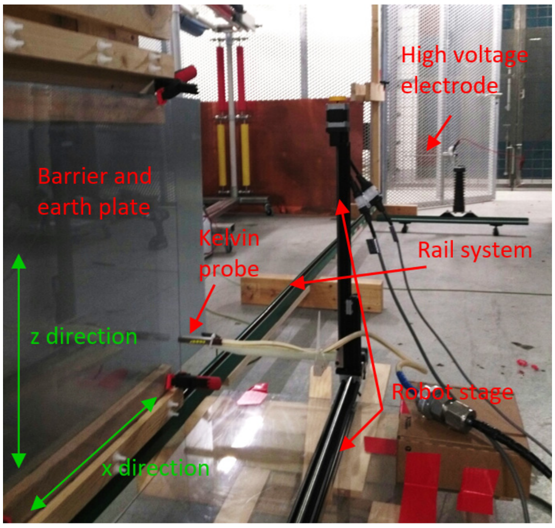

Fig. 3. Picture of the set up with surface charge measurement in the front and high voltage electrode connected to the Marx Generator in the back.

After the charging of the barrier surface by corona discharges by the high voltage electrode, the whole barrier and ground plate were moved on a rail system to the surface potential measurement with the Trek electrostatic voltmeter. The experimental setup can be seen in Fig 3. The distance between the place where the high voltage LI was applied and the place where the surface potential was measured was necessary to protect the surface potential measurement system in case of a occurring flashover.

4 Results

In Fig 4 a line plot of the surface potential, which is due to the accumulated surface charges is shown for measurements and a simulation. The plot is shown in the middle of the barrier at a z position of 200 mm over the whole 600 mm length of the barrier in x direction.

The peak of the measured surface potential is located around the x position 300 mm.

The influence of the surface resistance can be seen in this plot. The maximal accumulated surface potential decreases with decreasing surface resistance. 80 kV was applied at the HV electrode in every measurement.

At the shown z position 200 mm the maximal accumulated surface potential of 14 920 V was measured when the barrier had its maximal surface resistance of $2 \cdot 10^{12}$ **Ω**. This was the case without any graphite spray applied to the PMMA barrier surface. At a surface resistance of $3 \cdot 10^{11}$ **Ω** the maximal surface potential was 6210 V. At the lowest measured surface resistance of $5 \cdot 10^{6}$ **Ω**, the accumulated surface potential was 60 V. The last result might be affected by noise due to limited precision of the probe. Also the 60 V amplitude is not visible due to re scaling of the axis.

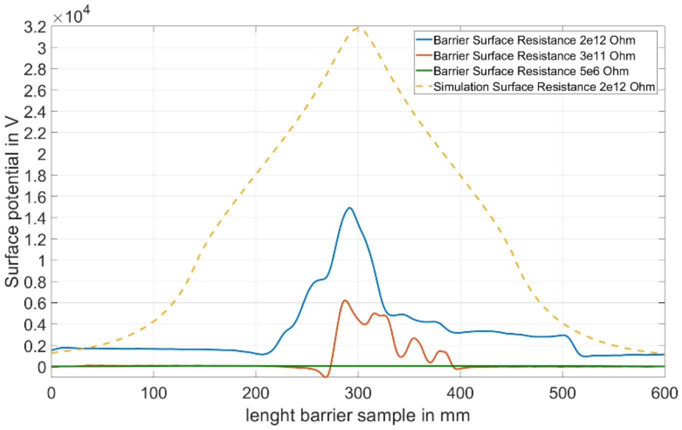

Fig. 4. Surface potential due to accumulated surface charges at the barrier along the middle of the barrier. Shown are measurements with solid lines and a simulation with a dashed line.

The simulation was performed according to [10] based on a purely capacitive model (with infinite surface resistance that approximately corresponds to the case without graphite spray). The simulated saturated surface potential shows a maximal value of 32 kV at the position of the high voltage electrode.

In Fig 5 – 7, the measurements results are shown along the whole surface of the barrier for all three measured surface resistances of $2 \cdot 10^{12}$, $3 \cdot 10^{11}$ and $5 \cdot 10^{6}$ **Ω** in form of color plots.

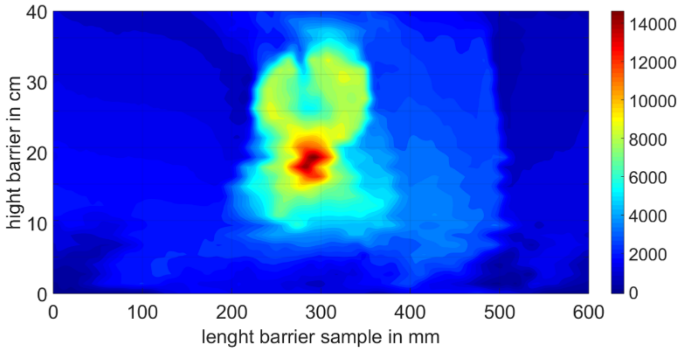

Fig. 5. Measured surface potential on whole barrier with a barrier surface resistance of $2\ 10^{12}\ \Omega$.

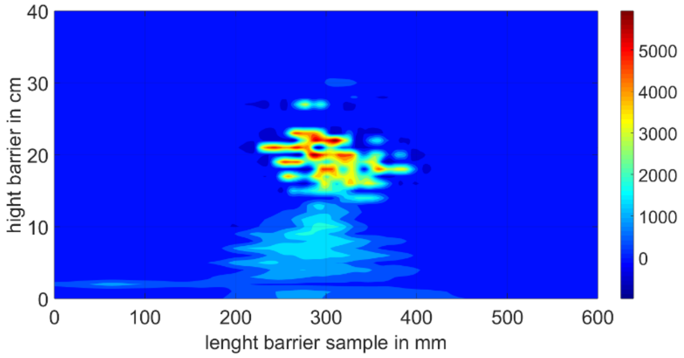

Fig. 6. Measured surface potential on whole barrier with a barrier surface resistance of $3\ 10^{11}\ \Omega$

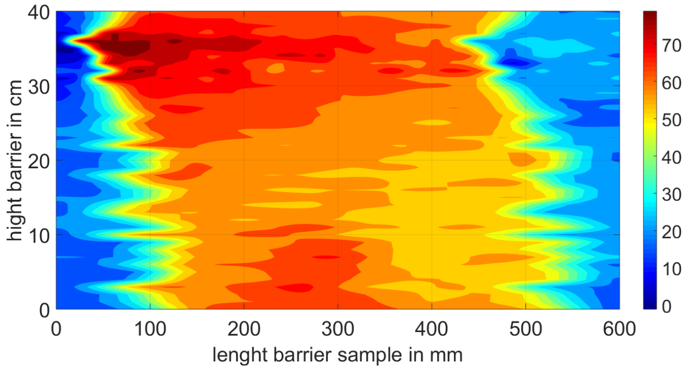

Fig. 7. Measured surface potential on whole barrier with a barrier surface resistance of $5\ 10^{6}\ \Omega$.

For the measurement with the highest surface resistance, shown in Fig 5, the maximum surface potential is in the middle of the barrier directly under the high voltage electrode and decays to zero till the edges of the barrier. The decay of the surface potential is continuous from the middle till the edges.

For the measurement with $3 \cdot 10^{11}$ Ω surface resistance this not the case anymore. The surface potential still shows a maximum at the middle of the barrier where the rod shaped high voltage electrode was located, but the decay to zero is much more abrupt than the measurement with $2 \cdot 10^{12}$ Ω showed.

At a surface resistance of $5 \cdot 10^{6}$ Ω the surface potential corresponds to the residual charge remaining on the surface without clearly localized maximum. The pattern in Fig 7 indicates that the charging activity dominates in the vertical direction where the distance to the edge of the barrier is shorter.

5 Discussion

A significant influence of the surface resistance on the accumulated surface potential has been clearly demonstrated in this work. At the highest value of surface resistance the highest value of accumulated surface potential was measured. Following the Marx-Roser model this would reduce the electric field between high voltage electrode and barrier the most. Thus the highest breakdown voltage would be expected. This is clearly the case like it can be seen in Fig 1.

In Fig 8, the results of 2D FEM simulations of the field distribution along the gap are shown. In this simulation model the measured surface potential for a certain surface resistance (shown in Fig 4) was put as a boundary condition on the barrier surface. The electric field strength in the 20 mm gap between barrier surface and high voltage electrode is shown for the three measured surface resistances and the corresponding surface potential. It can be clearly seen that at the case with the highest surface resistance and thus the highest accumulated surface potential the electric field in the gap is the smallest due to field reduction. So at $5 \cdot 10^{6}$ Ω surface resistance the electric field strength at the high voltage electrode is increased from 7.7 kV/mm at $2 \cdot 10^{12}$ Ω to 11.04 kV/mm, an increase of 43 %, which is in both cases above the critical field of 2.6 kV/mm and above the inception level. So less surface charge on the barrier may lead to an earlier breakdown due to less field reduction. However the field strength at the totally insulating case (with the maximal surface potential) is above 2.6 kV/mm. In this arrangement suppression of streamer inception due to the accumulated surface potential cannot be confirmed. But still this effect cannot be totally excluded as explanation for the behavior shown in [8].

In the measurements presented in this publication only 80 kV was applied at every experiment. But in [8] much higher voltages up to 190 kV were applied. The saturation charge at a barrier surface depends strongly on the applied voltage at the electrode. So it possible that at 190 kV applied the surface potential of the barrier is much larger than shown in these measurements at 80 kV and inception suppression might have happened at high surface resistance values due to a large potential accumulation and field reduction. This has to be investigated in further experiments as it is questionable if a much higher accumulated surface potential due to the higher voltage will be in such a range to relax this much higher applied voltage.

In [9] and [8] it was also assumed that in addition to the possible effect of field reduction the barrier with low surface resistance can act as a floating electrode at a potential close to the high voltage electrode. This is due to a rather small voltage drop along a streamer bridging the air gap between the rod tip and the barrier [11]. Based on the stability field for the positive streamer, it was estimated that the potential of the floating barrier is just *20 mm*0,5 kV/mm=10 kV* lower than the applied voltage during the positive impulse [11].

Due to the high conductivity of the barrier this high potential will be transferred to the barrier edge, where field enhancement occurs which creates many inception points around the large and sharp barrier circumference which leads to the lower withstand voltage. This might also be a valid explanation for the effect but this has to be investigated in further detail to draw a conclusion which of the two effects is the main responsible for the decrease of the breakdown voltage at barrier systems with increased surface conductivity.

According to the simulation procedure proposed in [12] the maximum surface potential of around 32 kV has been calculated for the case with no graphite spray applied at the barrier at $2 \cdot 10^{12}$ **Ω**, see Fig 4 This is around twice the value the measurements showed. This difference could be due to charge decay. A rough estimation including the surface resistance and surface capacitances of the setup has shown that the time constant for the decay is below 1 minute. This is about the time that is needed to get the barrier ready for surface potential measurement after LI was applied. The scan of the whole surface of the barrier also takes about 6 minutes.

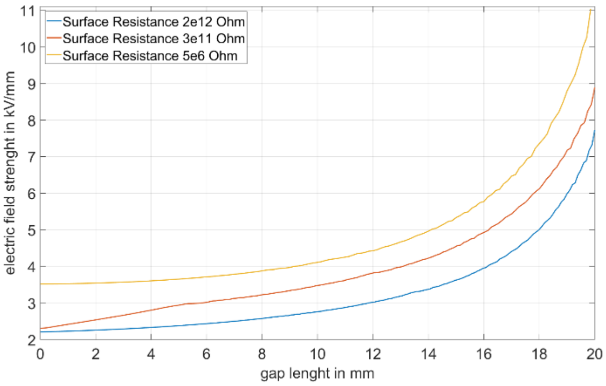

Fig. 8. Electric field strength distribution along the gap between the barrier (length = 0) and the tip of high voltage rod (length = 20 mm). Note: these curves have been calculated for different surface resistances by assuming the corresponding measured surface potential as a boundary condition along the barrier surface.

Still the calculations did show a qualitative agreement with the measurements. The simulations showed field reduction at higher surface resistance due to the higher amount of accumulated surface potential at the barrier but inception suppression is not possible according to the calculations.

These effects have to be investigated and measured in much more detail to fully understand the dependence of the withstand voltage of the barrier system depending on the surface resistance on the barrier which is shown in Fig 1.

6 Conclusions

According to the for gaseous insulation systems widely accepted Marx-Roser model the surface charges at the surface of the barrier have a huge impact on the breakdown voltage of the barrier system. In [9] it was shown that the breakdown voltage of a barrier arrangement decreases severely when the surface resistance of the barrier is decreased as well.

To investigate this effect, the surface potential due to accumulated surface charges on the barrier surface was measured for three different values of barrier surface resistance. It was shown in the experiments that at lower values of surface resistance, less surface charges are accumulated at the barrier surface. This leads to a decrease of the field reduction effect between high voltage electrode and barrier surface and might result in lower breakdown values of the system.

From the experiments presented in this publication we can conclude that less surface charge accumulation due to increased surface conductivity takes place on the barrier surface. This seems to have influence on the breakdown behavior of the barrier system but this has to be investigated and quantified in further detail in future experiments.

References

1. Marx, E. ‘‘Der Durchschlag der Luft im unhomogenen elektrischen Felde bei verschiedenen Spannungsarten’’, Electrotech. Z., Vol. H33, pp. 1161-1165, 1930.
2. Roser H, ‘‘Schirme zur Erhöhung der Durchschlagspannung in Luft’’, Electrotech. Z., Vol. H17, pp. 411-412, 1932.
3. Voloschenko N.F., ‘‘About the Barrier Effect Mechanism’’, Russian J. Electricity, No. 3, pp. 21-26, 1946.
4. Yoshino K., ‘‘Electrical Conduction and Dielectric Breakdown in Liquid Dielectrics’’, IEEE Trans. on Dielect. and Electr. Insul., Vol. 21, 1986.
5. Leontev Yu.N., Torbin N.M., ‘‘Influence of the Barrier Position on the Breakdown Voltage of Solids’’, Trans. USSR Universities, Electrical Engineering, No. 12, pp. 34_37, 1961.
6. Lebedev S.M., Gefle O.S., Pokholkov Y.P. “The Barrier Effect in Dielectrics The Role of Interfaces in the Breakdown of Inhomogeneous Dielectrics”, IEEE Trans on Dielect. and Electr. Insul. Vol. 12, No. 3; October 2011.
7. H.K. Meyer, F. Mauseth, R. Marskar, A. Pedersen, A. Blaszcyk, "Streamer and surface charge dynamics in non-uniform air gaps with a dielectric barrier", IEEE Trans. on Dielectrics and electrical Insulation, Vol. 26, No. 4, August 2019.

8. M. Schueller, M.K. Bucher, T. Franz, J. Smajic, "Effect of slightly conductive Barrier Systems on the Breakdown Voltage of an Air Insulated Rod Plane Arrangement shown in Experiment and Simulation", Int. Symp. on High Voltage Engineering, ISH 2017, Argentina, 2017
9. M. Schueller., A. Blaszczyk., A. Krivda., J. Smajic, “Influence of the surface conductivity of a single glass barrier on the breakdown voltage in an air insulated rod plane arrangement“, IEEE Conf. Electr. Insul. Dielectr. Phenomena, Toronto, 2016.
10. A. Pedersen , A. Blaszczyk, “An engineering approach to computational prediction of breakdown in air with surface charging effects,” IEEE Trans. on Dielectrics and Electrical Insulation, vol. 24, no. 5, Oct. 2017.
11. Pedersen A., Christen T., Blaszczyk A., Böhme H. „Streamer inception and propagation models for designing air insulated power devices”, IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), 2009
12. H.K. Meyer, A. Blaszczyky, M. Schueller, F. Mauseth, A. Pedersen, "Surface charging of dielectric barriers in short rod-plane air gaps – experiments and simulations", IEEE Conf. on High Voltage Engineering and Application, ICHVE 2018, Greece
13. W.A. Zismann, “A new method of measuring contact potential differences in metals”, Rev. Sci. Instrum., Vol. 3, pp. 367-368, 1932.
14. M. Schueller, R. Gremaud, M. Baur, L.G. Hermann, J. Smajic, "Kelvin probe for surface potential measurements on epoxy insulators for HVDC applications", IEEE Conf. on High Voltage Engineering and Application, ICHVE 2018, Greece