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Breakdown in Air Gaps with Solid Insulating Barrier under Impulse Voltage Stress

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Abstract: The influence of solid insulating barriers to the impulse strength of air gaps has been investigated by few researchers. It is well known that thin insulating materials increase considerably the breakdown voltage, sometimes two to three times. Some researchers performed thorough investigations for the determination of the parameters of the barrier effect that influence the impulse level for the breakdown. The distance of the barrier from the high voltage electrode is the most important parameter. The field distribution is also important as well as the shape of the insulating sheet. The experimental investigations led to some theoretical models for the breakdown process. This paper analyzes and discusses those models and spots the points where they agree as well as the differences between them. Finally, it attempts to compose a model that sheds light on the barrier effect and complies with all the experimental and theoretical analyses.

Keywords: Air gaps, barrier, breakdown, impulse voltages.

1 Introduction

Few researchers have investigated the influence of the barrier effect to the dielectric behaviour of air gaps under lighting stresses. On the other hand, the experimental setups that were used by each of the individual researches differ not only in the dimensions and the material of the barrier but also in the shape of it as well as in the gap geometry and the shape of the impulse voltage and its polarity. Various insulating materials were used like kraft paper, hard paperboard, glass, bakelite and

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other synthetics. The more common gap was the well known rod-plane arrangement (Fig. 1) with rod tip of various shapes (cone, needle, sphere etc) although in some cases rod-rod or plane-plane gaps were used. Most of the published results concern small or medium gaps (from few cm up to 50 cm). Only one researcher performed experiments on large gaps (up to 2 m). The measuring techniques included streak and still cameras, impulse oscilloscopes and space charge measuring devices.

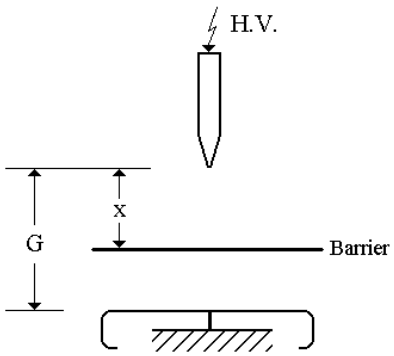


Fig. 1. Rod-plane air gap with insulating barrier (G: gap clearance, x: distance between barrier and high voltage needle).

The investigation of the barrier effect under d.c. or a.c voltages is more common in the international bibliography, especially in small gaps. Few researchers have experimented with impulse voltages that require special installations and equipment. The aim of this paper is to study the barrier effect under impulse voltages because the breakdown mechanism is more complicated. On the other hand the effect under impulse voltages is more beneficiary than under d.c. or a.c voltages. Thus only experiments with any type of impulse voltages are discussed in this paper.

2 The First Approach for the Understanding of the Barrier Effect

The first experiments were carried out by Marx [1] on small and medium needle-plane air gaps (with clearance up to 50 cm). He used various insulating materials like presspan 3 mm thick, kraft paper 0.05 and 1.5 mm thick, thin glass etc. That investigation started from lightning impulse voltages of positive and negative polarity and extended to DC and AC voltages. Considering the means of that era, the use of Lichtenberg figures in order to record the traces of the breakdown channel was quite innovative and successful. Pictures of the gap at the instant of the breakdown under a.c. and d.c. stresses were also taken.

Marx also investigated the influence of the polarity of the impulse voltage to the

breakdown mechanism. He determined that the positive impulse voltage (positive needle and negative plane) produce a positive, thin streamer discharge from the needle to the barrier with a lot of branching. The streamer cannot penetrate the barrier and stops there, accumulating positive charge on the surface of the barrier that faces the needle. This charge modifies to uniform the electric field between the barrier and the plane. Therefore, the gap between the barrier and the plane becomes uniform with the positively charged surface of the barrier acting as the positive electrode while the negative one is the plane. The potential is almost equal all over the charged surface of the barrier. That homogenization of the gap prevents the development of the leader, thus increasing the breakdown voltage. Depending on the gap length, the position of the barrier and the material and thickness of the barrier, the breakdown voltage increases considerably. The optimum position of the barrier is near the needle but not very close or in touch with it. For the optimum position of the barrier, the breakdown voltage may be doubled (Fig. 2).

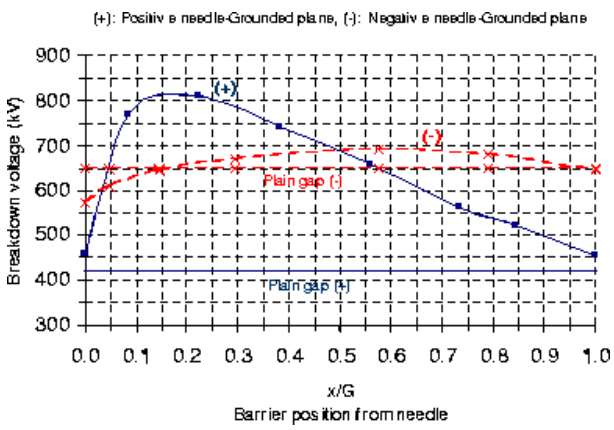


Fig. 2. Breakdown voltage [1] of a needle-plane gap (G=50 cm) with barrier (kraft paper 1.5 mm thick).

Contrary to the above, the improvement of the dielectric behaviour is negligible if a negative impulse voltage is applied to the needle. The experiments showed that the breakdown voltage slightly changes comparing to the breakdown voltage of the gap without barrier; it decreases under certain circumstances, even below that level. Generally speaking, the insertion of the barrier will not affect the breakdown, under a negative impulse stress, at least according to Marx experiments. This is owed to the completely different breakdown mechanism.

The negative streamers are developed in wide strips due to the different kinetics of the negative charge by contrast with the charge of the positive streamers. This phenomenon is observed in gaps in air while in electronegative gases the atoms

attract the electrons, thus forming negative ions with similar kinetics to the positive ones. Therefore, the difference between the positive and negative breakdown mechanism characterizes the gaps in air but not the ones in electronegative gasses.

The wide negative streamer approaches the barrier without branching as opposed to the intense branches of the positive streamer. It results in a rather small quantity of negative charge accumulated on a small area of the barrier. In such case, the field between the gap and the plane remains non-uniform. On the other hand, the field around the needle is quite strong. The dense field lines, which connect the needle with the plane through the barrier, permit the inception of discharges between the barrier and the plane. Finally, the discharges reach the plane and the gap is bridged. These discharges are not observed under a positive voltage stress. In that case, the barrier-plane field is uniform and, therefore, a higher voltage is required for the breakdown. That difference may be owed to the more intense polarization of the negative needle that emits electrons during the corona discharge. The positive electrode does not emit.

Another, in-depth experimental research of the barrier effect was carried out by Roser [2] on small gaps (with clearance up to 10 cm). He investigated, among others, the influence of the insulating material and of its thickness to the level of the breakdown voltage. It was concluded from the experiments that the contribution of those parameters is insignificant. It should be pointed out that the researches, which followed some decades later, reached the same conclusion. Today it is widely accepted that the critical point is not the thickness of the barrier, given that the thickness and the effectiveness of the provided insulation is negligible, as compared to the most important parameters: the gap length, the uniformity of the electric field, the shape of the applied voltage and the position of the barrier inside the gap.

The corona discharge and the ionization in strongly non-uniform fields induce electric charge on the surface of the barrier resulting to the homogenization of the barrier-plane field that consequently increases the withstand voltage. The barrier effect is not attributed to the additional insulation that improves quantitatively the field strength but to the presence of the barrier that affects qualitatively the breakdown mechanism. Therefore, the thickness of the barrier is a parameter of minor importance in non-uniform fields.

Polarization, corona and ionization do not appear in uniform fields. The breakdown channel starts from the high voltage electrode and propagates towards the barrier. The accumulated charge on the surface of the barrier does not influence the field because it is already homogenous. Hence, the presence of the barrier in uniform fields is also of minor importance irrespective of its thickness. Another evidence of that is that after the first breakdown and the puncture of the barrier the next breakdown penetrates the barrier at another point. It does not follow the

first path with the better conductivity that passes from the previously opened hole. Obviously, the voltage level for the second breakdown remains the same with the first. This means that, irrespective of the change of the insulation characteristics, the hole did not affect the phenomenon.

It must be noticed that very thick barriers, which would definitely affect the strength, were not investigated, since they concern the research of solid dielectrics and not the barrier effect.

Roser developed a theoretical explanation for the phenomenon, which is based on his experimental investigation performed on needle-plane gaps under a positive stress. Roser's model complies with Marx observations that the discharge accumulates charge on the barrier and homogenizes the barrier-plane gap. He assumed that the discharge is so intense that the voltage drop across the channel is very low. Practically, this means that the potential of the barrier becomes equal to the potential of the needle i.e. the test voltage is applied almost directly to the barrier-plane gap. This gap is now uniform due to the accumulated charge on the barrier. If the voltage is high enough the barrier-plane gap is bridged. Therefore, the breakdown voltage of the non-uniform needle-barrier-plane field is equal to the breakdown voltage of the uniform barrier-plane field. According to this assumption, the breakdown voltage is lower in gaps with the barrier placed far from the high voltage needle because it has to bridge a shorter barrier-plane gap. Hence, his assumptions agree with Marx observations that the dielectric strength of the gap is maximized when the barrier is placed near the high voltage electrode.

To verify his determinations, he conducted comparative experiments with positive impulses on a needle–plane gap with barrier and on a plane-plane gap (without barrier) with a clearance equal to the distance between barrier and plane of the first gap (Fig. 3). As expected, the values of the breakdown voltage of the needle-barrier-plane arrangement were found to be very close to the breakdown voltage of the plane-plane gap. The uniform field of the later is equivalent to the barrier-plane field of the first arrangement.

The only deviation appeared when the barrier was placed very close to the high voltage needle or near the grounded plane. If the barrier is placed near the needle then the discharge is quite short and the accumulated load on the barrier is not enough to modify to uniform the remaining barrier-plane gap. Therefore, the field of the whole arrangement remains non-uniform. If the barrier is placed near the plane then the uniform barrier-plane gap becomes so small that slightly influences the whole gap. The arrangement remains non-uniform. Once again, Roser agrees with Marx.

Rosers' model and his experimental results were verified much later by Koenig and Lantenschlaeger [3] who also observed in their experiments that the break-

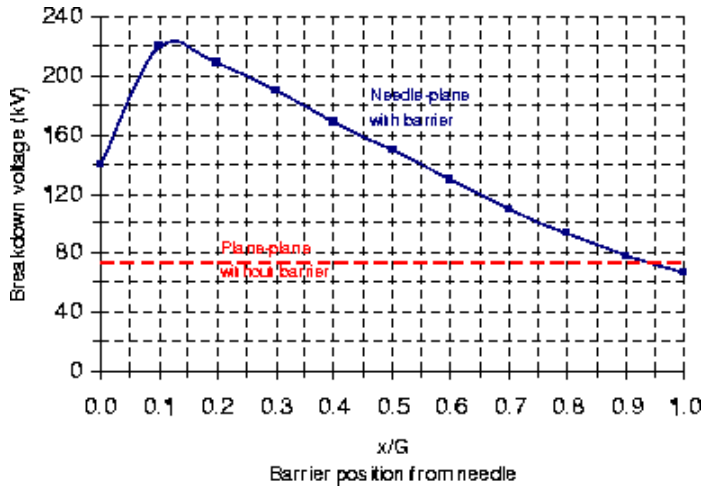


Fig. 3. Barrier effect on the breakdown voltage [2] of a needle-plane gap (G=10 cm) with barrier (paper 0.5 mm thick) under positive lightning impulse stress (T=2.25 μs).

down process is random and does not depend on the insulating characteristics of the barrier. They also noticed that after the first breakdown the next one does not follow the first path and penetrates the barrier at another point. The strength of the gap changes after the insertion of the barrier (irrespective of the pre-existing holes from the previous punctures) because the breakdown mechanism is qualitatively different. It should be noticed that the high voltage electrode was a sphere of small diameter and the earthed electrode was a plane.

3 Barriers with Opening

Roser's experiments verified that the barrier effect is not just a topic of insulation but a completely different phenomenon. This consideration urged him to investigate barriers with a circular opening. He performed d.c. experiments on a small gap with the barrier placed at a specific position. Changing the diameter of the opening, he observed that the breakdown voltage remained at high levels. It proved that the barrier contributed to the dielectric strength, even with the hole. The breakdown voltage decreased at wider openings but it was still higher than the one of the gap without barrier. It was obvious that the accumulation of the load on the surface of the barrier homogenized the field at a certain degree depending on the "useful" area of the barrier (initial surface minus the area of the opening).

The idea of Roser to investigate the effect of a barrier with a circular opening was adopted some decades later by Wasilenko and Olesz [4]. They used impulse voltages as well as a.c. voltages, thus complementing the d.c. research of Roser.

Their experiments confirmed that the barrier retains the improved strength of the gap even with the circular opening (Fig. 4). The diameter of the opening plays an important role. For small diameters, the breakdown voltage slightly differs from the one with plain barrier. The barrier becomes less effective for larger diameters. The experiments on a 30 cm gap with a barrier of 45 cm in diameter showed that the barrier effect is eliminated for an opening diameter larger than 8 cm. Those experiments corroborated the view of Roser for the breakdown mechanism in a gap with barrier.

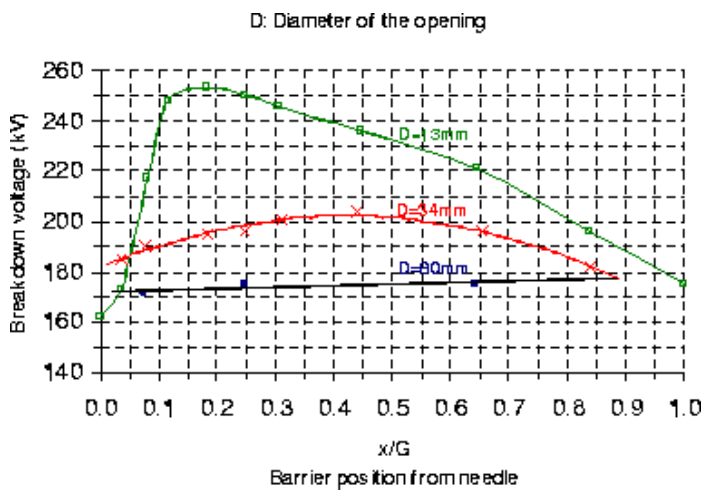


Fig. 4. Positive lightning impulse stress of a needle-plane gap (G=30 cm) with barrier (laminated paper board 5 mm thick) with circular opening [4].

Another interesting finding was that the material of the barrier and its thickness influence the voltage level for the breakdown. That finding could be considered that is in contradiction of the observations from Marx and Roser. However, Wasilenko and Olesz gave a substantiated explanation that complies with the established theory and verifies the validity of all the previous researches. According to them, the maximum of the charge density appears around the central point of the barrier. It means that the arc will penetrate the barrier outside the area of the highest charge density. The opening removes a crucial part of it, thus reduces the remaining surface charge, and changes its distribution.

In case of a thin barrier (kraft paper 0.01 mm thick) with small diameter of the opening, the puncture of the barrier may be more favourable than the passage through the opening. However, it does not happen with barriers having a higher breakdown voltage. Those materials (PVC foil 0.19 mm thick and laminated paper board 5 mm thickness) impede the puncture and the streamers have to pass through the opening. In such case, the voltage required for passage through the opening is

much higher.

The above conclusions do not apply in case of very small air gaps. The experimental research of Ming et al. [5] on a gap with 5 cm clearance concluded that a small hole on the barrier surface leads to a significant reduction in breakdown voltage, which depends on the location of the hole. If it is located at the central point of the barrier, it eliminates all of the beneficial effects of the barrier. It seems that even a small opening is not negligible considering that the dimensions of the gap are small too. However, a hole located far from the central point of the barrier is not so important and the breakdown voltage remains quite high but not as high as without the hole. It is obvious that any disturbance in the field of very small gaps becomes important if it is located around the axis where the field lines are very dense. Remote disturbances affect in a lesser degree the field and, consequently, the breakdown.

4 In Depth Investigation of the Breakdown Process

An important investigation of the mechanism of the barrier effect was performed by Remde and Boecker [6]. They experimented on a small needle-plane gap (with 6 cm clearance) stressed by positive square impulses of long duration; the time to half value of the impulse tail was 3 ms. They also used negative square impulses of long duration. The barrier was a kraft paper 2 mm thick. Apart the other measurements, they took photos of the pre-discharge phenomena and of the breakdown using a streak camera.

The breakdown process with positive impulses (positive needle, grounded plane) is divided in three phases: a) Breakdown of the gap between high voltage needle and barrier, b) Breakdown of the gap between barrier and plane and c) Puncture of the barrier and complete breakdown of the whole arrangement.

The first phase starts with a spark that appears as the impulse voltage is increased. The spark propagates from the needle towards the barrier and finally bridges the gap between them. The spark is associated with a high current pulse owed to one or two streamers. The initial streamers are strongly ionized. They gradually develop to an arc between the needle and the barrier. It consists of several individual, primary and secondary, avalanches. The arc reaches the barrier and the first surface discharges appear on it. A high current of the arc flows to the surface of the barrier. Thus, a strongly ionized, thermal arc is established that emits light. Instantly, the breakdown occurs between needle and barrier.

In the mean time, the surface discharges continue to develop forming several branches, which accumulate positive load on the surface of the barrier. The load spreads across the branches. However, the branching is so dense that renders a

rather uniform load distribution.

The more the load accumulates on the barrier, the higher becomes the voltage between barrier and plane while the voltage between needle and barrier becomes lower. That process resembles the charging of a capacitor; one plate being the side of the barrier that faces the needle and the other plate the grounded plane. The strengthening of the field causes the inception of glow discharges between the opposite side of the barrier and the grounded plane. Those discharges are more intense at the areas of dense accumulation of load. However, the intensity of the glow discharges is not efficient to bridge the barrier-plane gap; at least until the impulse voltage level reaches a certain value.

The second phase of the breakdown starts when the impulse voltage level reaches the value that is needed for the transition of the more intense glow discharge to thermal arc. The arc is associated with a high current pulse. Several intense surface discharges are formed around the trace of the arc on the surface of the barrier that faces the plane. The development of surface discharges continues on both sides of the barrier. That process also resembles the charging of a capacitor with plates the two sides of the barrier and dielectric the barrier itself. Obviously, the capacitance is higher than at the first phase and the current is higher too. That is the reason of the wider spread of the surface discharges.

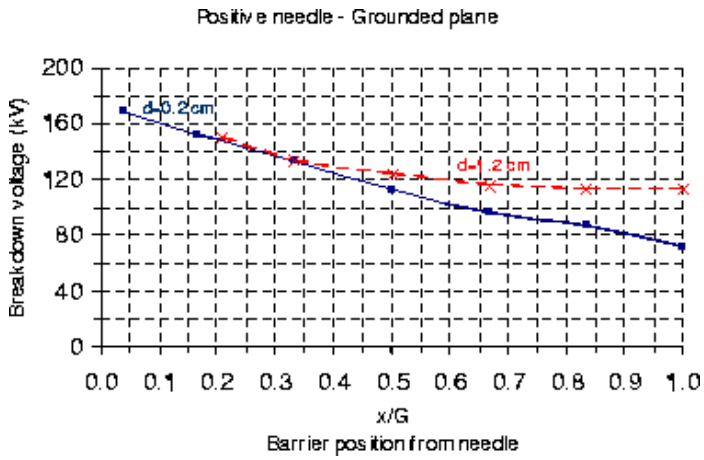
The third phase of the breakdown process starts when the impulse voltage level reaches the value to puncture the barrier. This happens at the weaker point of the barrier irrespective of its position. The route of the complete breakdown is formed by an arc between needle and barrier, a surface discharge on the barrier surface that faces the needle, a hole in the barrier, a surface discharge on the barrier surface that faces the plane and an arc between the barrier and the plane. Obviously, this route is not straight, meaning that the discharge does not follow the shortest route.

The breakdown process with negative impulses (negative needle, grounded plane) is completely different. The negative corona emits electrons with high kinetic energy. They reach the barrier very fast. The accumulated charge on the barrier strengthens the field between the barrier and the plane. This results to the breakdown of the barrier-plane gap. The process is faster than the one described previously with the positive needle because the accumulation of the negative charge is attained through radiation and not through the positive arc.

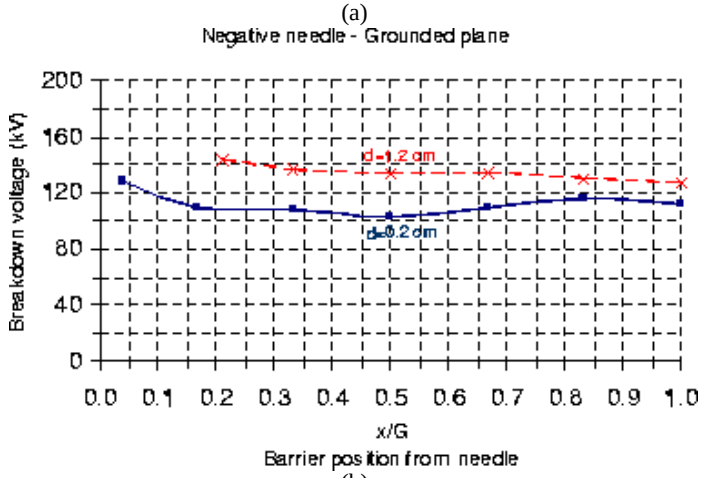
The negative needle continues to emit electrons. This load flow is supported by the surface discharges on the barrier and the arc that has already bridged the barrier-plane gap. This causes the breakdown of the needle-plain gap. If the impulse voltage is raised to a certain level, then the barrier is penetrated and the complete breakdown of the arrangement occurs.

The research of Remde and Boecker concentrated to the qualitative investiga-

tion of the breakdown of a small gap with barrier. Their model of the breakdown mechanism generally agrees with the models of Marx and Roser. They also observed that the breakdown phenomenon differs completely between the positive and the negative impulse stress (Fig. 5). They agree with Marx and Roser that the voltage level is quite higher for the breakdown of the positive gap than for a negative gap of the same configuration.



(a)



(b)

Fig. 5. Breakdown voltage [6] of a needle-plane gap (G=6 cm) under square lightning impulses with barriers of different thickness (0.2 cm: solid line, 1.2 cm: dashed line).

The differences between the experimental observations, which led in some cases to different theoretical explanations, are owed to the long duration of the impulses used Remde and Boecker and the square-type impulses. They recorded a glowing thermal arc during the breakdown of the positive needle-grounded plane

gap. That intense arc was not recorded by Marx and Roser. A possible explanation is that the long duration of the impulse provides more electrons to the discharge, enabling the development of the glowing arc. The validity of this explanation is supported by the long times to breakdown that reached the 10 μs in some cases.

Remde and Boecker also discovered that the value of the elements of the generator play an important role to the breakdown. According to their measurements, the breakdown depends not only to the peak value of the impulse but also to the value of the front capacitor and of the front resistance. Especially the value of the front capacitor determines the amplitude of the breakdown current. This will be proved later that is very crucial for the breakdown. Some researchers measured quite high breakdown voltages because they used impulse voltage generators with inadequate front capacitor. Tests with the standard impulse voltage 1.2/50 μs could not bridge the gap because the inadequate front capacitor could not give the required current and the short duration of the impulse could not accumulate enough surface charge on the barrier. Such problems did not appear in tests with voltages of longer duration like the standard switching impulse 250/2500 μs.

5 Quantitative Analysis of Spaces Charges

More recent researches with advanced measuring equipment allowed an in-depth investigation of the breakdown progress through the measurement of the electric field in the gap and the charge produced by corona discharges. Hidaka and Kouno [7, 8, 9] measured the field in the space as well as on the back surface of the barrier, which faces the plane electrode, using a Pockels device and an optical system for the detection of the change of the refracting index of the crystal. In addition, the light emitted by corona discharge was observed using a streak camera. They experimented with medium rod-plane gaps in air (from 10 to 50 cm), which were stressed by lightning and switching impulse voltages. The barrier was a kraft paper 0.05 mm thick.

The research found that the electric field at the centre area of the barrier exceeds the applied electrostatic field. It becomes the maximum at the centre of the barrier and decreases linearly with increasing the radial distance on the barrier (Fig. 6). This fact shows that the space charges play a main role on the barrier effect.

After the application of the voltage, corona streamers start from the tip of the high voltage electrode. The barrier prevents the development of the streamers to the plane electrode. The streamers accumulate surface charge on the barrier and the electric field between the barrier and the plane increases gradually. As the applied voltage increases, the corona discharges become more intense and the electric field between the barrier and the plane reaches the value that corresponds to

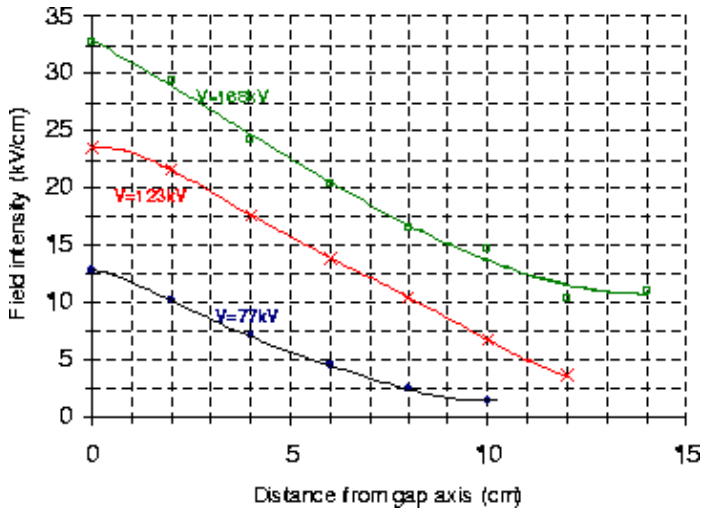


Fig. 6. Electrostatic field on the back surface of the barrier (gap length: 10 cm, barrier: kraft paper, thickness: 0.05 mm, position from needle: 3 cm, applied voltage: positive lightning impulse 77 kV, 123 kV, 168 kV) [9].

the breakdown. Streamers appear now in the barrier-plane gap. Up to this instant, no light emission is observed in the gap. Finally, the streamers bridge the gap. A leader development from the tip of the high voltage rod follows. The bright tip of the leader propagates towards the barrier and joins with the streamers between the barrier and the plane, passing through the barrier and emitting a strong light.

The measurement of the charge at various areas of the barrier showed that the charge density decreases linearly with increasing the radial distance on the barrier. It means that the charge distribution over the surface of the barrier is not uniform. This fact is in contradiction of the assumptions of Marx and Roser. Observing carefully the experimental results, one can see the reason of that contradiction. Marx used a thick material that resists to penetration, forcing in that way the corona discharge to accumulate more charge over the surface of the barrier. As more charge reaches the barrier, it repulses the accumulated charge far from the centre. Thus, the charge spreads up to the edges resulting to a rather uniform distribution. However, strictly speaking, this not true.

Hidaka and Kouno claim that the breakdown in the experiments of Marx occurred through a surface discharge on the barrier without penetrating it. Maybe this happened sometimes but some Lichtenberg images show clearly discharge channels starting from the backside of the barrier and ending to the grounded plane. In any case, the discharge in the experiments of Marx required a higher voltage level to develop the complete breakdown (Fig. 7). The barrier of Hidaka and Kouno was

much thinner, thus it was always penetrated at a lower voltage level. The validity of the above explanation is confirmed by the quite higher values of the breakdown voltage in the test arrangements of Marx than the ones of Hidaka and Kouno for the same test arrangement.

The charge measurements showed that approaching the barrier to the high voltage electrode, the accumulated charge on the barrier reduces the electric field near the electrode. It then suppresses the corona discharges from the rod tip. Consequently, the accumulation of the charge on the barrier decreases and the development of streamers between the barrier and the plane is also suppressed. However, the development of streamers between the barrier and the plane is necessary for the breakdown. Hence, the complete breakdown is impeded when the barrier approaches the high voltage electrode. Generally, if the distance of the barrier from the electrode is around one third of the gap length then the breakdown voltage becomes 2 or 3 times higher than the one of the same gap without barrier. Once again, the conclusion of all the previous researches is confirmed that the breakdown voltage reaches its maximum with the barrier placed near the high voltage rod but not very close or in touch with it.

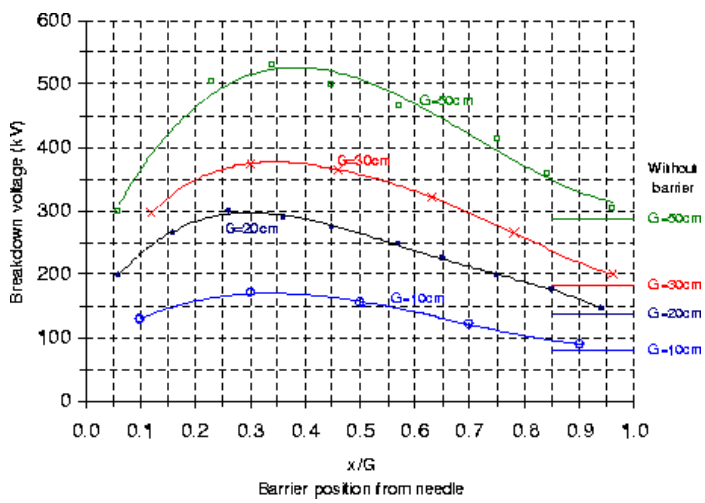


Fig. 7. Breakdown under positive lightning impulse stress [9] of medium needle-plane gaps ($G = 10 \div 50$ cm) with barrier (kraft paper 0.05 mm thick).

6 Flashover Around the Barrier without Penetration

Boubaker et al. [10, 11, 12] conducted experiments on medium and long air gaps (50 cm-200 cm) under lightning and switching impulse voltages of positive polarity.

The high voltage electrode was a rod with pointed end and the grounded electrode was a flat plate. They also experimented with a.c. voltages and switching impulse of negative polarity. Their experiments on long air gaps are the only available in the international bibliography. It should be noticed that their investigation didn't aim to the penetration of the barrier but to the flashover around it. Evidently, they used barriers with smaller dimensions of the plane electrodes in order to allow the discharge to pass round the barrier without puncturing it. Besides, the barrier was a square bakelite 3 mm thick i.e. with quite high dielectric strength.

The objective of the research was to measure the increase of the breakdown voltage of the gap due to the increase of the length of the discharge channel. The bending of the discharge around the edge of the barrier is not only due to the presence of the barrier as a geometrical obstacle but also and mainly due to the electrostatic obstacle which consists of the electric charge accumulated on the surface of the barrier facing the high voltage rod electrode.

It was observed that the breakdown occurs either directly or in steps, depending on the polarity of the impulse, the distance of the barrier from the rod tip and the dimensions of the barrier. If the polarity of the applied impulse voltage is positive and the barrier is placed at distances varying from to 20% to 60% of the gap length, then the breakdown is direct. However, if the barrier is placed near the tip or far from it (distance shorter than 20% of the gap length or longer than 60%), then the breakdown takes place in steps. The impulses of negative polarity lead to breakdown in steps irrespectively of the position of the barrier with the exception of gaps with length shorter than the length or width of the barrier.

The direct discharge starts from the rod tip and propagates directly to the barrier edge without surface discharges, following the shortest way. It continues its propagation to the earthed plane until it bridges the gap. Therefore the length of the breakdown path is equal to the shortest way that connects the rod tip with the barrier without penetration of the barrier. This means that the gap with barrier corresponds to a gap without barrier, with gap clearance equal to the length of the above path. Consequently, the breakdown voltage of the gap will be increased at the level of the breakdown voltage of a gap without barrier with clearance equal to the length of the above path.

The breakdown in steps, with positive rod tip, starts with streamers growing directly from the rod tip towards the centre of the barrier. Then sliding discharges appear on the surface of the barrier that faces the rod tip. The discharges turn around the edge of the barrier and propagate directly from that point to the earthed plane.

The above process differs in case of rod tip of negative polarity. One streamer emanates from the rod tip and a second one from the earthed plane. The streamers

reach the barrier where sliding discharges are developed until the breakdown occurs after joining of the two streamers.

The experimental results of Boubaker et al. agree with all the other researches to the point that the breakdown voltage reaches its maximum if the barrier is placed near the high voltage electrode but not very close or in touch with it. They also agree that approaching more to the rod tip the breakdown voltage decreases slightly nevertheless quite high as compared to the plain gap without barrier. Their research reports an increase of the breakdown voltage by 130% in the medium gap of 50 cm and by 20% in the gap of 2 m. Approaching the earthed plane the beneficiary effects of the barrier become negligible. The research in question also agrees with Marx that the insertion of a barrier in gaps with rod electrodes of negative polarity does not influence the breakdown voltage although the published results are not so extensive like the ones with positive polarity.

7 Barrier Effect in Symmetric Fields

The breakdown voltage of a point-plane air gap slightly differs from the respective value of a point-point gap with equal clearance. However, the insertion of a barrier in a point-point gap exhibited more beneficiary effects. Topalis and Stathopulos [13, 14] conducted experiments on small and medium air gaps with clearance up to 40 cm. The voltage stress was either the standard lightning impulse 1.2/50 μs or the switching impulse 250/2500 μs, both of positive polarity. Kraft papers were used as barriers with thickness 0.12, 0.27 and 0.39 mm.

The experimental results can be compared with the ones of Kouno et al. [9] who performed their experiments with the same type of impulse voltages and on gaps of the same clearance. The measured values of the breakdown voltage of the point-point gaps are slightly higher (5%) than the ones of the point-plane gaps (Fig. 8). Generally, there is a good agreement between the research in question and all the previous ones when they deal with similar arrangement. However, considerable discrepancies appear in arrangements with the barrier very close to the high voltage electrode. Approaching the barrier to the positive rod tip of the rod-rod gap, the breakdown voltage does not decrease to the degree that the other researches report for their rod-plane gaps. In fact, the breakdown voltage of the rod-rod gap takes the maximum value near the high voltage tip (at a distance 10%-20% of the gap length) and then is stabilized exhibiting just a slight decrease rate. On the contrary, the other researchers observed a noticeable decrease of the voltage at short distances from the tip of the rod-plane gap. It is assumed that the streamers that reach the barrier do not spread their positive electric load over a wide area because the negative rod tip from the opposite side attracts it. Therefore, it remains around

the centre of the barrier. It seems that the grounded rod does not influence the load distribution when the barrier is far from it, thus the variation of the breakdown voltage near the high voltage rod is little.

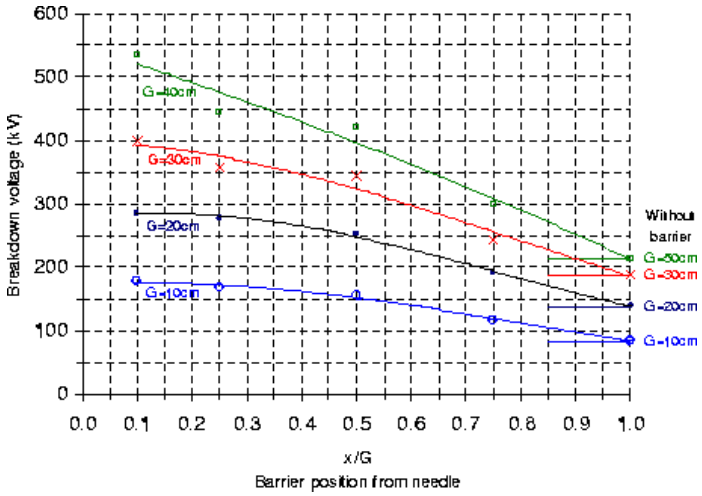


Fig. 8. Breakdown under positive lightning impulse stress [13, 14] of symmetric needle-needle gaps ($G = 10 \div 50$cm) with barrier (kraft paper 0.39 mm thick).

8 Investigations with other Types of Voltages

Apart from the investigations with impulse voltages, some of the analyzed above investigations include experiments with d.c. and/or a.c. voltages [1], [2] and [8]. Also, some others researchers conducted experiments with voltages other than impulses. One research [15] used transient impulses (uni-directional, cos-bi-directional and sin-bi-directional) to test the barrier effect on small needle-plain gaps with 4 cm clearance. The barrier was a kraft paper 70 μm thick. Experiments with pulses of some kV were also performed on very small rod-plane gaps with flat tipped high voltage rod and length varying from 0.25 mm to 5 mm [16]. The barrier was a dielectric sheet PET 25 μm thick. The a.c. breakdown of small gaps (up to 20 cm) was investigated in [17] using PVC and acrylic barriers. The electrode arrangement was a combination of a rod and a conductor under different polarities. Another research used PP-film composites as barriers in order to determine the d.c. breakdown of small needle-sphere gaps [18]. On the other hand, some researchers measured the properties of air gaps containing floating conductive electrodes, instead of insulating barriers [19].

9 Conclusions

The research work that has been carried out through the past 75 years managed to explain the breakdown mechanism in air gaps with insulating barriers. It has been proved that a thin barrier, without any special dielectric characteristics, improves considerably the dielectric strength of the gap. In some cases, the insertion of the barrier increases breakdown voltage by 2 or even times. All the researchers agree that the best dielectric performance of the arrangement is achieved if the barrier is placed near the high voltage point but never very close to it. The optimum distance is equal to 20% of the gap length. Approaching more the barrier, the dielectric strength deteriorates. The worst choice is to place the barrier near the grounded points. In that case the beneficiary effects of the barrier are eliminated and the barrier becomes useless or even harmful. The material of the barrier is not as important as the position of it. Even a low-cost kraft paper improves the strength if it is placed properly. Nevertheless, a rather thick material of few mm with a good dielectric constant is advisable.

It is a matter of future work to investigate the performance of new materials and their effectiveness to the insulation of gaps. Comparative measurements should be performed with all types of voltage stresses (a.c., d.c. as well as standard and non-standard impulse voltages). Moreover, the research must include not only the gaps in air but also other insulating gases e.g. SF_6 etc. It is expected that such a research work will be very beneficiary for the technology of electrical insulation.

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