The Effect of a Metallic Particle near a Spacer on Flashover Phenomena in SF_6

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ABSTRACT

This paper presents a study of the flashover mechanism initiated by metallic particles in SF_6 gas. Using a high-speed Imacon photographic camera it was established that a metallic particle near the insulator surface plays an important role in flashover development. The influence of the particle on flashover development depends on the pressure of the SF_6 gas. At atmospheric pressure, the flashover was always initiated at a point on the particle farthest from the nearest electrode. At high pressures, it was found that breakdown develops from the electrode of relative positive polarity in the form of a leader. The velocity of the discharge crossing the gap increases exponentially when the distance between the particle and the insulator surface decreases.

1. INTRODUCTION

In recent years, significant progress has been made in elucidating the events that take place if gaseous insulation is subject to high electric stress; this includes the process that leads to breakdown of electronegative gas. It has been established that the complex phenomenon of nonuniform field breakdown in SF_6, gas at pressures of technical interest involves a stepped leader discharge [1-3]. A quantitative model has been developed, which permits accurate prediction of breakdown voltage for fast-rising, positive polarity step pulses applied to arbitrary electrode geometries and gas pressures [4]

The design levels of electric stress in practical applications of SF_6 gas as an insulating medium are only a fraction, $\sim 0.1\times$ of the theoretical breakdown strength of SF_6. The reason for this is the sensitivity of SF_6 to electric field enhancements, such as those caused by the presence of solid insulators and metallic contamination.

All gas insulated systems require solid insulating materials to provide mechanical support for conductors. The breakdown strength of gas insulation is adversely affected by the presence of insulator surfaces, unless special design precautions are taken [5]. An interesting qualitative stepped-leader model was derived for the discharge propagation along an insulator surface in compressed SF_6 [6]. This model does not consider the contribution of the insulator material near the discharge in the gas, or to the production of charge carriers [7]. There is also ample evidence that in practical gas insulated systems, solid

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insulators acquire surface and/or bulk charge, which can cause local field enhancement sufficient to initiate flashover [8].

Practical gas insulated systems suffer from contamination by metallic particles. These can be introduced during assembly or are produced during operation as a result of vibrations, abrasion of components, *etc.* It is generally accepted that conducting particles with dimensions < 0.5 mm, do not cause a large reduction in the breakdown strength of gas insulated systems [9, 10]. Long metallic particles, however, cause a substantial impairment of the maximum obtainable performance of gaseous insulation because they can migrate to critical regions [11–15]. Consider, for example, a horizontal coaxial conductor arrangement. A particle lying on the inner surface of the outer conductor will obtain a charge, which is proportional to the local field. Thus, the particle experiences an electrostatic force. At sufficiently high applied voltage, the particle will lift off and begin to move in the gas space between the conductors. Under 60 Hz ac excitation, a particle does not fall down when the voltage is near its zero crossings, but will, due to inertia, respond in a time-averaged manner. It will acquire a slow (compared to 60 Hz) bouncing movement. The bounce height increases with the applied voltage. At a sufficiently HV, a particle is able to cross the gap between the conductors and can initiate breakdown. Experimental and theoretical studies have shown that particle initiated breakdown is a two-stage process [14, 15]. Under appropriate voltage conditions, local breakdown occurs between the center conductor and a particle moving very close to this conductor. This local breakdown may continue in the rest of the gap between particle and outer electrode. It has been established that for a certain electrode arrangement, the free moving particle-initiated breakdown voltage is slightly lower than the breakdown voltage resulting from a particle stationary at a short distance from the surface of the high field electrode, and that this latter voltage is lower than the voltage associated with a particle fixed onto the surface of the high field electrode, at SF_6 gas pressures < 100 kPa [14].

During the bouncing movement of a particle in a horizontal coaxial conductor system, a horizontal velocity component is generated due to the irregular shape of the particle and/or electrode surface roughness. As a result, metallic particles will reach vertical insulator surfaces. The combination of metallic particle contamination and a solid insulator has proven to be the most crucial dielectric design consideration; however, only a few systematic studies have been made to determine the effect of this combination on the dielectric strength of compressed SF_6 gas insulation [16–20].

This paper presents results of an experimental investigation which was mainly aimed at observing the temporal and spatial development of the discharge in SF_6 gas under lightning impulse voltages, for the condition that a metallic particle is held at various distances from the surface of a solid insulator. Impulse and dc breakdown voltages measured for different particle to spacer distances as a function of gas pressure are also presented.

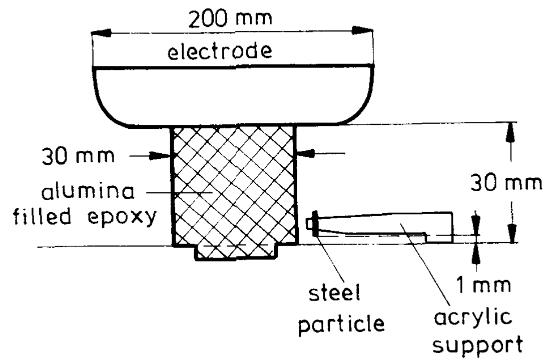

Figure 1. Geometry of the test gap.

2. EXPERIMENTAL ARRANGEMENT

THE test gap used is shown in Figure 1. It consisted of a cylindrical insulator, mounted in the uniform field region between two aluminum electrodes. The insulator, which was cast from alumina filled epoxy, had a diameter and height of 30 mm. A 6 mm long particle, cut from 0.5 mm diameter steel wire, was held in place by means of an acrylic arm glued to the surface of the bottom electrode. No effort was made to shape the ends of the particle. The particle was oriented perpendicular to the electrode surface. The distance between the particle and the insulator surface was varied, but a 1 mm spacing between the end of the particle and the surface of the bottom electrode was maintained in all tests to simulate a free particle in flight, close to its critical position near an electrode surface. The test voltage was applied to the top electrode while the bottom electrode was grounded.

The experiments were conducted in a steel vessel, which had two windows at 90° angle with respect to each other to permit proper observation of flashover paths. In preparation for a series of tests, the vessel was first evacuated with a rotary pump to a pressure of 10 Pa before it was filled with SF_6 gas to the desired pressure.

Breakdown tests were carried out with dc and lightning impulse voltages. The onset of corona and its location were observed by means of a Machlett Model 25-135 image intensifier. Photographic recordings were made, under impulse voltage, with a high speed Imacon 600 camera using streak and framing modes. This image convertor camera is capable of operating at streak rates from 0.05 to 11 ns/mm and at a maximum framing rate of 2×10^7 s^{-1}, with an image tube possessing a spectral response of S 20 UV, covering wavelengths of 450 to 750 nm. In order to strengthen the light output from the Imacon 600 to a level that is sufficient to allow recording on film, an EMI type 9694 image intensifier with a gain of 10^6 was employed. For the synchronization of voltage application and camera operation an electronic delay system was used, as described in [26–28].

3. RESULTS

THE experimental results clearly show the influence which a metallic particle, close to an electrode surface, has on the development of the discharge and the value of the breakdown voltage.

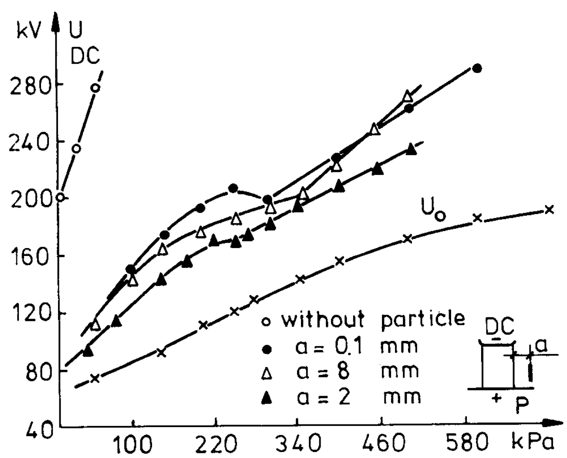

Figure 2.

Breakdown voltage as a function of gas pressure measured with negative polarity dc. U_0 is the corona onset voltage.

The results of breakdown tests which were carried out with negative polarity dc voltage, over a range of gas pressures, are presented in Figure 2. It can be seen that the value of the breakdown voltage is reduced drastically by the presence of the particle. The reduction in the breakdown voltage increases with pressure. It is interesting to note that there is no clear dependency between the particle distance from the insulator surface and the dc breakdown voltage. Taking into account the measurement scatter (~ 5%) it must be concluded that the dc

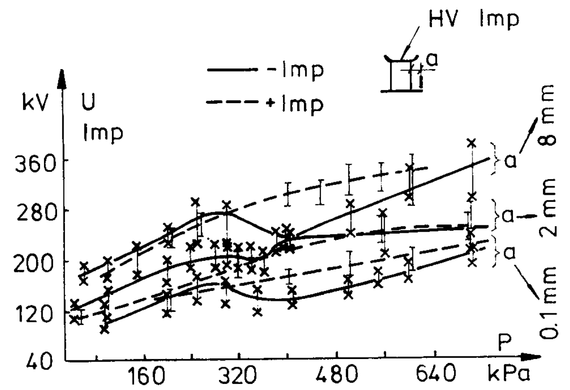

Figure 3.

Breakdown voltage as a function of gas pressure measured with positive and negative polarity lightning impulse voltage.

breakdown voltage is not significantly affected when the distance between the particle and the insulator surface is increased from 0.1 to 8 mm. Observation of the first appearance of corona, by means of an image intensifier, did not reveal any influence of the particle to insulator distance on the onset voltage of visual corona. The initial corona always appeared at the tip of the particle. With a negative dc voltage applied to the upper electrode of the test arrangement, the particle has a positive polarity relative to the distant upper electrode. Accordingly, the breakdown curves associated with the presence of a particle exhibit a shape that is characteristic of positive polarity nonuniform field breakdown of SF_6. However, over the range of pressures that could be obtained with the test vessel, corona always preceded breakdown even after the characteristic bend in the breakdown curves, which in the literature has been explained as a result of the corona space charge [1].

Figure 3 presents the results of breakdown test that were carried out over a wide range of pressure with lightning impulse voltage of both polarities. It is to be noted that in the case of impulse voltage breakdown the value of the breakdown voltage decreases with decreasing distance between the particle and the spacer surface. Again, for negative applied voltage, *i.e.*, positive particle polarity, the breakdown curves display the typical shape associated with positive polarity non-uniform field breakdown of SF_6.

A high-speed camera was used to study the development of the discharge resulting from the application of an impulse voltage. Figure 4 is a typical streak picture of the initial stage of the development of a discharge under a positive polarity impulse and for a particle-to-insulator

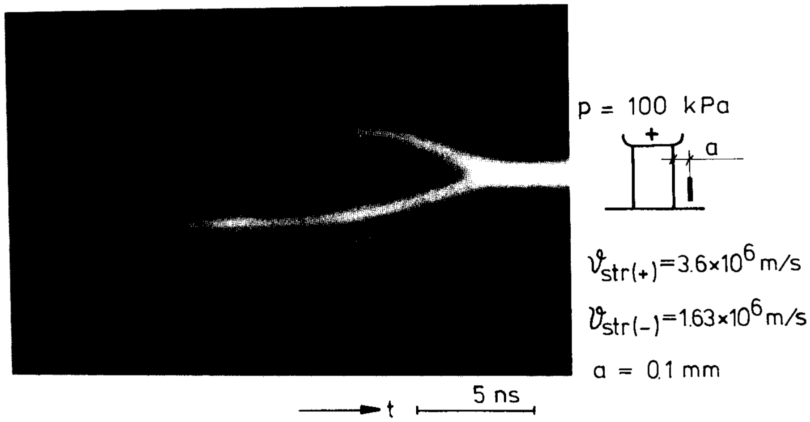

Figure 4.
Streak photograph of the initial stage of breakdown development, positive impulse voltage, p = 100 kPa, particle-to-insulator distance a = 0.1 mm.

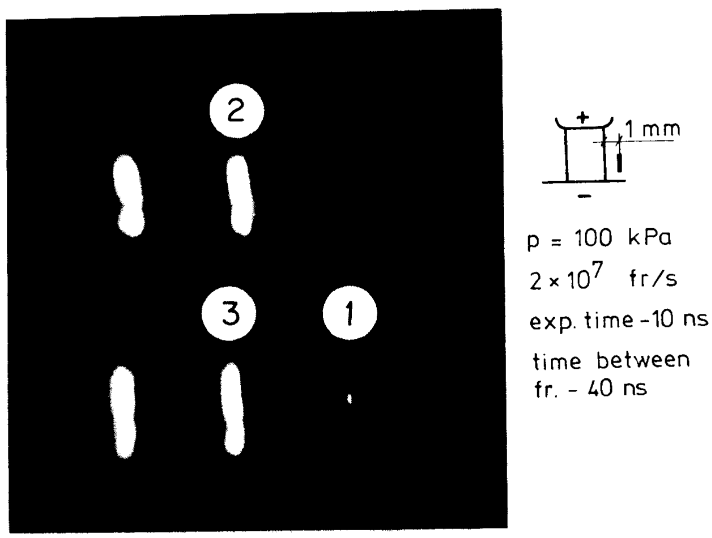

Figure 5.
Framing records of the development of the breakdown, positive impulse voltage, p = 100 kPa, distance a = 1 mm.

distance of 0.1 mm and a gas pressure of 100 kPa. As in all experiments of this investigation, the particle was held 1 mm above the surface of the grounded electrode. It can be seen that the light is first visible at the upper tip of the particle, that is, the tip which is farthest away, 7 mm, from the adjacent, *i.e.* grounded electrode. Discharge activity becomes visible in the 1 mm gap between particle and ground electrode after 5 ns. This sequence of events is different from what was expected to happen in free particle initiated breakdown. The corona discharge at the upper tip of the particle remains restricted to the region near this tip of the particle for more than 8 ns and then a light emitting region, which may be the head of a streamer, moves in the direction of the upper, positive polarity electrode. In the mean time, discharge activity has taken place at the surface of the upper electrode and is followed by the propagation of a positive streamer towards the grounded electrode. The velocity of propagation of both streamers is of the same order of magnitude, *i.e.* $\approx 3.6\times10^6$ m/s for the positive streamer and 1.6×10^6 m/s for the negative streamer. When both streamers meet, a partial arc is formed which extends from the upper tip of the particle to a point on the surface of the insulator approximately at mid height. This situation lasts for

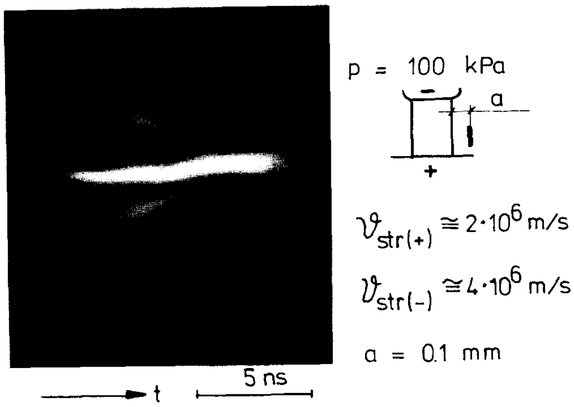

Figure 6.

Streak photograph of the initial stage of breakdown, negative impulse voltage, p = 100 kPa, particle to insulator distance a = 0.1 mm.

$\sim$ 60 ns, after which the partial arc evolves into a complete breakdown arc that bridges the gap between the electrodes. The latter sequence of events can be seen in the slower streak and framing photographs. For this same arrangement, Figure 5 shows the development of the breakdown recorded with the camera in the framing mode. The discharge to the insulator surface can be seen in the first frame. The above results were obtained with positive impulse voltage applied to the upper electrode. In this case, the particle is close to the electrode of negative relative polarity. Upon reversal of the polarity of the applied voltage, an interesting change in the initial stage of the breakdown development is observed. The duration of the initial light emission at the upper tip of the particle is considerably reduced. An example of the difference in duration is obtained from a comparison of Figures 4 and 6 which are for a gas pressure of 100 kPa and the particle located 0.1 mm from the surface of the insulator. The velocities of propagation of the negative and positive streamers are of the same order of magnitude for both polarities of applied voltage. In the development presented in Figure 6, the negative and positive streamers have velocities of $\approx 4\times10^6$ and 2×10^6 m/s, respectively.

The propagating velocity of the streamers decreases if the separation between particle and insulator surface is increased. For instance the streak record of the earlier stage of the breakdown, at 100 kPa and the particle to insulator distance of 8 mm, shows the reduction in streamer velocity to be 8.8×10^5 and 8.9×10^5 m/s for negative and positive streamers, respectively.

With 8 mm distance between the particle and the insulator the discharge can develop entirely in the gas at a certain distance from the insulator surface as shown in Figure 7.

A decrease in the velocity of propagation of the streamer head with an increase in the distance between the metallic particle and the insulator surface is associated with the role the insulator plays in the multiplication of charge carriers. It has been shown that the streamer propagation velocity is a function of the charge density at the head of the streamer channel [21]. The velocity is found to be proportional to the cube root of the charge density at the streamer tip [22]. Based on this and the experimental results, Figure 15, it is estimated that increasing the distance between the insulator surface and the site of discharge initiation from 0.1 to 8 mm, reduces the charge density approximately by a factor of sixty during the development of the breakdown.

An increase in gas pressure is a major cause for an increase in the velocity of streamer development. It can, for example, be seen from Figures 6 and 8 that an increase in gas pressure from 100 to 400 kPa caused an approximately tenfold increase in the speed of propagation of the streamer head (from 1×10^6 to 2×10^7 m/s). A decrease in the duration of the initial corona, which precedes the streamer developing from the upper tip of the particle, is also observed if the gas pressure is increased.

At high gas pressure, 580 kPa, the development of the discharge is different from that at atmospheric pressure. First, the initial discharge in this case is always initiated at the electrode that has positive relative polarity, regardless of the actual location of the particle. Thus, with positive impulse voltage applied to the upper electrode and the particle adjacent to the electrode of negative relative polarity, the discharge is initiated at the region of the upper electrode. As shown in Figure 9 this discharge propagates as a positive leader towards the upper tip of the metallic particle until the distance between upper electrode and particle is bridged. At this time, a discharge between the particle and the lower electrode has bridged this 1 mm gap. A partial arc is formed between the upper tip of the particle and the insulator surface as can also be seen in Figure 10.

Maintaining the high gas pressure of 580 kPa, but reversing the polarity of the voltage applied to the upper electrode, resulted in temporal development of the breakdown as shown in Figure 11. The discharge is initiated at the lower electrode, which in this case has the relative positive polarity, and is a micro discharge between this electrode and the particle. This micro discharge connects the particle conductively to the positive polarity electrode, thus creating a large protrusion from which a

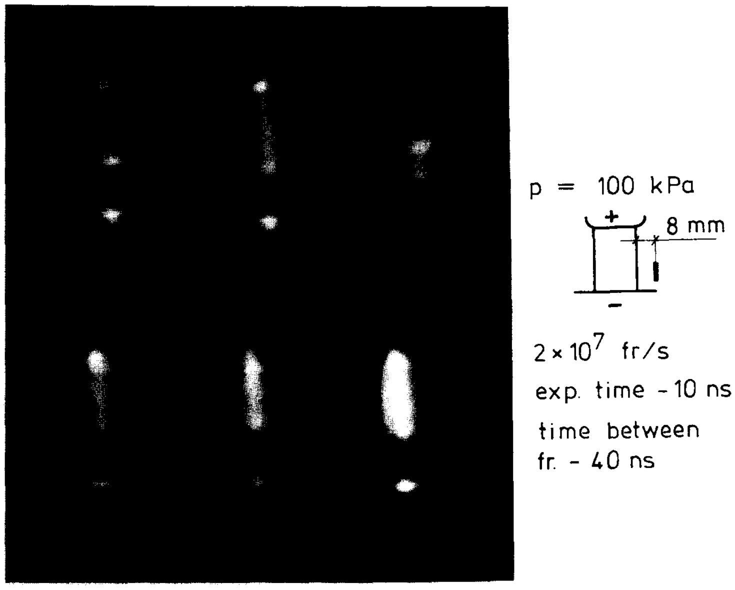

Figure 7.

Framing records of the development of the early stages of the breakdown, positive impulse voltage, $p = 100$ kPa, particle to insulator distance $a = 8$ mm.

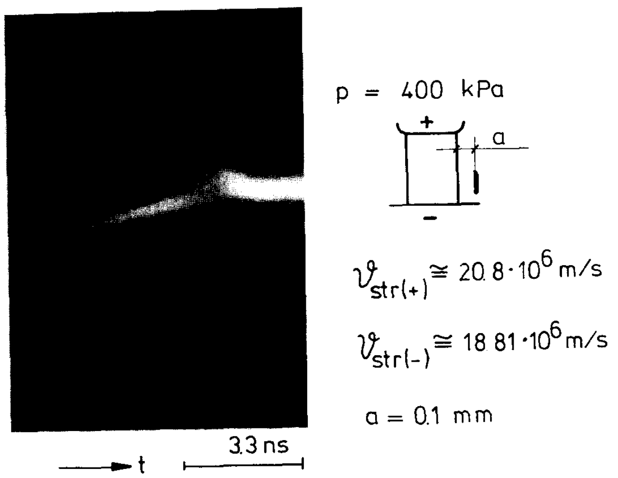

Figure 8.

Streak photograph of the breakdown development, positive impulse voltage, $p = 400$ kPa, particle to insulator distance $a = 0.1$ mm.

positive stepped leader discharge develops, the sequential steps of this leader discharge can clearly be seen in Figure 11. The time intervals between steps are estimated to be $\sim$ 2 ns each. The effective velocity of propagation of the leader can be derived from Figure 11 and is $\sim 3\times10^6$ m/s. The same type of breakdown development recorded with the camera in the framing mode is shown in Figure 12. It is worth noting that Figure 12 and other framing pictures obtained at the same polarity, show that the discharge development does not have to involve the insulator surface. This observation does not necessarily contradict any conclusions presented by others [20, 23].

4. DISCUSSION

4.1 ROLE OF THE METALLIC PARTICLE IN THE DISCHARGE DEVELOPMENT

It is a well established fact that the presence of conducting particle contamination drastically reduces the withstand voltage of compressed gas insulated systems. Experimental and analytical studies have shown that the largest reduction of insulation strength of a system occurs if metallic particles are free to move in the gas and can come near, but not touch, the surface of the electrode, which is opposite to the one from which the particles were lifted [14, 15]. The particle initiated breakdown is a two-gap process, which may be studied by means of a particle fixed at a certain critical distance from the electrode with the higher electric field at its surface [14]. Since the response of particle motion to voltage variation is slow, the effect of free conducting particles on the breakdown voltage, due to their movement, is of no consequence even

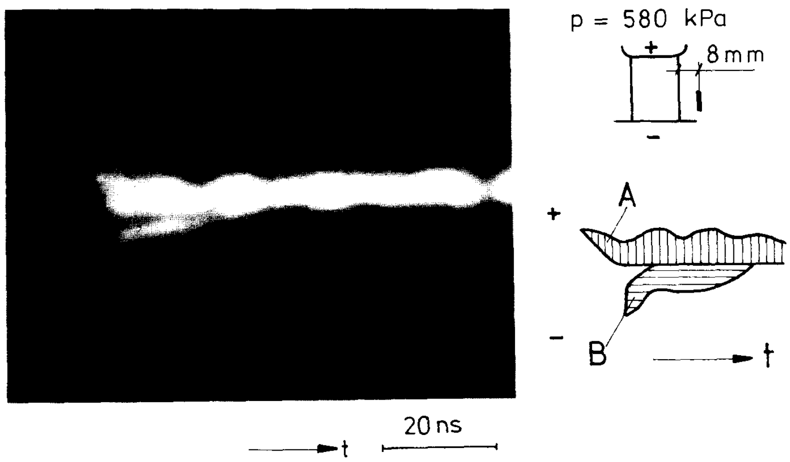

Figure 9.
Streak photograph of the breakdown development, positive impulse voltage, $p = 580$ kPa, $a = 8$ mm.

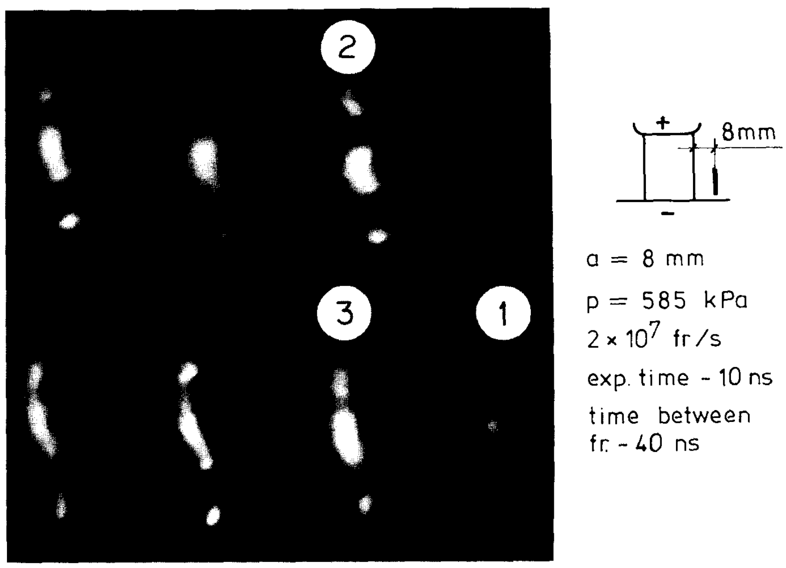

Figure 10.
Framing record of early stages of the development of breakdown, positive impulse voltage, $p = 585$ kPa, $a = 8$ mm.

under switching surges. However, impulse voltages are used to enable the recording of the temporal development of discharge with high-speed photographic techniques.

It was observed that at atmospheric pressure a discharge, recorded with the apparatus, always was detected first at the upper tip of the particle, that is, that end of the particle farthest away from the nearby electrode. Figures 4 and 6 are two examples of this observation. This does not contradict the generally accepted explanation of free particle initiated breakdown being a two-gap process in which the breakdown is initiated by a micro discharge between the particle at a short critical distance from the highest field electrode. The investigations reported in this paper were carried out with particle fixed at a distance from the grounded electrode which differed from the critical distance. The first light emission (corona) that can be observed occurred at the upper tip of the particle. The occurrence of corona is associated with

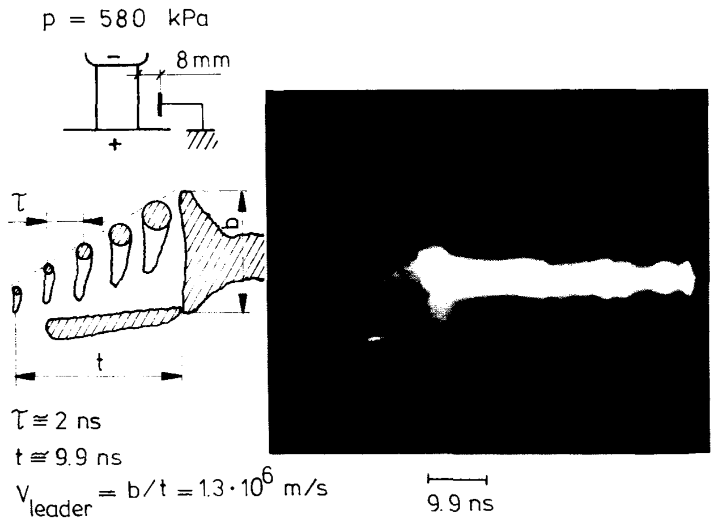

Figure 12.
Framing records of breakdown development, negative impulse voltage, $p = 585$ kPa, $a = 8$ mm.

Figure 11.
Streak photograph of the positive step leader development from upper tip of the particle, $p = 580$ kPa, $a = 8$mm.

a corona current. This current must pass through the short, 1 mm gap, between particle and lower electrode. For this, the particle must be conductively connected to the lower electrode. It is conceivable that, regardless of the polarity of the applied impulse voltage, the actual initial event is a low intensity, not observable, discharge in the nonuniform field of the 1 mm gap. This conductivity connects the particle to the lower electrode, which considerably increases the field enhancement factor at the upper tip of the particle. By this time, the magnitude of the applied voltage has increased to cause corona at the upper tip of the particle with an intensity that can be observed.

4.2 PARTIAL ARCS AND INSULATOR DAMAGE

The observed partial arc event is not yet fully understood. Because of the law of continuity, the partial arc current must follow a path that forms a complete circuit. Probably the current circuit is completed through the capacitance between the tip of the partial arc and the upper electrode, and the capacitance created by the upper part of the insulator (Figure 13). On the insulator surface, charge is generated with a relatively high density. This surface charge interacts with the charge of the head of the developing breakdown channel. As a result, two forces are acting on the head of the developing breakdown channel, F_p, formed by the external field, and the second one, F_n from the surface charge. The polarity of the applied voltage impulse and the presence of a surface charge will determine whether the developing flashover

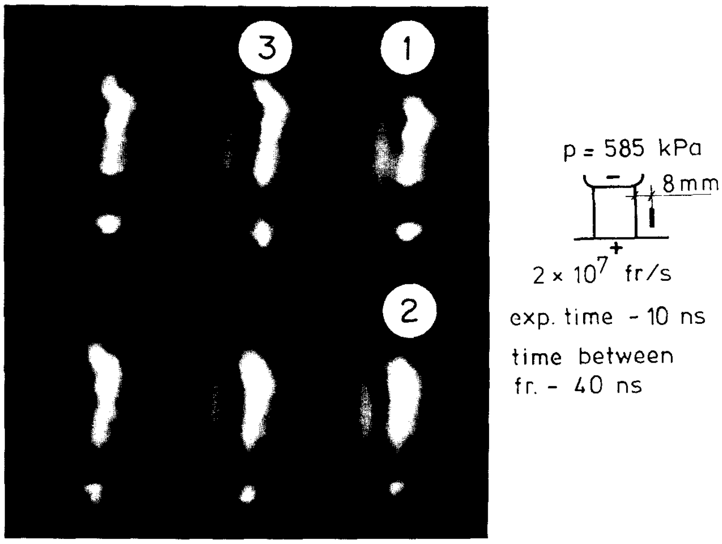

Figure 13. Electric forces and equivalent capacitances for a partial arc.

channel will follow a path through the surrounding SF_6 medium or will be diverted to the surface of the insulator. An example of this is shown in Figure 10, where a positive voltage impulse is applied to the upper electrode at a pressure of 580 kPa, and the breakdown channel is directed to the insulator surface, even though the particle is located 8 mm from the surface. Based on a series of framing and streak photographs, it has been observed that the partial arc at high pressure (580 kPa) persists $\approx$ 200 ns before the complete breakdown arc that bridges the electrodes is formed. This time is considerably longer than that observed at atmospheric pressure. The interaction of the tip of the partial arc and the insulator may cause damage to the insulator. A rather extreme example of damage experienced during these particular experiments is shown in Figure 14.

After changing the polarity of the applied impulse voltage to the upper electrode, the positive step leader developed from the upper tip of the particle. In this case, especially at the highest pressure, the discharge channel is instead pushed away from the insulator surface (Figure 12), and insulator damage is less probable.

4.3 VELOCITY OF THE DISCHARGE DEVELOPMENT

The many streak photographs that were made show that the velocity of propagation of streamers during the initial stages of the discharge varies with the gas pressure and the distance between the particle and the insulator

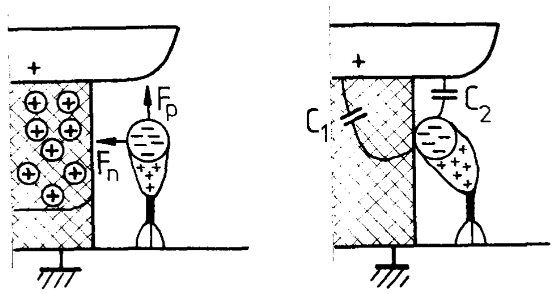

Figure 14. Damaged insulator.

surface; however, it was clearly shown that the propagation velocity of streamers is practically independent of the pressure [1]. The actual cause of the apparent increase in streamer velocity with pressure, is the increased electric field that is associated with the higher breakdown voltages at higher gas pressures.

The results obtained here indicate also that the distance between the particle and the insulator surface influences the velocity of flashover development. From many stress photographs obtained at a pressure of 100 kPa, the average streamer propagation velocity was established as a function of particle to insulator distance. This relationship for the positive streamer is shown in Figure 15. It can be seen, that streamer propagation velocity decreases exponentially with increasing distance between particle and insulator.

An increase in SF_6 pressure also leads to a transition

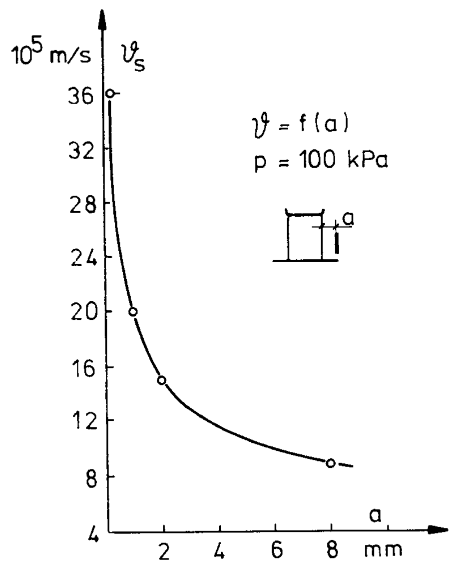

Figure 15.

Propagation velocity of initial streamer at p = 100 kPa as a function of particle-to-insulator distance.

from a streamer mechanism to a stepped leader mechanism of discharge. It was observed that at higher pressure, 580 kPa, the leader discharge always originated from an electrode that had the positive polarity. The stepwise development of a leader may be characterized by the step length, the time interval between steps, and the effective velocity of propagation. Figure 11 is a clear example of a positive leader developing from the tip of the metallic particle that is conductively connected by a microdischarge to the electrode that has a relative positive polarity. The individual steps in the leader occur in time intervals of $\sim$ 2 ns. This interval is shorter than $\sim$ 6 ns at 500 kPa mentioned by Niemeyer for a point to plane geometry without an insulator [3]. A slightly shorter time interval could be caused by the small difference in gas pressures. It has been observed that the pause time between steps decreases approximately inversely proportional with pressure [24]. Also, the step length varies inversely with the gas pressure [25]. Thus, an increase in pressure tends to decrease the time interval between steps. The velocity of propagation of the leader shown in Figure 11, follows from the gradient of the trace of the leader head as shown in the photograph and is $\approx 1.3 \times 10^6$ m/s

5. CONCLUSIONS

In the presence of a metallic particle, the breakdown strength of an SF_6 test gap bridged by an alumina filled epoxy spacer is drastically reduced. The discharge always involves the particle. The breakdown strength has a tendency to increase when one increases the distance between the particle and the insulator in the presence of a lightning impulse voltage. The velocity of the breakdown development is also dependent on the particle-to-insulator distance, and increases exponentially as the distance decreases.

An important element of the development of particle initiated flashover is a discharge between the upper tip of the particle and the insulator surface, which we call a partial arc. At high pressure, 580 kPa, and with positive impulse voltage applied to the upper electrode, a partial arc may exist for as long as 200 ns. This we assume, causes the insulator damage.

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