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Influence of corona discharges on the breakdown voltage of airgaps

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Abstract

Measurements with rod-rod and rod-plane gaps result in a large scatter in the values of breakdown voltage at certain gap distances. The scatter in the figures depends on the change of the corona mode. The transition in predischarges at certain gap distances results in two different breakdown voltages. It is shown that this scatter can be observed with all investigated voltage shapes (alternating and direct voltages, lightning and switching surges). The paper also deals with the possibilities of influencing the scatter of the values of breakdown voltage.

1 Introduction

In recent years, many experiments have been conducted on the breakdown mechanism of airgaps with inhomogeneous fields. Most of the tests have indicated the influence of corona behaviour on the flashover mechanism.[1–5] As a result of these investigations at short distances, the primary processes, the physical behaviour of the predischarges and the transition of predischarges into the final breakdown, have been partly explained. However, from the engineering point of view, it is also important to know the values of breakdown voltage, their scatter, the physical causes of the scatter, and the way to influence them.

Especially with lightning impulses, the breakdown voltage at certain sizes of airgap having an inhomogeneous field distribution shows a large unexplained scatter."[6, 7] The paper shows that the scatter in the breakdown voltages of airgaps at large distances can be explained by the consideration of predischarges.

For the technical application of airgaps as protection gaps or as references in the design of electrical apparatus, knowledge of the scatter in the values of breakdown voltage is very important. It is also necessary to know how this can be influenced.

Therefore, in the experiments performed, the range of breakdown voltages observed was that in which a large scatter occurs. The physical cause of the scatter in breakdown voltages is normally the corona discharge, and tests were conducted with various voltage waveshapes to demonstate that the variation in the corona behaviour changes the breakdown voltage for all these wave shapes. If the different possibilities that influence the breakdown voltage are known it is possible to design the apparatus in such a way that the influence is optimal or beneficial.

2 Test arrangement and test procedure

All tests were performed on vertical rod-plane or rod–rod gaps in air. The shape of the rod electrode was either hemispherical, pointed, with a 0·3mm-radius tip, or blunt-edged; the diameter of the rod was 20mm. Investigations were carried out with direct voltages, alternating voltages (50Hz), switching surges of 60/525μs and lightning surges of 1·2/50μs. The breakdown voltage was always corrected to normal atmospheric conditions (20°C, 760torr, 11gf/m^3).[8]

For direct and alternating voltages, the mean value of the breakdown voltage was determined with 20 flashovers. These were entered on the probability paper in accordance with the method given by Henning and Wartmann.[9]

The results of impulse tests were also obtained from the probability paper. Every flashover probability was measured with at least 20 impulses.[8] For a normal distribution of the flashover probability, the 50 % breakdown voltage was determined with about 7 $\times$ 20 impulses. For mixed distributions, the number of shots can be seen from the Figures.

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3 Results

Within a certain range of gap distances, a large scatter in the breakdown voltages can be observed with all voltage shapes. In Fig. 1, a measured example shows the principal

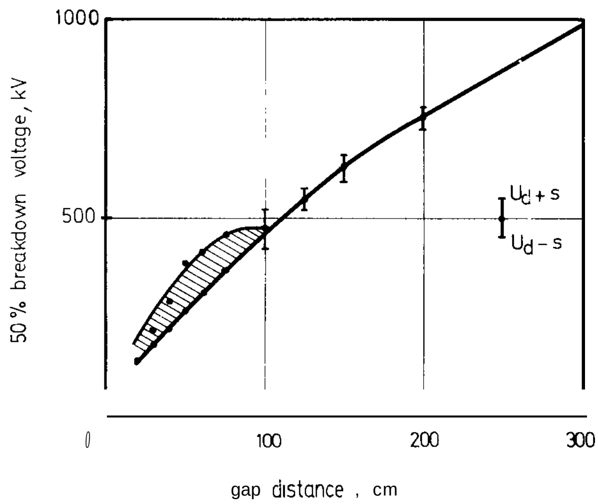

Fig. 1
50 % *breakdown voltages for a rod–plane gap with positive switching surges*

behaviour of breakdown voltage as a function of gap distance including that range for a rod-plane gap with positive switching surges. For this gap arrangement, a transition range can be observed at a distance of 20cm $\leqslant a \leqslant$ 100cm. At gap distances greater than 100cm, the relationship between the 50 % breakdown voltage and the gap distance is characterised by a normal distribution, resulting in only one 50% breakdown voltage for a given gap distance. All the following measurements pertain to the transition range.

On the probability paper, one can often recognise this range of the mixed distribution of the flashover probability in impulse voltages or of the cumulative curve in the flashover voltages with alternating and direct voltages. From the statistical point of view, a mixed distribution means that two different parameters influence the flashover mechanism. Such a situation can be characterised by two mean values and two standard deviations, which are obtained by dividing the mixed distribution, according to the rules of statistics, into two normal distributions (Fig. 2).

In Fig. 2, the mixed distribution of the flashover probability is divided into two normal distributions. For this 50cm rod–plane gap (shape of the electrode: 2cm-diameter hemisphere) with switching surges, the 50 % breakdown voltage is given by two values (U_{d1} = 263 kV, U_{d2} = 391 kV). These two values are entered in Fig. 1, and it is evident that the 50% values of Fig. 1 are received by only one measurement at every gap distance. For a distance of 20cm $\leqslant a \leqslant$100cm, the measurements resulted in mixed distributions. When only one parameter is responsible for the flashover, a Gaussian distribution of the breakdown voltage for airgaps with inhomogeneous fields will normally result (Fig. 2*a*, pointed electrode). It is also possible to obtain a normal distribution in the transition range, when one parameter is dominant.

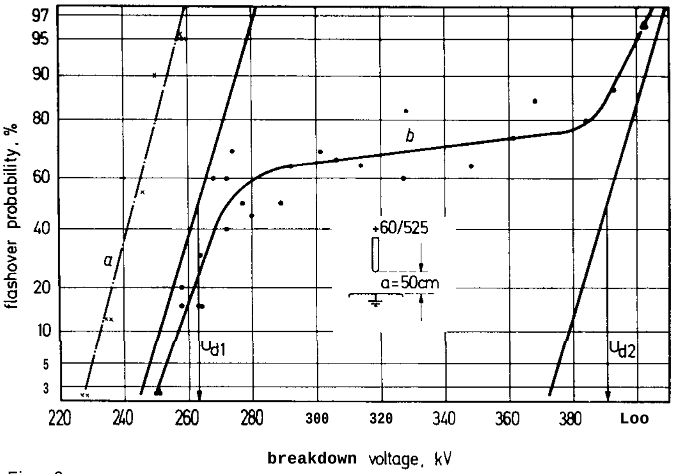

Fig. 2

Flashover probability of 50cm rod-plane gap with positive switching surges

Parameter: shape of the electrode

· · · · 20 impulses
x x x x 20 impulses

a Pointed
b 2cm-diameter hemisphere

For airgaps with inhomogeneous fields it is logical to investigate the corona behaviour to seek an explanation for the scatter in the values of breakdown voltage. This can be illustrated in three ways, each method contributing a different physical explanation:

(a) Each corona mode will be associated with a different current across the gap.[10]

(b) Photographic records of the corona modes can also indicate the two different types of the predischarge (Fig. 3).[14,20] The light emission can also be measured with a photomultiplier, with photographic paper placed between the electrodes, or with an image convertor.

(c) Owing to the change in the kind of predischarges, the time to breakdown will be influenced by the altered distribution of space charge.[10,11]

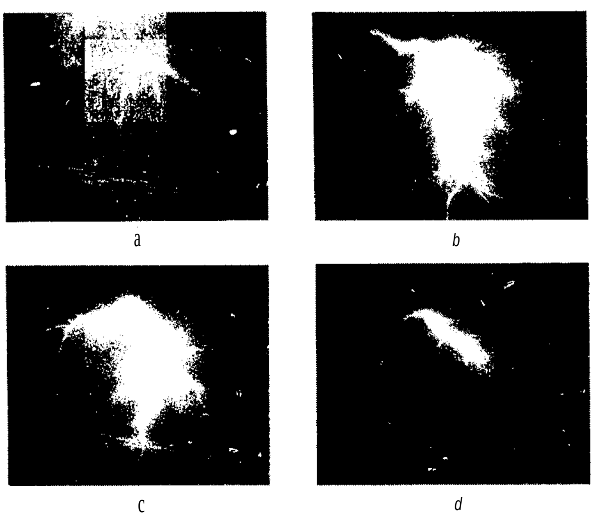

Fig. 3

Photographic record of corona behaviour of 50cm rod-plane gap with positive switching surges

a 2cm-diameter hemisphere
U = 250kV
streamer corona
b 2cm-diameter hemisphere
U = 250kV
leader corona
c Pointed electrode
U = 250kV
leader corona
d Pointed electrode
U = 190kV
leader corona

The connection between a mixed distribution in the flashover probability and the physical cause of it will now be illustrated on one example with method (b). If one considers the predischarges for a 50cm rod-plane gap with switching surges, one can observe the streamer corona (Fig. *3a)* or the leader corona (Fig. 3b). In about 50% of all impulses, the leader corona can be observed. Owing to this alternative corona behaviour, a mixed distribution in the flashover probability appears (Fig. 2), because two different parameters influence the flashover mechanism. For the leader corona, the breakdown voltage corresponds to the lower breakdown voltages of about 263 kV, whereas, for the streamer corona, the higher values will be measured. This can be illustrated with the change of the shape of the electrode. With a pointed electrode, instead of a 2cm-diameter hemisphere, the flashover probability is characterised by a normal distribution. The values of the breakdown voltages correspond to the lower breakdown voltages of the mixed distribution (Fig. 2). The photographic records of the predischarges for the pointed electrode always show the leader corona (Figs. 3*c* and d). Thus the mixed distribution, which is suggested by statistical methods can be explained by the different corona behaviour. The dependence of the breakdown voltage on the gap width also points to this conclusion.[14]

For the investigated waveshapes, the change in the corona behaviour and the consequent scatter in the values of breakdown voltage will now be discussed, and some of the possible ways of influencing this scatter will be considered.

The most important parameter in this respect is the voltage waveshape, since the corona-discharge mode is closely dependent on the wave shape.[8] For example, with lightning surges there is no associated glow corona.[12, 13]

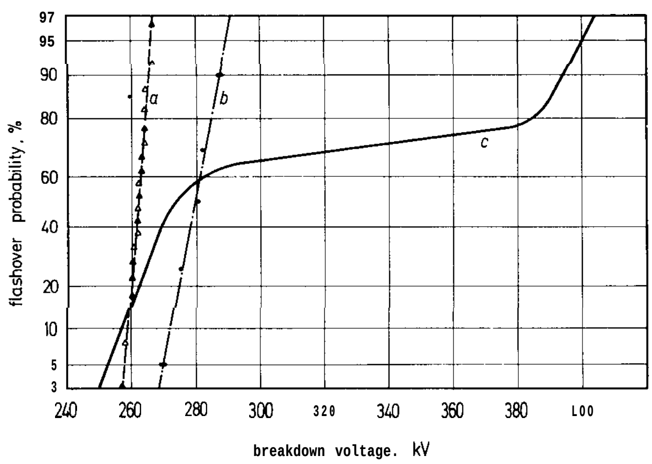

Fig. 4

Flashover probability of 50cm rod-plane gap by different voltage waveshapes with positive polarity

a Direct voltage
b Lightning voltage 1·2/50
c Switching voltage 60/525

Fig. 4 gives a comparison of the distribution of breakdown voltages with various voltage wave shapes of positive polarity for a rod-plane gap of 50cm. For this gap distance a transition range is observed only with positive switching surges, and in this case the transition of streamer corona into leader corona is the physical reason for the mixed distribution, as we have just seen.[14] With lightning impulses and with direct voltages, the breakdown occurs only from the streamer corona. The defined corona behaviour results in a small scatter of the breakdown voltages for the two latter waveshapes.

A further example of the influence of voltage wave shapes on the characteristics of breakdown voltages is shown in Fig. 5. For the negative rod-rod gap with an electrode separation of 50cm, the flashover probability of the lightning voltage and that of the switching voltage is characterised by mixed distributions. Many results reported in the literature, particularly for lightning impulses, show a large scatter in the values of breakdown voltage, but no explanation is given.[1,6,7] In both cases, the physical cause of the mixed distribution is the corona behaviour of the earthed electrode. The onset voltage of the earthed anode is reached, and the breakdown may be either preceded by a streamer **corona or** may take place without any predischarges on the earthed electrode. The lower breakdown voltages of the mixed distributions belong to the flashover following the streamer corona at the anode.[14,15] Note that the tests with lightning impulses are performed with about 6000 impulses.

parameter that influences the transition range is the arrangement of the gap, and, especially for rod-rod gaps, the height of the earthed electrode. In Reference 18, it has been reported that the corona behaviour of a rod-plane gap will be affected when the electrode configuration is reversed. For lightning impulses, the influence of the height of the earthed electrode

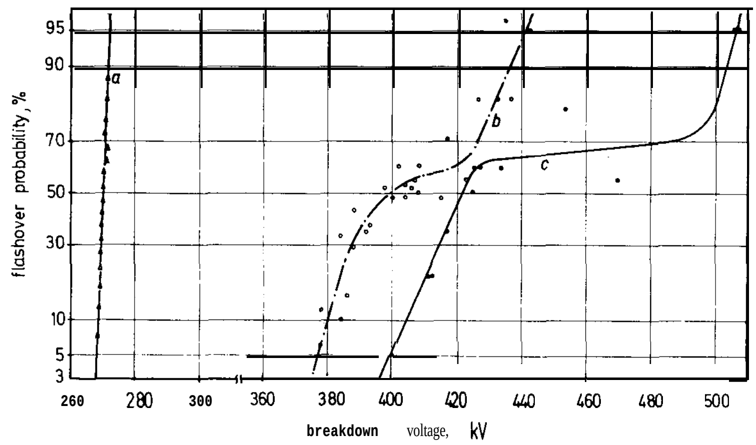

Fig. 5

Flashover probability of 50 cm rod-rodgap by different voltage waveshapes with negative polarity

• • • *20* impulses
0 0 0 100 impulses
a Direct voltage
b Lightning voltage 1·2/50
c Switching voltage 60/525

For the gap arrangements investigated, the transition ranges with different voltage wave shapes are compared in Table 1. Further examples of observed transition ranges, especially those associated with alternating voltages, are given in the literature.[16, 17] Table 1 shows that only at certain distances is a transition range possible. In most gap arrangements, a normal distribution occurs, as is known from the literature. But, although the mixed distribution is only possible at a small range of gap distances, it is very important from the engineering point of view to know where this range occurs and how it can be influenced.

It is almost impossible to define precisely the limits of transition ranges as these depend on several parameters. One

upon the 50% breakdown voltage of a 50 cm gap is given in Fig. 6. In this case, the corona behaviour of the high-voltage electrode, the cathode, does not change in any essential way; however on the earthed electrode, from a certain height of the rod (*h* > 70cm) and over, corona may or may not occur. Presence of corona on the anode leads to a lower breakdown voltage.[15] For heights of the earthed rod of below 70 cm, the flashover probability is characterised by a normal distribution (Fig. 6). A similar effect can be observed in other transition ranges for alternating and direct voltages and **for** switching surges.[8,14]

The next parameter that can influence the breakdown voltage in the transition range is the shape of the electrode.

Table 1

MEASURED TRANSITION RANGE FOR DIFFERENT VOLTAGE WAVESHAPES

Voltage wave shape	Gap arrangement	Shape of electrode	Predischarge I	Predischarge II	Gap distance
Lightning impulse 1·2/50	negative rod-plane	blunt-edged 2cm-diameter hemisphere	diffuse glow corona	streamer corona on the cathode	cm $5 \leqslant a \leqslant 60$ $5 \leqslant a \leqslant 35$
	negative rod-rod	2cm-diameter hemisphere blunt-edged	no corona	streamer corona on the anode	$30 \leqslant a \leqslant 90$
		pointed	no corona	streamer corona on the anode	$15 \leqslant a \leqslant 40$
Switching impulse 60/525	positive rod-plane	2cm-diameter hemisphere	streamer corona	leader corona on the anode	$20 \leqslant a \leqslant 100$
	positive rod-rod	2cm-diameter hemisphere	streamer corona	leader corona on the anode	$30 \leqslant a \leqslant 125$
	negative rod-rod	2cm-diameter hemisphere	no corona	streamer corona on the anode	$40 \leqslant a \leqslant 125$
	negative rod-plane	blunt-edged	diffuse corona	streamer corona on the anode	$10 \leqslant a \leqslant 55$
Direct voltage	positive rod-rod	blunt-edged	glow corona	streamer corona on the anode	$a > 50$
	positive rod-plane	2cm-diameter hemisphere	glow corona	streamer corona on the anode	$20 \leqslant a \leqslant 60$
Alternating voltage	rod-plane rod-rod	pointed 2cm-diameter hemisphere	streamer corona	leader corona	$a > 50$ $9 g/m^3 \leqslant \phi_a \leqslant 20 g/m^3$

The results of measurements with lightning impulses verify this statement (Fig. 7). With a 2cm-diameter hemisphere electrode on the earthed side of the rod-rod gap, it is possible to observe a mixed distribution for the flashover probability. When the hemispherical anode is replaced by a pointed electrode, a normal distribution results. The reason for this is that the field on the anode is far beyond the onset voltage. The effect of the influence of the shape of the electrode was also discussed earlier (Fig. 2).

The above two parameters alter the static electric field. It should be pointed out that this field can be influenced also by the geometry of surroundings and the high-voltage connection. This observation has been confirmed by calculations and measurements of the onset voltage on sphere gaps made by Steinbigler.[19]

It is also very interesting to observe that the breakdown voltage, as shown in Fig. 8, can be influenced not only by the resultant electric field (including space-charge effects), but also by discharge products of those predischarges that occur away from the investigated electrode, e.g. the high-voltage lead. Positive ions produced by streamer corona on the vertical high-voltage lead may move into the interelectrode space, thus affecting the electric field and thereby causing the breakdown voltage to rise. Thus the onset voltage rises with consequent alteration of the gap distance for which the transition from breakdown without predischarge to that with streamer corona takes place. Once the electrode goes into corona, the influence of corona on the high-voltage lead becomes negligible (Fig. 8, a = 180cm). At all these tests shown in Fig. 8, the standard deviation was smaller than 2%.

For the development of the predischarge, the atmospheric conditions are also important, in particular the humidity. In the test represented by Fig. 9, the streamer corona and the leader corona can be observed as the two causes of the

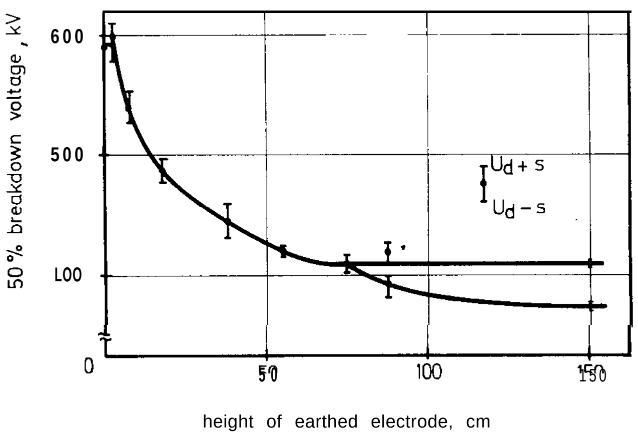

Fig. 6

Influence of height of earthed electrode on 50% breakdown voltage of a 50cm rod-rod gap with negative lightning impulses

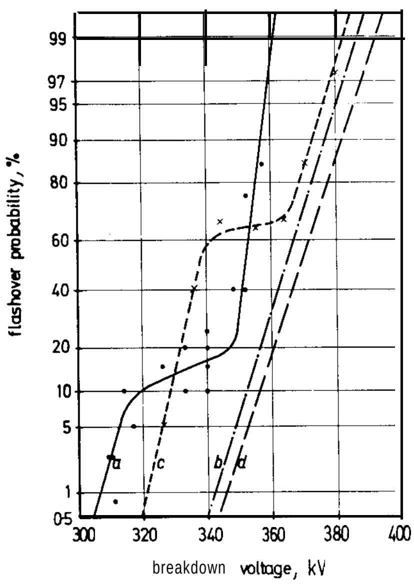

Fig. 7

Influence of shape of electrode on flashover probability of 40cm rod-rod gap with negative lightning impulses

● ● ● 20 impulses
x x x 20 impulses

a 2 cm-diameter-hemisphere/2 cm-diameter-hemisphere
b 2cm-diameter-hemisphere/pointed (30°)
c Pointed (30°)/2 cm-diameter-hemisphere
d Pointed (30°)/pointed (30")

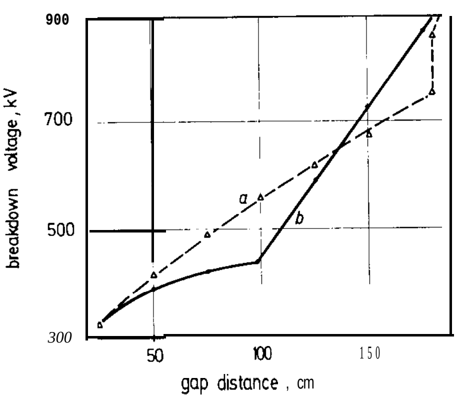

Fig. 8

Influence of corona on high-voltage lead on breakdown voltage of 25cm sphere-plane gap with positive direct voltages

a With corona on the lead
b Without corona on the lead

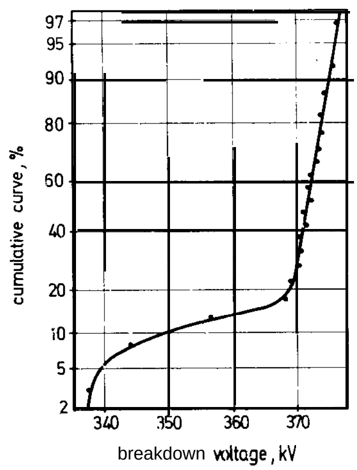

Fig. 9

Alternating breakdown voltages of 70cm rod-rod gap with pointed electrode

Absolute humidity
ϕ_a = 12·6 gf/m³)

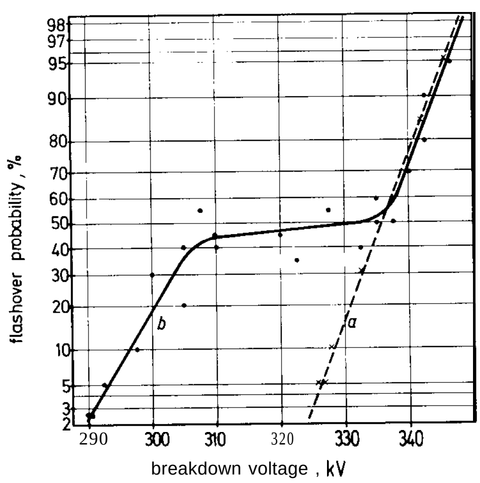

Fig. 10

Influence of source impedance on breakdown voltage of 40cm rod-rod gap with negative lightning impulses

● . ● 20 impulses
x x x 20 impulses

a C_h = 500 pF
b C_b = 1500 pF

mixed distribution. For reduced absolute humidities, only the streamer corona would be observed, while for higher absolute humidities the breakdown occurs from the leader corona.[20]

It should be noted that the source impedance of the voltage generator also has an influence on the breakdown voltage in the transition range.[15] For $1\cdot2/50\,\mu s$ lightning impulses, for example, with the 40cm rod-rod gap with negative excitation, the influence of the source impedance on the breakdown voltage can be observed. For the higher source impedance, corona discharge on the earthed electrode always takes place (Fig. 10).

4 Conclusions

Based on results of tests with alternating and direct voltages, as well as with switching and lightning surges applied to rod-plane and rod-rod gaps in air, it is concluded that the change in the corona mode at gap electrodes significantly influences the breakdown voltage. The predischarge process itself is determined by the waveshape of the applied voltages, by the arrangement of the gap, by the shape of the electrodes, by the geometry of the surroundings, by the atmospheric conditions and by the source impedance. The possible variation in predischarges is associated with the observed large scatter of breakdown voltages.

For an optimal design of electrical apparatus, the transition range and its physical cause must be known. Only with this knowledge is it possible to explain the observed large scatter in results from comparative tests.[6,7]

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