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Breakdown Behaviour of Air Spark-Gaps with Non-Homogeneous Field at Bias Voltages

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Breakdown Behaviourof Air Spark-Gaps With Non-Homogeneous Field at Bias Voltages

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This paper examines the breakdown behaviour of air spark-gaps with a non-homogeneous field at bias voltages (d.c. voltage with superimposed impulse voltage). The results show the decisive role played by pre-discharges in the breakdown process. Besides the influence of d.c. voltage on the 50% breakdown voltage, the author also examines the influence exerted on the volt-time-curve by preliminary stress due to d.c. voltage. In the case of air spark-gaps with large distances, bigpre-discharge currents occur during short disruptive periods $(T_d < 5\,\mu s)$ before the voltage breakdown. The space-charge applied to the gap by the predischarge current increases with the diminution of the breakdown-time. Part of this charge can be absorbed by a preliminary d.c. voltage stress, while the volt-time-curve itself is not influenced by the value of d.c. voltage.

Although information on breakdown behaviour of non-homogeneous fields such as prevailing in high voltage networks and switching stations can be obtained only by experimental investigation, no systematic research on the strength of air at bias voltage stresses has yet been made. Such investigations are however an essential preliminary condition for an optimum design of electric equipment, as it is precisely at the highest working voltages that the continuous working voltage stress may reach values of the order of overvoltage value. It is also well understandable that the behaviour of air spark-gaps is influenced by a continuous stress,

Up to date, systematic experimental research covering the behaviour in air of insulating devices at d.c. and superimposed impulse voltages has been done at voltages under 100 kV [1;2]*.

The present contribution investigates experimentally the behaviour of air spark-gaps with non-homogeneous field distribution at high d.c. voltages (up to 500 kV) and superimposed high impulse voltages (up to 2000 kV).
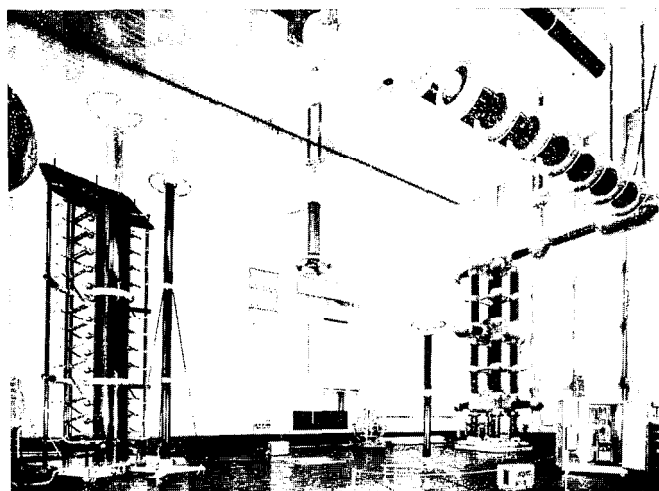

Fig. 1
Bias test system with 3 MV impulse voltage generator
and 1.4 MV d.c. generator

*cf. literature index at the end

Test Circuit

The experimental investigations were done at the High Voltage Institute of the Munich Technical University [3] (fig. 1). D.c. voltage was generated by means of a 1.4 MV d.c. system consisting of a 1.2 MV transformer, a rectifier and a 16 nF smoothing capacitance. Measurement of the d.c. voltage was made by the intermediary of an ohmic voltage divider with an electrostatic voltmeter. Unipolar overvoltages were produced by means of a 12-stage Marx-type 3 MV impulse generator. Impulse voltage was measured directly on the spark-gap by means of a damped capacitive voltage divider [4] with an impulse peak voltmeter.
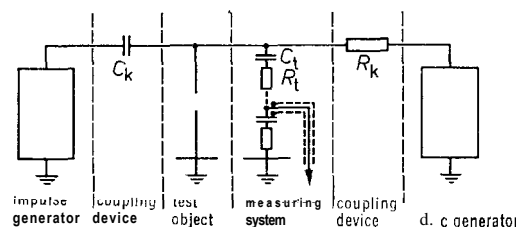

Fig. 2
Basic diagram of a combined d.c. and impulse voltage stress
C_k 48 nF coupling capacitor C_t 291 pF divider capacitance
R_k 4 MΩ coupling resistance R_t 758 Ω divider resistance

The basic diagram of the whole test circuit is shown in fig.2. Both voltage generating systems are uncoupled by means of appropriate coupling devices which have to warrant a reaction-free superposition of the two voltages. With other words, while no resistance is shown to their own circuit, they must oppose an infinitely high resistance to the adjoining circuit.

A 48 nF capacitor was used as a coupler between the impulse generator and the object under test, this capacitor being at the same time an additional smoothing capacitance of the d.c. system.

Coupling of d.c. voltage was achieved by means of a 4 MΩ water resistance. This arrangement made it possible to superimpose any desired d.c. voltage amplitude and polarity on any desired impulse voltage.

All measurements were done on vertically mounted spark-gaps earthed at one pole. Investigations covered not only the rod-plane

2. Quadrant
negative d.c. voltage
positive impulse voltage

1. Quadrant
positive d.c. voltage
positive impulse voltage

3. Quadrant
negative d.c. voltage
negative impulse voltage

4. Quadrant
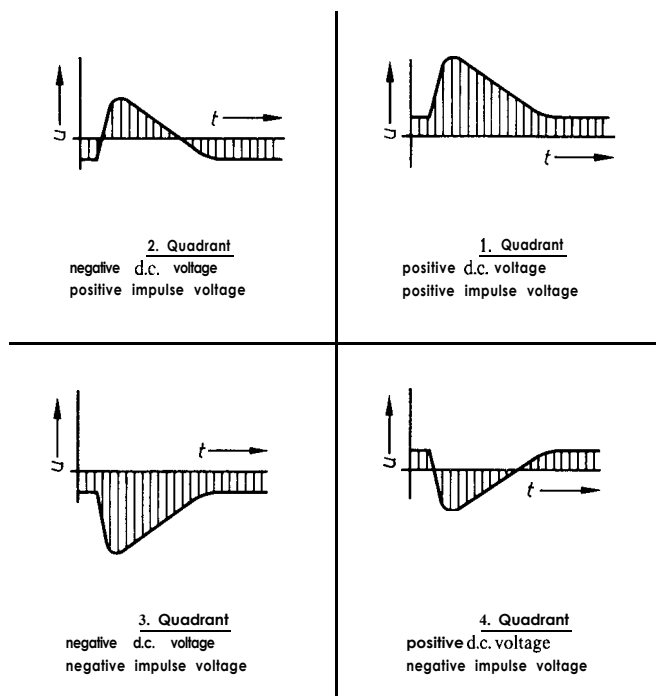positive d.c. voltage
negative impulse voltage

Fig. 3
Schematic repartition of curves with two superimposed voltages
t time; *u* voltage

spark-gap, where pre-discharges are limited to one electrode, but also the rod-rod spark-gap.

A 2 x 2 m² aluminium plate was used in the rod-plane spark-gap arrangement. The rod electrode consisted of a brass tube having a diameter of 20 mm.

In the rod-rod spark-gap arrangement, the rod electrode to earth was 2 m high, its diameter being equally 20 mm. The brass tubes could be terminated by various electrode heads (2 cm-hemisphere, 30°-pointed, obtuse) [5].

Test Procedure

An impulse voltage is superimposed on a d.c. voltage having a determined value and polarity, the amplitude of this impulse voltage being modified in such a way that breakdown probability can be measured between 0...100%. The distribution curve obtained is set up by means of at least 140 voltage impulses; %-values under 20% and over 80% of breakdown probability are determined, for statistical reasons, with the double number of voltage stresses [6]. If the breakdown process is influenced only by one significant parameter, the breakdown probability can be estimated with the aid of a normal distribution. In such cases, a measurement is clearly defined by the value of a 50%-breakdown-voltage and the standard deviation. Under particular conditions, breakdown process is influenced by several parameters and the observed mixed distribution can be split up, according to statistical laws, in two or more normal distributions. The physical reason of the mixed distribution is the change in predischarges which, in case of spark-gaps with non-homogeneous fields, has an essential influence on the breakdown process [7 ; 8].

Correction of air density for the measured voltage values is made according to [9]. Correction of humidity is not done.

Breakdown voltages U_d of a test arrangement can be well represented by means of four quadrants (fig. 3). Breakdown voltage U_d corresponds in this case to the sum, with proper plus/minus signs, of d.c. voltage U_{gl} and of the 50% value of impulse voltage $U_{d\ 50\%}$. The four possible combinations of bias voltages can thus be featured as follows:

Quadrant 1: positive d.c. voltage with positive impulse voltage
Quadrant 2: negative d.c. voltage with positive impulse voltage
Quadrant 3: negative d.c. voltage with negative impulse voltage
Quadrant 4: positive d.c. voltage with negative impulse voltage.

Fig.3 also shows the basic voltage shape in each of the four quadrants.

Test Results
*Influence of dc. voltage value on the
50%-breakdown-voltage*

Fig. 4 shows the breakdown, voltage in function of the d.c. voltage, with a 25 cm spacing between the rod-plane spark-gap having a 2 cm hemispheric terminal electrode. The figure shows that the parallels to the abscisses mean that the breakdown voltage does not depend on the d.c. voltage value. The voltage value from the interrupted 45°-line on and up to the positive breakdown line represents the share of the positive 50% breakdown voltage. A corresponding value from the 45°-line down to the negative breakdown line results for the negative polarity. According to fig. 4, a positive 345 kV impulse voltage is necessary for a negative − 200 kV d.c. voltage, in order to reach the positive breakdown line. A negative breakdown calls for a negative − 180 kV impulse voltage. This illustration clearly shows the influence of d.c. voltage on breakdown voltage.
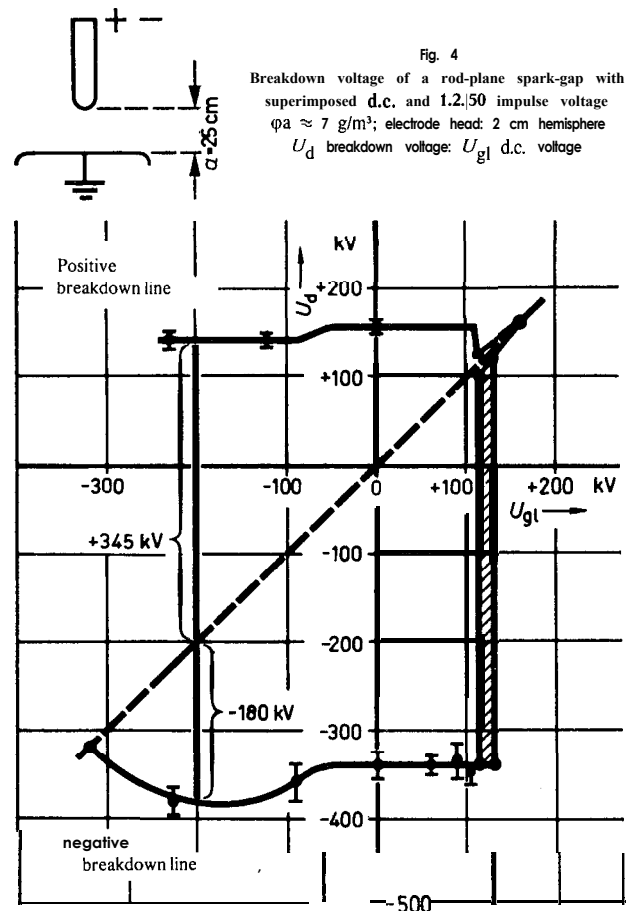

Fig. 4
Breakdown voltage of a rod-plane spark-gap with superimposed d.c. and 1.2.|50 impulse voltage
$\varphi a \approx 7$ g/m³; electrode head: 2 cm hemisphere
U_d breakdown voltage: U_{gl} d.c. voltage

Fig. 4 also shows that pre-stressing the spark-gap with a negative d.c. voltage leads to a slight voltage jump when streamer-corona starts; this voltage jump becomes a voltage drop of about 12 kV in case of positive impulse voltage, while it results in a voltage increase of about 22 kV in case of negative voltages. A negative d.c. voltage breakdown results in a lower breakdown voltage.

Much more remarkable is the behaviour of this arrangement with positive d.c. voltage. D.c. voltage breakdown follows out of the glow-corona under the given ambient conditions. Fig. 4 shows that a voltage rise corresponds to glow-corona at both polarities of impulse voltage. Breakdown voltage is independent of d.c. voltage value up to the point when glow-corona starts.

If one considers the probability of breakdown in function of the breakdown voltage when a positive + 115 kV d.c. voltage is superimposed to a negative impulse voltage, two significant influencing parameters appear very clearly (fig. 5).
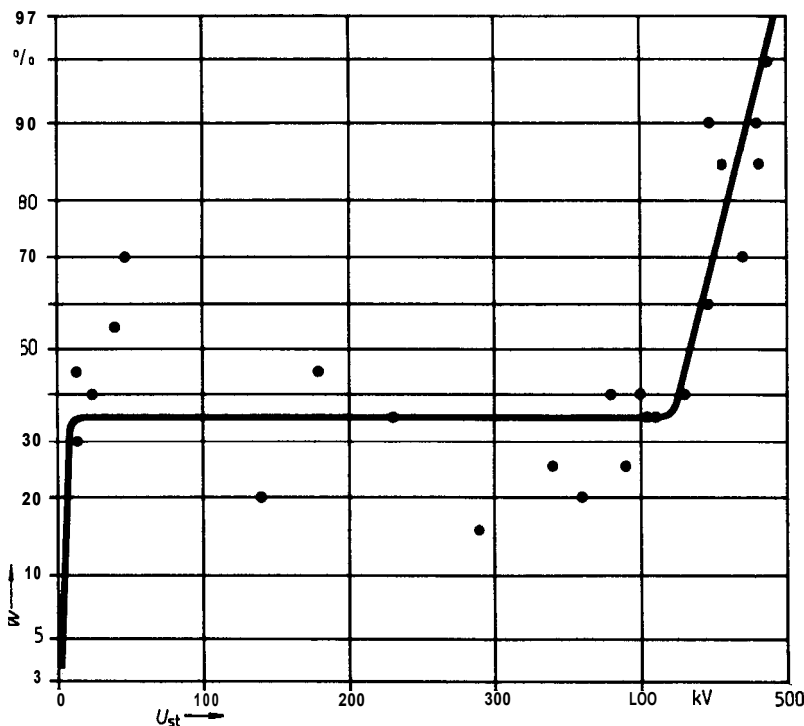
voltage strength of 4.6 kV/cm for the steamer-corona can be expected. The impulse voltage amplitude is not a determining factor for the disruption of the glow-corona (fig. 5).

These results have been confirmed by measurements made by *Jaumann* [11], *Toepler* [12], *Deutsch* [13] and *Rasquin* [1], who have also found, in the glow-corona range, a high sensitivity of d.c. voltage strength to a superimposed impulse voltage.

If spacings are larger, d.c. voltage breakdown on the 2 cm hemispheric electrode at positive polarity originates from the streamer-corona, and at negative polarity also from streamer-corona. Fig. 6 shows that in case of negative pre-stress, value of d.c. voltage has practically no influence on breakdown voltage. The total breakdown voltage value is more or less constant at both impulse voltage polarities. If a 30" electrode spike is used, no influence can be seen on the positive breakdown characteristic, as breakdown originates from the streamer-corona. The third quadrant illustrates very distinctly an influence on breakdown voltage due to modification of the pre-discharge on the 30° spike. Breakdown voltage decreases about 20% up to the pre-discharge alteration and increases again when streamer-corona appears; it approaches the breakdown voltage values when a 2 cm hemisphere is used as an electrode head. Use of the latter electrode did not lead to any impulseless negative pre-discharge in the investigated range.

A slight decrease of breakdown voltage as from the value of the onset-voltage can be observed in case of superimposed positive voltages (first quadrant). D.c. voltage breakdown shows the lowest breakdown voltage value.

If a negative lightning impulse voltage is superimposed on a positive d.c. voltage, an important drop of breakdown voltage value occurs from a certain

Fig. 5
Breakdown probability of a 25 cm rod-plane spark-gap with a
+ 115 kV positive pre-stress
U_{st} impulse voltage W breakdown probability

An average breakdown probability of 35% was found for an impulse voltage range of about 15 kV to about 440 kV. This range, where the mixed distribution was measured, is shown by the hatched zone in fig.4. When d.c. voltage is increased up to + 135 kV, breakdown probability rises to about 90%, while the range of the transition zone remains unchanged. In this d.c. voltage range ($U_{gl} > 105$ kV), even a small positive impulse will lead to a breakdown of the spark-gap.

This enormous dispersion can be physically explained by the breakdown due to glow-corona. A time to breakdown of some 100 μs occur in case of glow-corona breakdown, and can be explained by the duration period of positive ions [10]. The superimposed impulse voltage brings the negative space-charge on the positive electrode out of balance and the resulting streamer-corona leads to breakdown. This becomes possible as soon as the voltage reaches a value of over + 115 kV, as, under these conditions, ($\varphi_a \approx 7 g/m^3$), a

d.c. voltage value on, when a 30" pointed electrode is used. The spark-gap is solicitated with a positive d.c. voltage which is entirely compensated by a negative impulse voltage. With a corresponding amplitude of negative impulse voltage ($U_{st} > U_{gl}$), the spark-gap is, for a short while (some 10 us), under solicitation of a negative voltage, which does not yet lead to a breakdown with this spacing.Together with d.c. voltage, the then again decreasing 1.2150 impulse voltage forms a positive switching impulse voltage, its amplitude being given by the d.c. voltage value. The front duration of the switching impulse voltage is given by the wave shape of the lightning impulse voltage tail, while the tail duration of the switching impulse voltage remains infinite. This so originated switching impulse voltage leads to an important decrease of breakdown voltage value. This voltage drop occurs particularly at big spacings [5], as, under such circumstances and due to the leader discharge, the positive switching voltage shows a lower strength
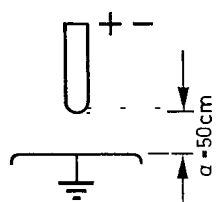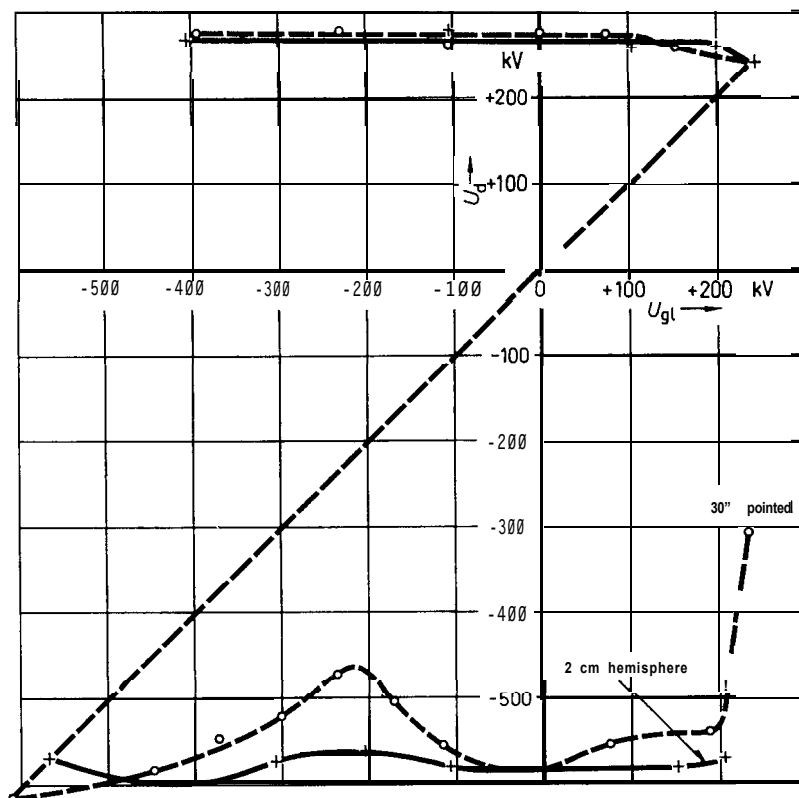
Fig. b
Breakdown voltage of a rod-plane spark-gap with superimposed d.c.
and 1.2|50 impulse voltage
$\varphi a \approx 8...11 \, g/m^3$; **parameter: electrode head**

cf. Fig. 4 for other indications

For a positive d.c. breakdown voltage, breakdown time values lie between several 100 and 1000 μs [10].

Fig. 7 shows the influence of d.c. voltage value on breakdown voltage in the case of a rod-rod spark-gap and this influence is clearly noticeable from the beginning of the onset-voltage on. When pre-discharges appear, an important voltage drop can be observed in the case of negative d.c. voltage and due to streamer-corona generated on the earthed side. Further voltage drop up to the value of the negative d.c. voltage breakdown follows only when d.c. voltage value increases to at least 90% of d.c. breakdown voltage.

Breakdown voltage value also marks a drop in quadrant 2, when onset-voltage value is exceeded. In case of further increase of d.c. voltage, breakdown voltage augments slightly. An important solicitation drop in the breakdown range due to streamer-corona occurs only shortly before a negative d.c. breakdown voltage. The reason for this low breakdown voltage is to be found in the art of the ambient space-charge. In case of d.c. voltage, this charge is built up under favourable conditions and attains an optimum value after a certain time period. The ambient space charge is destroyed by the superimposed impulse voltage and a breakdown is thus initiated when voltage (switching voltage) is applied once more. Breakdown time in such a case has values of several 100 μs.

When positive voltages are superimposed, breakdown voltage decreases from the moment onset-voltage is applied, while no influence of breakdown voltage due to d.c. voltage value is noticeable in case positive d.c. voltage and negative impulse voltage are superimposed. Different spacings (a = 75 cm, a = 100 cm) lead in principle to identical results [5].

Influence of pre-discharge

Modification of the form of electrode with a constant spacing (a = 25 cm) of a rod-plane spark-gap demonstrates the importance of pre-discharge on the breakdown process (fig. 8). A 2 cm hemisphere, a 30" pointed and an obtuse electrode were used as electrode heads. Initiating ranges of possible pre-discharges at d.c. voltage are very distinct.

Variation of pre-discharge can be observed on a 30" spike with negative d.c. voltage. A streamer-corona takes place instead of an impulseless discharge. In case of positive d.c. voltage, there is only a streamer-corona with such an electrode head. In accordance with this pre-discharge behaviour in the case of a 30" spike, this pre-discharge variation can be ascertained by the breakdown voltage. As long as there is a negative glow, breakdown voltage decreases, while in the other quadrants the process is determined by stream-

than d.c. voltage. This switching voltage can be determined by measuring the breakdown duration value of several 100 us. According to [14], such a voltage characteristic may occur during the reversal of rectifier units of a high voltage d.c. transmission system, so that these results are of practical importance.

A spacing of 50 cm gives a value of less than 3% for the standard deviation of breakdown voltage U_d at positive polarity of the impulse voltage. Stray values up to 8% have been found for negative rod-plane spark-gaps [5].

Breakdown time gives an insight into the physical behaviour and allows physical understanding of a determined abnormal comportment. At both impulse voltage polarities, mean breakdown duration values of about 10 μs for 50% breakdown impulse voltages of a 50 cm rod-plane spark-gap remain practically independent of the value and polarity of the d.c. voltage, in case of positive impulse voltage; they are of about 5 μs in case of negative impulse voltage. Same as in the case of breakdown characteristics, no determining influence of d.c. voltage value is noticeable in the case of breakdown time [5]. One exception is that of switching voltage solicitation with positive d.c. voltage and superimposed negative 1.2150 impulse voltage. At 235 kV d.c. voltage, an average value of breakdown time
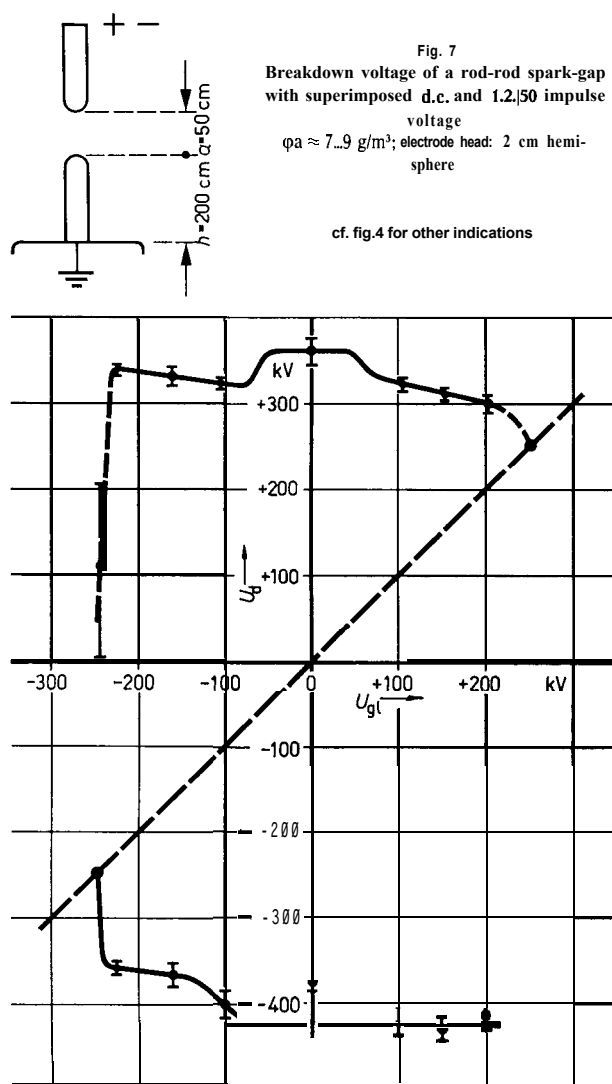
$$T_d = 270 \pm 60 \, \mu s$$

is obtained for the negative breakdown impulse voltage.

Fig. 7
Breakdown voltage of a rod-rod spark-gap
with superimposed d.c. and 1.2.|50 impulse
voltage
$\varphi a \approx 7...9$ g/m³; electrode head: 2 cm hemi-
sphere

er-corona, which leads to a slight decrease of breakdown voltage
as soon as onset-voltage is applied. An obtuse electrode head
brings, at negative impulse voltages and small spacings (a<50 cm),
a very clearly defined transition range [5]. The positive d.c. voltage
breakdown is due with this electrode form to glow-corona and this
voltage drop is again noticeable in the d.c. voltage range. Due to
the fact that a glow-corona is more stable, the impulse voltage am-
plitude necessary to destroy the glow-corona is higher. Quadrant 4
shows that breakdown voltage decrease is due to the generated
switching impulse voltage, a fact confirmed by breakdown time
values of several 100 μs.

In case of negative rod-plane spark-gaps with 1.2150 impulse
voltage solicitation, one can observe a transition range, the physi-
cal origin of which is due to a pre-discharge formation on the ob-
tuse electrode [5]. This transition range is confirmed by d.c. voltage
with superimposed impulse voltage. The glow-corona is destroyed
in case of positive d.c. voltage from about 125 kV upwards, so that
lower breakdown voltages occur, while in case of superimposed
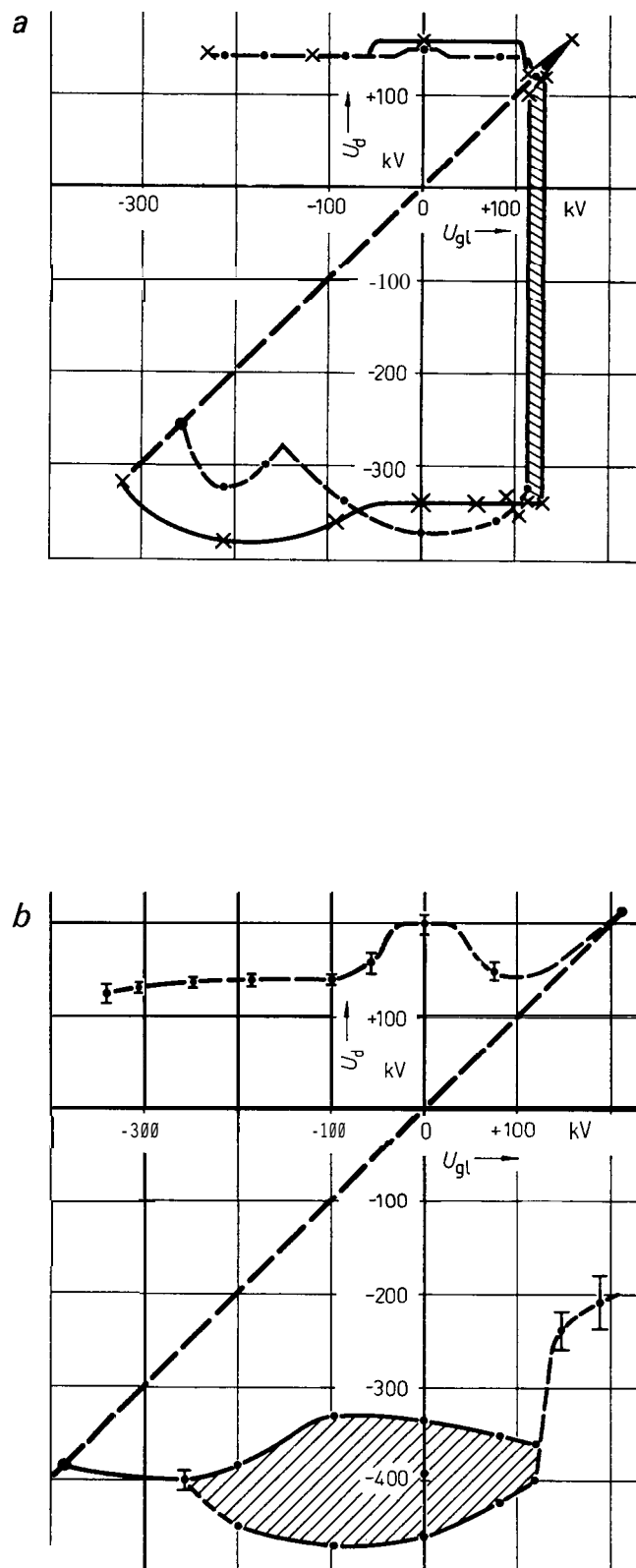negative voltages, a negative voltage forms a diffuse glow-
streamer-corona.

Fig. 8
Breakdown voltage of a 25 cm rod-plane spark-gap with superimposed d.c. and 1.2150
impulse voltage
'pa $\approx$ 7-11g/m³; parameter: electrode head
a electrode head: 2 cm hemisphere ($\times$) 30°-pointed($\bullet$)
b electrode head: obtuse

Fig. 9
Breakdown voltage of a rod-plane spark-gap
with superimposed d.c. and 60|525 impulse
voltage
φa ≈ 10...11 g/m³; electrode head: 2 cm hemi
sphere
cf. fig.4 for other indications
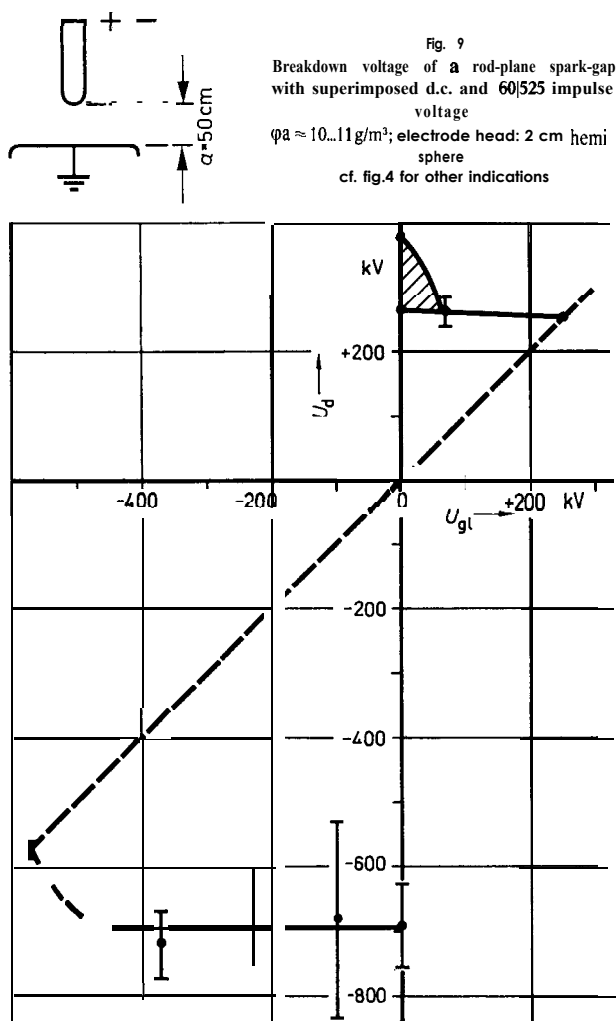
Pre-discharge due to d.c. voltage leads to a voltage drop in case of positive impulse voltages.

Pig. 10
Breakdown voltage of a rod-plane spark-gap with superimposed d.c. and 60|525 impulse voltage
φa ≈ 7...1 1 g/m³; parameter: electrode spacing

cf. fig. 4 for other indications
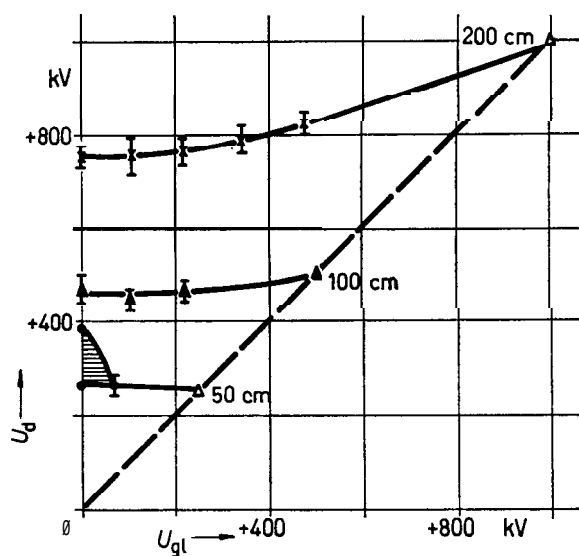
The influence of various pre-discharges is even more evident if the three different electrode forms are compared. In case of identical pre-discharge behaviour, breakdown voltages are comparable.

Influence of the impulse shape of the impulse voltage

Electric sub-stations may have to cope with 1.2|50 lightning impulse voltages as well as with overvoltages having front wave duration values of 50...200 us. These so-called switching impulse voltages result in a minimum value of breakdown voltage.

Fig. 11
Breakdown voltage of a rod-rod spark-gap
with superimposed d.c. and 60|525 impulse
voltage
φa ≈ 7...10 g/m³; electrode head: 2 hemi-
sphere

cf. fig.4 for other indications
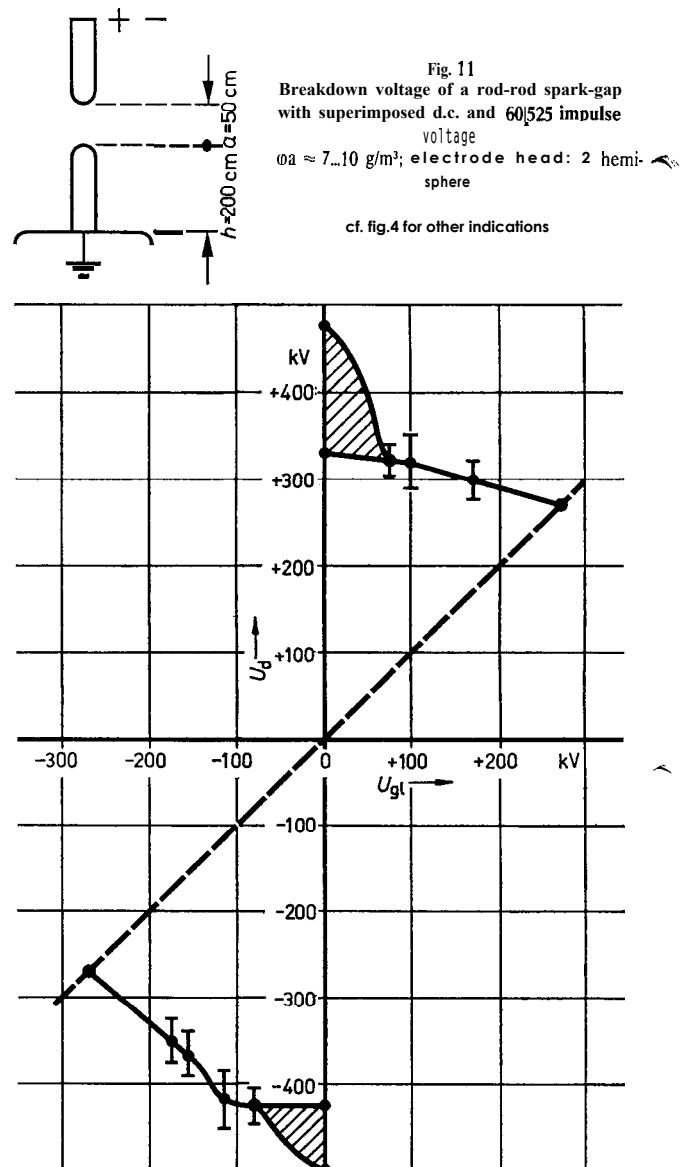
A characteristic transition range [8] results, with 601525 positive polarity switching impulse voltage; in case of a rod-plane spark-gap with a 2 cm hemispheric electrode head and having a spacing of up to 1 m. A breakdown due not only to streamer-corona but also to the leader corona is possible. This leader corona is responsible for the low strength of air spark-gaps in case of switching impulse voltages. By superimposing a d.c. voltage, and from the moment onset-voltage is applied, only the leader corona occurs, thus explaining in fig. 9 the lower strength of the mixed distribution with the superimposed circuit. This is physically understandable, as the streamer-corona due to d.c. voltage is already the origin of the leader corona, for which the ionisation conditions are favourable.
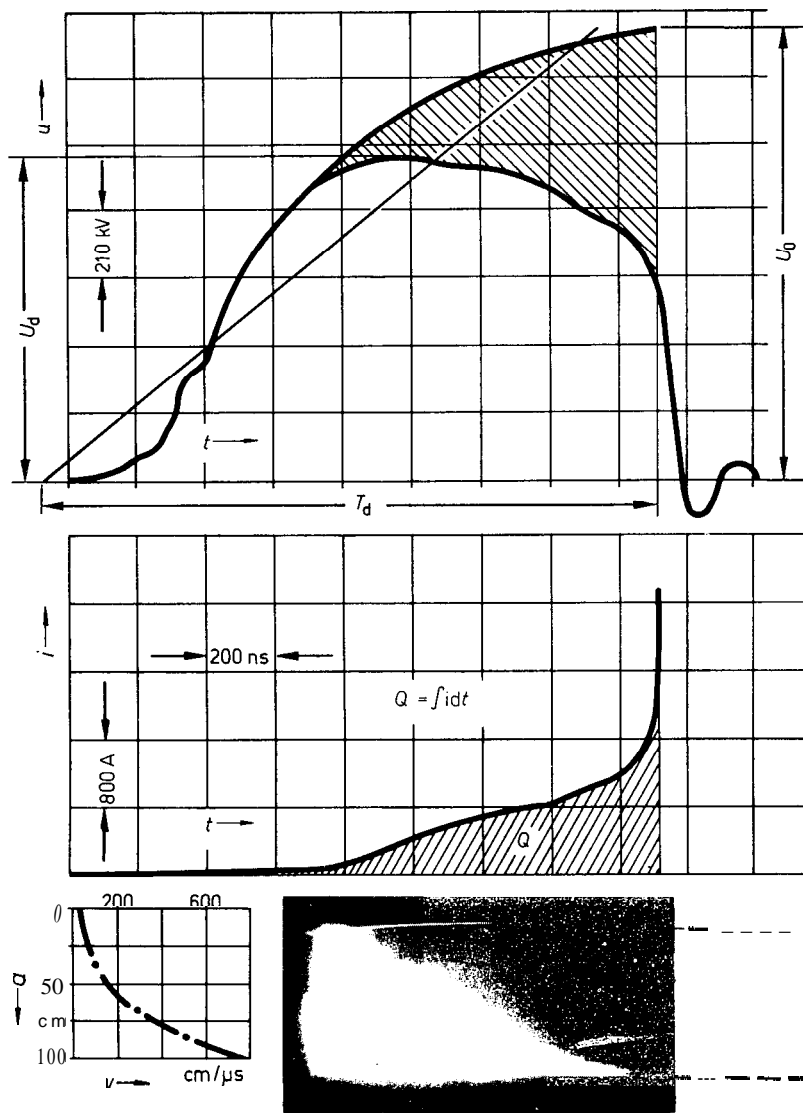
a

Fig. 12
Voltage and current curve, as well as discharge **pnenomena** of **100 cm rod-plane** spark-gap **in the range of volt-time-curve**
Evaluation of stress characteristic values
a sparkover spacing; T_d breakdown U_d breakdown voltage;
U_o original voltage; u voltage; v speed

at about 75 kV corresponds to lower strength at switching impulse voltages (fig. 11).

With negative polarity, the cause of mixed distribution is the excess of onset-voltage value on the earthed electrode. With d.c. voltage pre-stress conditions, the electrode arrangement always exceeds the onset-voltage on the anode, creating thus definite pre-discharge conditions for a breakdown process. If d.c. voltage continues to increase, breakdown voltage decreases more or less linearly (fig. 11).

Influence of d.c. voltage value on the volt-time-curve.

Faultless coordination of insulation is dependent not only on the 0...100% breakdown probability distribution curve in function of breakdown voltage, but equally on the behaviour of insulating arrangements at overshooting impulse voltages. Relationship between breakdown impulse voltage and breakdown time is illustrated by volt-time-curves (cf[15] for definition). Influence of d.c. voltage on volt-time-curve of air spark-gaps with non-homogeneous field and with large sparkover distances will be investigated in the following paragraph.

Characteristic values

A 1.2150 lightning impulse voltage is superimposed to a definite d.c. voltage in the previously described test arrangement. It appears that an important pre-discharge current prepares a breakdown in case of spark-gaps with non-homogeneous field in the scope of the volt-time-curve. This leads to considerable difficulties in the evaluation of test results, as the form of voltage is influenced by the pre-discharge current owing to voltage drop on the source impedance.

Fig. 12 illustrates the characteristic values which enable an interpretation of the test results. This figure shows that to define clearly the experiment, it is necessary to consider not only the breakdown voltage U_d and breakdown time T_d, which form together the volt-time-curve, but also the original voltage U_o as well as the charge Q = Iidt brought into the spark-gap by pre-discharge. The source impedance is responsible for a certain voltage progress on the test object; this progress diverges from the ideal original voltage, i.e. voltage without test object, by several 100 kV, owing to a pre-discharge current of several 100 A.

Oscillograms thus allowed to evaluate breakdown voltage, breakdown time and original voltage at the moment of breakdown, and this by means of a standard normalized oscillogram. The moment of breakdown was chosen to be the moment of sudden voltage collapse, as shown in photogram (fig. 12), which illustrates that at this precise moment, the sparkover spacing is bridged by a conductive channel. Moreover, the current rises at this moment to

Fig. 10 shows that in case of larger sparkover spacmgs, d.c. voltage improves the field conditions so that spark-gap strength increases.

No noticeable influence is to be expected with negative polarity of the high voltage electrode as, for larger spacings (a > 50 cm), the voltage/sparkover distance curves also show no marked influence resulting from the voltage shape. Up to 400 kV, no influence of d.c. voltage value has been observed (fig.9) and d.c. voltage breakdown is some 17% lower.

Rod-rod spark-gaps show clearly defined transition ranges at the investigated sparkover spacing of 50 cm [8]. Clearly defined pre-discharge conditions arise in the gas space, due to pre-stressing with d.c. voltage. Mixed distribution in breakdown probability, depending on breakdown voltage at switching voltages, is supplanted by a normal distribution when voltages are superimposed. If the high voltage electrode has a positive polarity, a streamer-corona is initiated with d.c. voltage pre-stressing as soon as onset-voltage is exceeded. Favourable conditions are then created for the leader corona, which always initiates breakdown. This is the reason why a breakdown voltage with positive d.c. voltage pre-stress beginning

9

a short-circuit current value. The current process made it possible to integrate the charge.

The shifting of the zero time spot makes it difficult to evaluate the breakdown time [16]. This is why the characteristic oscillation in the impulse voltage front was used to calibrate the zero time spot. All time values were evaluated from this oscillation and converted to the zero time spot by adding a constant amount. Each point of the volt-time-curve was determined by statistical methods out of at least 10 voltage applications.

Influence of d.c. *voltage on the*
volt-time-curve

Fig. 13 shows the volt-time-curve, the original voltage curve and the space charge curve of a 100 cm rod-plane spark-gap at positive lightning impulse voltage, in function of breakdown times. A drop of orginal voltage curve occurs at breakdown times under 6 us, owing to pre-discharge current, so that there is divergence between original and breakdown voltages. Fig. 13 also clearly shows that the charge necessary for the progress and heating-up of the breakdown channel increases considerably with shorter breakdown-times. This is so more understandable that several channels are formed simultaneously. A pre-current charge of some

650 μC can be obtained with a 2 μs breakdown time, the breakdown voltage having a value of about 940 kV.

Pre-discharge currents of several 100 A were also observed on air spark-gaps solicited by steep 0.03143 μs impulse voltages [17]. In such a case too, a pre-current charge of several 100 μC has to be brought into the spark-gap.

If a spark-gap is pre-stressed by a d.c. voltage with a superimposed lightning impulse voltage, it appears, as shown in fig. 14, that the breakdown voltage of this 100 cm rod-plane spark-gap is practically not influenced by the d.c. voltage pre-solicitation, even though considerable pre-discharges (streamer-corona) occur already with 400 kV d.c. voltage. On the other hand (fig. 15), both the original voltage curve and the charge characteristic are actually influenced. A 400 kV d.c. voltage covers already a certain charge requirement. This dependence also indicates that the breakdown of a spark-gap with a non-homogeneous field necessitates a certain charge. Influence of pre-stress on breakdown voltage can only be expected if the impulse shape modification of impulse voltage, due to voltage drop on the source impedance, influences the breakdown process; it is, of course, well known that under certain circumstances, voltage shape has an influence on breakdown voltage [18].

In the case of the 100 cm rod-rod spark-gap too, and at both impulse voltage polarities, there is only a slight influence of d.c. voltage value on breakdown voltage (fig. 16 a and b). A negligible decrease in strength at increasing d.c. voltage is due to symmetry conditions of the spark-gap owing to pre-discharges at d.c. voltage. As is well known, a rod-rod spark-gap with d.c. voltage at both polarities has nearly the same breakdown voltage as a positive rod-plane spark-gap.

Fig. 17 shows the influence of d.c. voltage value on the volt-time-curve for a negative rod-plane spark-gap. In this case too, breakdown voltage is hardly influenced by pre-solicitation, while the original voltage-curve is once again influenced, the pre-current charge for this spark-gap consisting again of several 100 μC. Part of this charge can be due to d.c. voltage.

Charge requirement at breakdown of a rod-rod spark-gap with constant sparkover spacing is about half as large as in case of a rod-plane spark-gap (fig. 18). Influence of polarity is not noticeable for either of the spark-gap types.

Practical Conclusions

To obtain evidence of its impulse voltage strength, electric apparatus has to be subjected to an ordinary impulse voltage test. Measurements show that in case of air spark-gaps, this strength can be influenced by d.c. voltage pre-stress. Owing to the fact that in case of normal operational conditions, overvoltage is always superimposed to d.c. voltage, it should be investigated to what extent a normal impulse voltage test does correctly establish the characteristics of an insulating device. It appears that breakdown voltage of air spark-gaps with non-homogeneous field can be considerably influenced if glow-corona builds up due to d.c. vol-
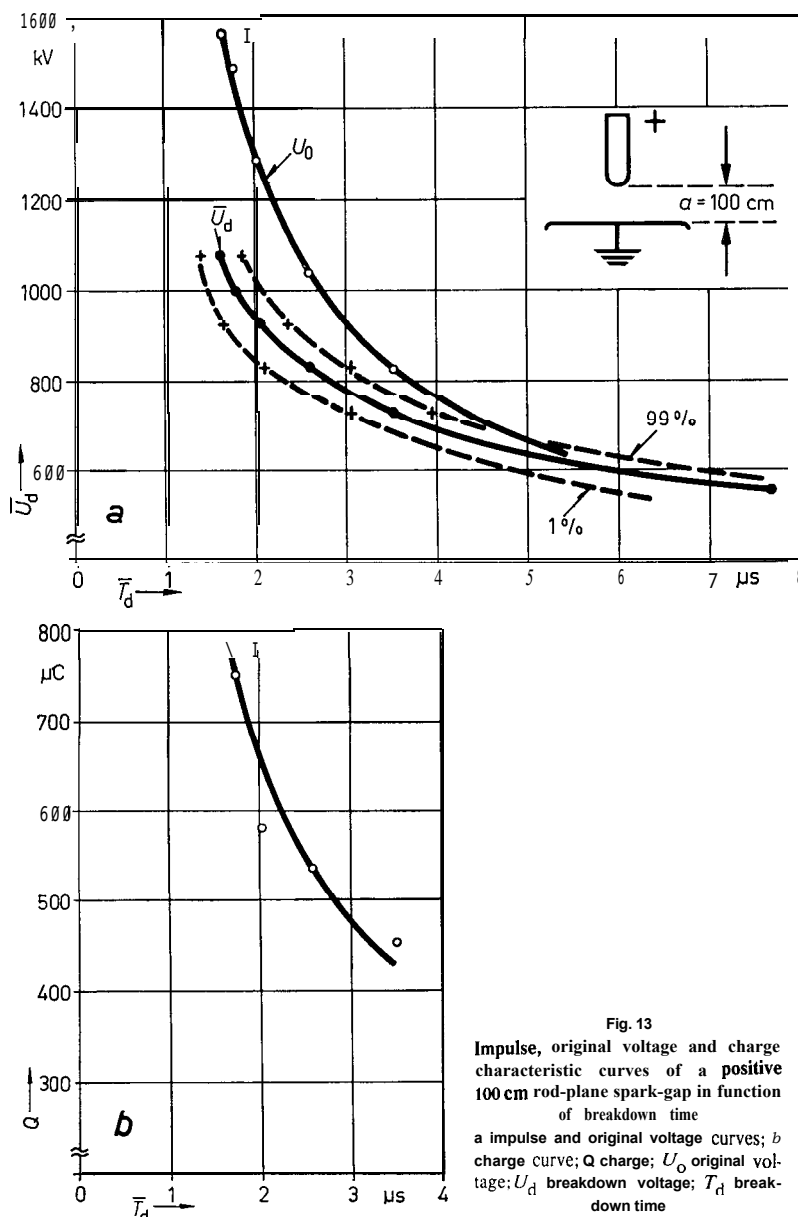

Fig. 13
Impulse, original voltage and charge characteristic curves of a positive 100 cm rod-plane spark-gap in function of breakdown time
a impulse and original voltage curves; b charge curve; Q charge; U_o original voltage; U_d breakdown voltage; T_d breakdown time

tage. Breakdown voltage is however not modified m an important manner in case of streamer-corona.

A reliable design of electric devices and plant components requires an evaluation and knowledge of the electric strength of all insulating devices in relation to any possible voltage stresses. Oil-immersed insulating gaps are noticeably influenced by pre-solicitation, in case of bias voltage stresses [19]. It can thus result that an insulating device will easily withstand a normal impulse voltage test. Nevertheless, and under operational conditions, a slight over-load can lead to a breakdown. As an example, in a protective spark. gap on a transformer, the breakdown voltage of the inner insulation, i.e. oil, can be, owing to pre-stress, lower than the breakdown value of the level spark-gap [19].

Obtained results also show that an air spark-gap with non-homogeneous field can cause an effective voltage decrease. As pre-currents increase considerably at shorter breakdown times, a level spark-gap will cause, particularly at steep voltage stresses such as close lightning strokes, a voltage drop of the generated overvoltage on the apparatus to be protected [17].

Investigation and tests on air insulated spark-gaps with non-homogeneous field are conditioned by the fact that the source impedance can influence the breakdown voltage owing to the pre-current charge of several $100\,\mu C/m$, necessary to obtain break-

down. It is also necessary to pay attention to the influence on the breakdown process of the modification of voltage shape on . he test object, due to pre-discharge current.

Summary

The following summary can be stated as regards superposition of d.c. voltage on single polarity overvoltages:

1. A glow-corona built-up by d.c. voltage is destroyed by a super-imposed impulse voltage. If the value of d.c. voltage is sufficiently high to provoke a streamer-breakdown (5 kV/cm at normal conditions), a breakdown follows after an impulse-shaped voltage stress, the value of impulse voltage not being decisive for the breakdown process. Measured breakdown times of several $100\ \mu s$ indicate that breakdown is originated by positive ions.

2. In case of streamer-corona in a rod-plane spark-gap, influence of pre-stress on breakdown voltage can be neglected. A voltage decrease is noticeable in a rod-rod spark-gap as soon as onset-voltage is on.

3. No influence of electrode shape on breakdown voltage can be observed under identical pre-discharge conditions.

4. In case of d.c. voltage pre-stress and at determinded pre-discharge conditions, there occurs no mixed distribution in the breakdown probability in function of breakdown voltage.

Fig. 14
Influence of d.c. voltage value on the volt-time-curve of a positive 100 cm rod-plane spark-gap
.   0   kV d.c. voltage
o   117,5   kV d.c. voltage
□   210   kV d.c. voltage
x   330   kV d.c. voltage
+   440   kV d.c. voltage

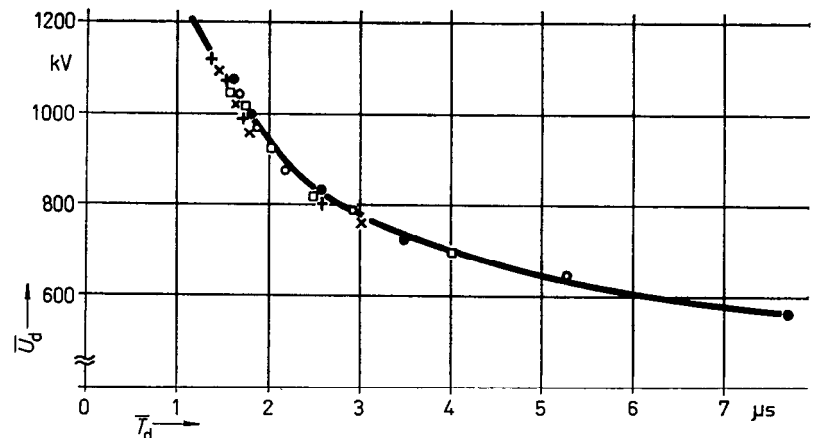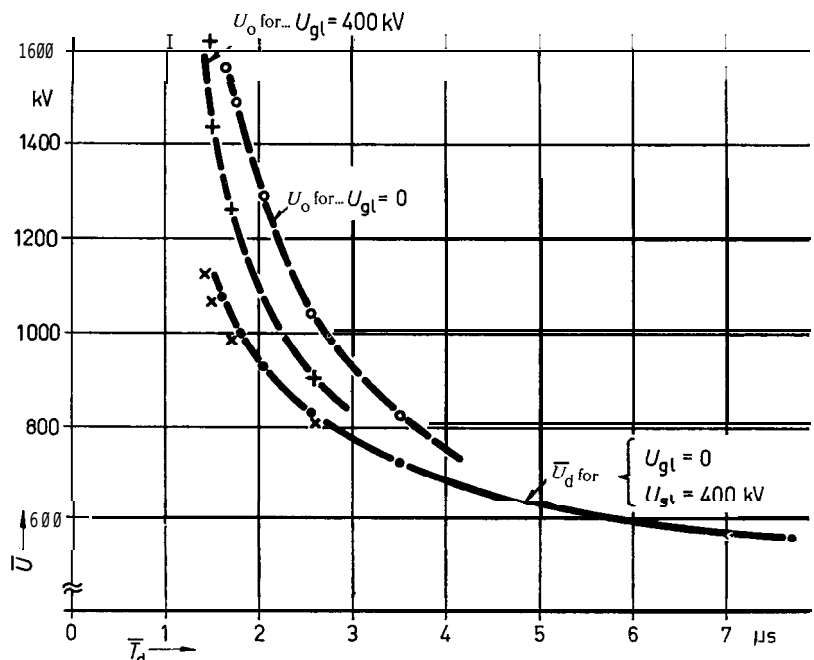cf. fig. 13 for other indications

Fig. 15
Influence of d.c. voltage value on the original voltage-curve of the positive 100 cm rod-plane spark-gap

U voltage
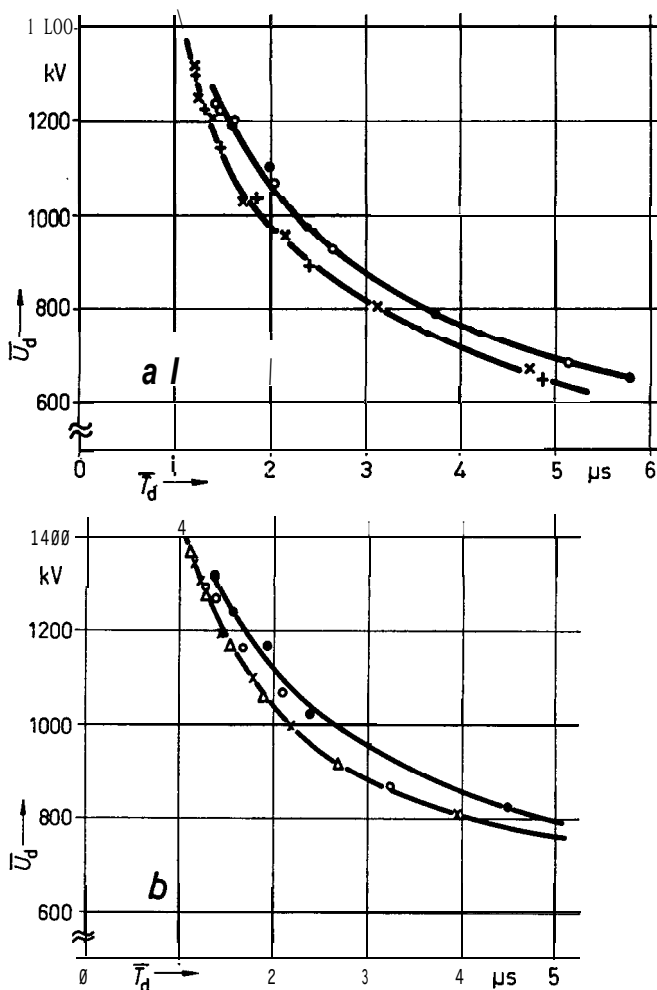
cf. fig. 12 for other indications

Fig. 16
Influence of d.c. voltage value on the volt-time-curve of 100 cm rod-rod spark-gaps

a positive voltage

. $U_{gl} = 0\,kV$	× $U_{gl} = 274\,kV$
o $U_{gl} = 138\,kV$	+ $U_{gl} = 396\,kV$

b negative voltage

● $U_{gl} = 0\,kV$	× $U_{gl} = 244\,kV$
o $U_{gl} = 102\,kV$	△ $U_{gl} = 393\,kV$

cf. fig. 13 for other indications

5. The volt-time curve will practically not be influenced by a d.c. voltage pre-solicitation, even though pre-current charges of several 100 μC/m have to be applied to the spark-gap before breakdown. On the other hand, there is considerable influence exerted on the original voltage.
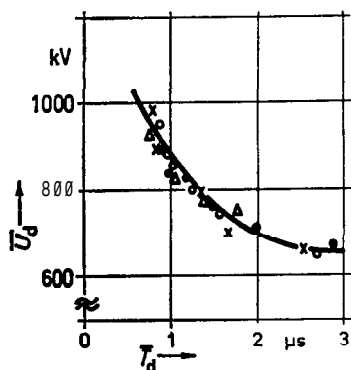

Fig. 17
Influence of d.c. voltage on the volt-time-curve of a negative 50 cm rod-plane spark gap

● $U_{gl} = 0\,kV$
o $U_{gl} = 119\,kV$
× $U_{gl} = 252\,kV$
△ $U_{gl} = 374\,kV$

cf. fig. 13 for other indications

Final Remark

The above-mentioned study has been made at the High Voltage and Engineering Institute of the Munich Technical University. The author wishes to express his thanks to the German Research Association for their generous assistance.
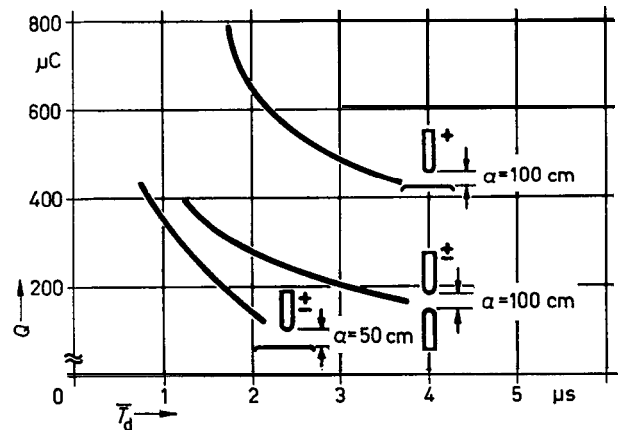

Fig. 18
Charge characteristics in function of breakdown time
Parameter: circuit arrangement

cf. fig. 13 for other indications

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