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Influence of the source impedance on the breakdown behaviour of air spark-gaps

By **Kurt Feser***)

Summary

Influence of the source impedance on the breakdown voltage exists, with any voltage type, in case of air spark-gaps with a non-homogeneous field. If the voltage shape is not modified by pre-discharges, as this is usually the case for d. c., a. c. and impulse voltages in the range of a 50 % breakdown impulse voltage, when the object under test has a capacitance totaling some 300 to 500 pF together with the possibly existing divider capacitances, it may happen that pre-discharge behaviour will be influenced by the source impedance in a determined range, i.e. in the transition areas. In the case of a "softer" voltage source and in a given circuit lay-out, there is at first a modification of pre-discharge formation. It was possible to bring this result in concordance with values known in the corresponding literature.

1. General

Contrary to "rigid" voltages of an interconnected network, which become effective with an impedance of some 300 Ω — corresponding to the line impedance — acceptance tests of electrical equipment are performed with voltage generating plants. Such systems partly neither reproduce the impedance of 300 Ω nor can they generally be considered as being sufficiently rigid.

In case of spark-gap with a non-homogenous field, considerable pre-discharges can occur before breakdown and they can withdraw a certain load from the voltage source. Should such a load withdrawal lead to a partial breakdown of the initial voltage, an influence of the source impedance of the breakdown voltage can be expected [19].

Fig. 1 shows a comparsion of the voltage shape on the test object with the initial voltage in the case of a rod-rod spark-gap at negative polarity of a 1.2|50 impulse. Fig. 1 a test lay-out with a larger load capacitance (C_b = 800 pF), while fig. 1 b illustrates the voltage curve on the same test lay-out with a larger load capacitance (C_b = 800 pF), i.e. with a more rigid voltage source. In these examples, pre-discharge modifies the initial voltage impulse. It is worthwhile noting that pre-discharge is effective with a more or less constant current of several hundred amperes during several microseconds [2]. In the case of the more rigid voltage source (fig. 1 b), alternation of voltage shape due to pre-discharge is considerably slighter. Measurements by J. Wiesinger [1] with steep impulse voltages at distances up to max. 30 cm show however that influence of the source impedance on breakdown voltage is slight even with a considerable alteration of voltage shape in the range of volt-time-curves. In the case of air spark-gaps with a non-homogeneous field, and with larger distances (a > 50 cm), this voltage drop due to pre-discharge can be observed also during large overswings of 1.2|50 voltage impulses [2]. In such cases, initial voltage depends on the source impedance, while breakdown voltage will practically remain uninfluenced.

In the range of 50 % breakdown impulse voltages, the voltage curve will remain practically unchanged under the influence of pre-discharges, even at larger spacing (fig. 1 c). The following investigations refer to the influence of the source impedance on breakdown voltage in case of sufficiently "rigid" voltage sources where the voltage impulse shape is not yet significantly influenced by the load requirement of pre-discharges. Influence of the source impedance on the breakdown process, when voltage shape is modified by pre-discharges, has not been investigated.

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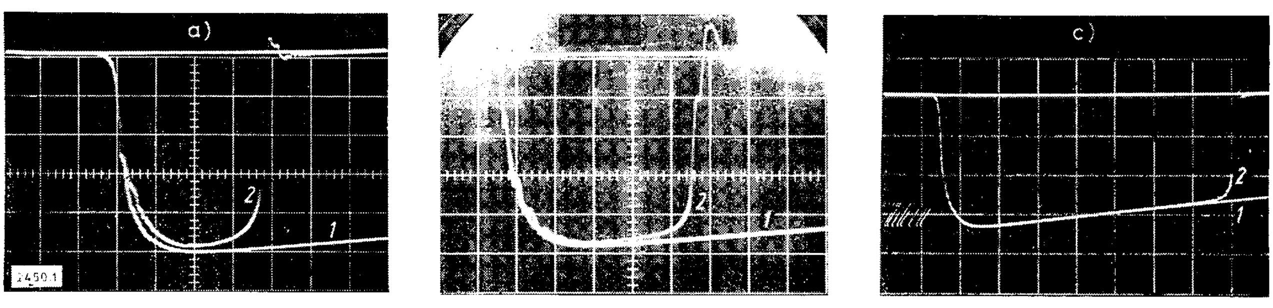


Fig. 1. Voltage curve with and without test object.

Test object: rod-rod spark-gap, a = 2 m, negative impulse.
Scale: 1 RE ≙ 420 kV; 1 RE ≙ 1 µs.
for Fig. 1 c: 1 RE ≙ 2 µs.

a) C_b = 300 pF, b) C_b = 800 pF, c) C_b = 300 pF.

1 no-load voltage (voltage curve without test object)
2 voltage curve with test object.

W. Widmann [3] has established the influence, in a critical distance range, of the source impedance on breakdown voltage in case of spark-gaps with a non-homogeneous field. Breakdown voltages of various test lay-outs produce at first in a "softer" voltage source lower values than in a "rigid" voltage source (f i g. 2), which, in a first instance, seems surprising and unaccountable. Theoretical considerations seem to show that pre-discharges "starve" in a "softer" voltage source, and thus that a higher breakdown voltage is measured [13].

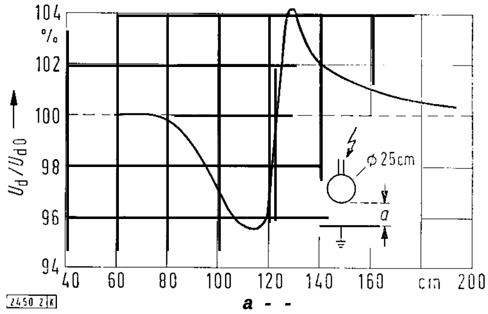
Influence of the source impedance on breakdown voitage in case of a. c. voltage stress is discussed under [3]. The present transaction tries to interpret measurements performed at d. c. voltages, 50 Hz a. c. voltages and lightning impulse voltages 1.2|50, with reference to the influence of the source impedance on breakdown voltage. The source impedance will be modified in broad limits by the different voltage sources at varying voltage form.

In the processes under consideration, one can neglect the time constant behaviour of the conductors and of the switching devices. In this way, it will be possible to represent the source impedance in a simplified form by the capacitance of the object under test, the capacitances of the test circuit and the possibly existing preliminary resistances between test object and test circuit capacitances (f i g. 3). It is clear that this equivalent circuit does not allow to consider transient phenomena during the build-up of pre-discharges, but solely the static conditions. However, as will be shown later, this simplified representation suffices to explain any basic relationship.

Capacitance C of impulse voltage test systems is represented essentially by a load capacitance and a divider capacitance, the latter having usually a value of 200 pF $\lesssim$ C $\leq$ 3 nF. A resistance between the load capacitance and the test object will, in the case of impulse voltage test systems, not have a value higher than a few hundred ohms. Thus, the source impedance of transmission lines (overhead line: Γ = 300 Ω) can be easily reproduced. Higher resistance values should be avoided, as a pre-discharge current of some amperes — such as usual in spark-gaps with non-homogeneous fields [4] — may already provoke a falsification of the initial voltage form. Capacitance C of a. c. voltage test system will also show values of some hundred picofarads. Its value is given by the stray capacitance of the a. c. voltage source and capacitive dividers. In d. c. voltge test systems however, capacitance C may attain values of several ten nanofarads, particularly if capacitance C is laid out as a one-way smoothing capacitor for the generation of d. c. voltage with a very slight ondulation. In both test lay-outs, resistance *R* can attain values up to several hundred kiloohms and these values will be limited by the voltage drop on the resistor, due to pre-discharge current and to capacitive current at a. c. voltage.

2. Test arrangements

Most of the tests were performed in the high voltage hall (dimensions 34 m $\times$ 23 m X 19 m) of the High Voltage Institute of the Munich Technical University [5]. Impulse voltage measurements were made with a 3 MV, 48.5 kWs impulse generator, while complementary measurements were performed at lower voltages in a second laboratory (dimensions 10 m X 10 m $\times$ 6.5 m) with a 5-stage 1 MV, 12.5 kWs impulse generator [6]. In the smaller laboratory, a height of 4 m, counted from the h. v. terminal, was provided for the test object, so that measurements were made only with spacings of less than 1 m. Impulse voltage was measured by means of a resistive voltage divider. A 1.2 MV a. c. voltage test cascade was available. with a nominal



F i g. 2. Breakdown voltage U_d of the "softer" voltage source, with reference to breakdown voltage of the "rigid" voltage source in function of spacing a [3].

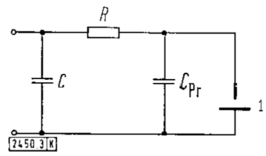


Fig. 3. Equivalent circuit of the voltage source of a test arrangement for the determination of the source impedance.

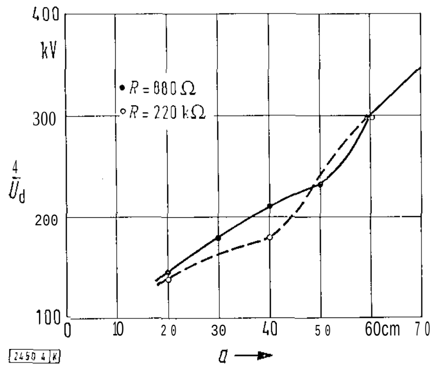
C capacitance of the test circuit on h. v. side;
working capacitances at
a. c. voltage: capacitance of test transformer and measurement circuit (C = 750 pF)
d. c. voltage: smoothing capacitance (C = 16 nF)
impulse voltage: load capacitance and impulse voltage divider
R damping resistor
C_{Pr} test object capacitance
1 test object

output of 800 kVar during 15 min of a 11.4 % short-circuit voltage and a stray-capacitance of about 600 pF. The voltage was brought to the object under test over 12 kΩ or 220 kΩ resistors. D. c. voltage measurements were made with the a. c. cascade connected with a one-way selenium rectifier and a smoothing capacitance of 16 nF [5]. For these measurements too, the voltage was applied to the object under test across resistances of 880 Ω or 220 kΩ. Tests arrangements used symmetrical and asymmetrical spark-gaps with a non-homogeneous field [4]. Following rod terminations have been studied: hemisphere with a 2 cm radius, 30° pin, blunt cylinder with 0.3 mm round edges, sphere having a diameter of 25 cm. A 2 m X 2 m aluminium plate electrode was used for spacings up to 1 m and a 4 m $\times$ 4 m plate for larger spacings. The vertically mounted spark-gap had its horizontal h. v. lead-in at a height of 11 m in the high voltage hall, so that field influence of the horizontal connexion could be largely eliminated. The rods used had a diameter of 20 mm, and the height of the ground rod in rod-rod arrangements was 2 m, whereas it was 1.5 m in the smaller laboratory. Measurement of impulse voltage in the h. v. hall was performed with the aid of a damped capacitive voltage divider — C = 291 pF, *R* = *758* Ω — together with an impulse peak voltmeter or a cathode ray oscillograph. Measurement error amounted to about $\pm$ *3* %.

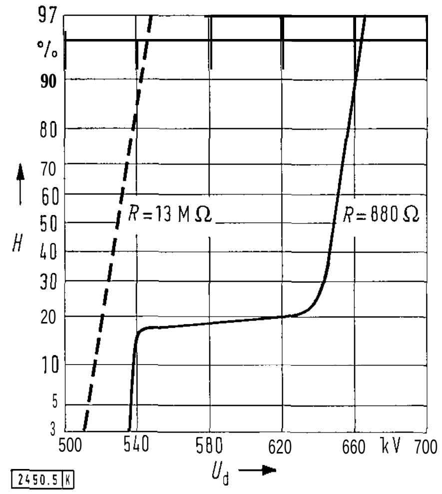
A. c. voltage was measured across a capacitive voltage divider with C = 102 pF by means of a moving coil meter with an approximate accuracy of $\pm$ 1 %. D. c. voltage measurement was made with a resistive voltage divider composed of block resistors with *R* = 4250 MΩ, together with an electrostatic voltmeter showing a $\pm$ 2 % error.

3. Performance of tests

Impulse voltage tests as well as d. c. and a. c. voltage measurements were assessed with the aid of a probability-paper. In this paper the ordinate is subdivided according to the Gauss integral, so that in the case of a normal dis-



F i g. 4. Influence of the source impedance R on the positive breakdown voltage U_d of a rod-plane spark-gap at d. c. voltage and humidity φ_a = 8 g/m³ with damping resistor as parameter.
Electrode termination: hemisphere with 2 cm radius.



F i g. 5. Frequency H of the negative breakdown voltage U_d of a 100 cm rod-plane spark-gap at d. c. voltage and humidity φ_a = 8.8 g/m³ with damping resistor as parameter.
Electrode termination: blunt, 0.3 mm edge radius.

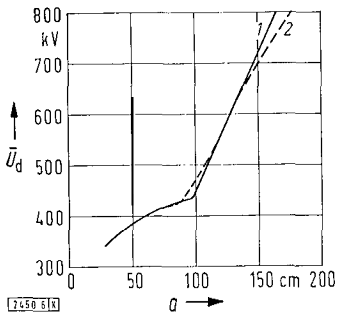


Fig. 6. Breakdown voltages U_d of a 25 cm sphere-plane spark-gop in function of flashover spacing a under d. c. and a. c. voltage stress.
1 d. c. voltage, positive polarity
2 a. c. voltage, 50 Hz

tribution of measurement values, the measure points can be more or less connected into a compensating straight line. The measurement is clearly defined by a 50 % value and by a standard deviation. If no straight line can be traced across the measured points, it is a case of a mixed distribution which can be decomposed in normal distributions according to the laws of statistics [4]. In such circumstances, breakdown behaviour is influenced by several significant parameters [6]. Two characteristic 50 %-values are obtained as a result of the assessment.

At least ten tests were performed to determine breakdown voltage during d. c. and a. c. voltage investigations. each of

T a b l e 1. Influence of the source impedance at positive breakdown voltage for a rod-rod spark-gap with determined pre-discharge conditions.

a	R_d	C_G	Breakdown voltage U_d with 95 % confidence limit
cm	kΩ	nF	kV
40	0.4	160	223.0 ± 1.5
	220	16	223.0 ± 3.6
	0.4	16	226.0 ± 1.3
60	0.4	16	325.0 ± 1.5
	220	16	325.5 ± 2.6
	0.4	160	327.0 ± 1.5
80	0.4	16	425.0 ± 1.8
	220	16	427.3 ± 1.4
	0.4	160	423.0 ± 10.2

them being recorded in the probability-paper, according to a methode indicated by *H. J. Henning* and *R. Wartmann* [7]. As to the determination of the 50 % breakdown impulse voltage, at least 140 voltage impulses were shot at different adjustments [8].

During d. c. and a. c. voltage tests and up to breakdown point, voltage was regulated with constant speed (about 5 kV/s), while impulse voltage tests were performed with an impulse sequence of 10 to 20 sec.

4. Correction of measured values

Each breakdown value was subjected to an air density and a humidity factor correction. Air density correction was made according to [9] and humidity correction in the humidity range of 4 g/m³ $\leq \varphi_a \leq$ 11 g/m³ according to [8]. This humidity correction according to values given in [8] need to be made only in the case of positive impulse-shaped pre-discharges. Breakdown due to glow corona calls for a reverse humidity correction, i. e. breakdown voltage value drops in case of increasing absolute humidity, while in the range of equal initial and breakdown voltages, influence of humidity is very slight — about 0.25 %/g/m³.

5. Test results

It is known from many test results (i. e. [3, 11]) that in a more or less homogeneous field, when breakdown voltage is at the same time the initial voltage, no influence of the source impedance can be observed on breakdown voltage. And as long as no pre-discharge currents circulate in the spark-gap, there will be no stressing of the voltage source. If pre-discharges occur on an electrode system, breakdown voltage will be mainly influenced by the pre-discharge characteristics. Some investigations have shown that under well determined pre-discharge conditions and with voltage sources sufficiently rigid to produce impulse-shaped pre-discharges, breakdown voltage will practically not be influenced by a modification of the source impedance. These facts are corroborated: by our own investigations on d. c. voltages (tab l e 1), which illustrate the influence of damping resistance and load capacitance on beakdown voltage in the case of a positive voltage applied to a rod-rod spark-gap at different spacings in the range of impulse-shaped pre-discharges; by results obtained, also with d. c. voltages, by *E. Peschke* [12]; by W. *Widmann* [3] with a. c voltages; and by K. *A. Markussen* [13] with switching impulse voltages, Results indicated in [14] show also that under determined pre-discharge conditions and with negative voltage applied on a rod-plane spark-gap, influence of the source impedance on breakdown voltage becomes negligible.

On the other hand, the source impedance influences breakdown voltage in the transition range of an electrode system, and breakdown process can initiate from various pre-discharges. A determined berakdown voltage always corresponds to the various possible pre-discharges. Mixed distribution can therefore occur in the transition range, depending on the breakdown frequency or breakdown probability [6, 14, 15]. F i g. 4 shows, for a positive voltage on a rod-plane spark-gap, that the transition range will be influenced and glow corona may change into streamer discharge when value of the damping resistor is increased. With a "softer" voltage source, the transition range will lie at lower voltage values. It is interesting to note in this case that the breakdown voltage of the lower voltage source will therefore become linearly dependent at an earlier stage, due to streamer discharge [8] and will thus show again, in a certain discharge spacing range, higher breakdown voltage values than a rigid voltage source. Breakdown voltage will also be influenced in the transition range by a variation of the smoothing capacitance [4].

Influence of a damping resistance on the breakdown voltage frequency becomes clearly evident with breakdown at negative voltage on a 100 cm rod-rod spark-gap with a blunt electrode (fig. 5). Impulse-free discharges having a stabilizing effect occur particularly on a blunt electrode. With such an electrode and without using a damping resistor, it is therefore possible to measure a mixed distribution in the breakdown voltage frequency, showing that breakdown can initiate from two different pre-discharges. A glow corona on a blunt electrode edge leads to a higher withstand strength. Only streamer discharge occurs on the ground-side of a rod-rod spark-gap, if a damping resistor is used, and breakdown voltage corresponds to the lower value of the mixed distribution.

Considering the withstand strength of air spark-gaps under d. c. and a. c. voltage stress, it will be observed that for smaller spacings (*a* < 100 cm) and under identical pre-discharge conditions, there will be only slight differences of breakdown voltage value [8]. This is the reason why a withstand strength comparison at d. c. and a. c. voltage is of interest for determining the influence of the source impedance. Provided the voltage form in the investigated range has no influence, a. d. c. voltage source having a large load capacitance can be considered as a rigid source, while in comparison, an a. c. voltage source will be a soft one.

Fig. 6 shows the breakdown voltage U_d for a 2.5 cm-sphere-plane arrangement under d. c. and a. c. voltage stress, in function of spacing a. It can be seen that breakdown voltage shows no discrepancy in the range of initial voltage equal to breakdown voltage. The transition range, however, becomes influenced into streamer discharge, and the softer voltage source (a. c.) shows pre-discharges already at smaller spacings. Together with the appearance of an impulse-shaped streamer discharge, there is also a voltage drop through [8], so that breakdown voltage value decreases with a. c. voltage stress to a value lower that the one under d. c. voltage stress. A. c. voltage characteristic curve of linear function, due to impulse-shaped pre-discharges, becomes apparent with a further enlargement of the gap distance on the other hand, a spark-gap modifies at d. c. voltage the pre-discharge only at larger spacings, so that d. c. voltage characteristic curve lies lower than the a. c. voltage curve within determined spacing limits. With still larger spacings (*a* > 130 cm), breakdown voltage value drops under a. c. voltage stress consequently to influence exerted by voltage form [8].

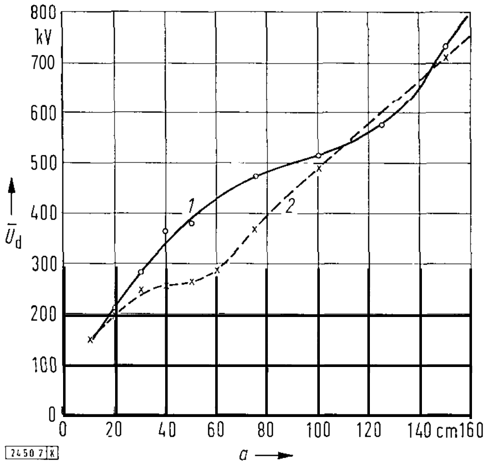


Fig. 7. Breakdown voltages U_d of a rod-plane spark-gap in function of spacing a under d. c. and a. c. voltage stress and humidity φ_a = 4 g/m³.
Electrode termination: blunt, 0.3 mm round edge radius.

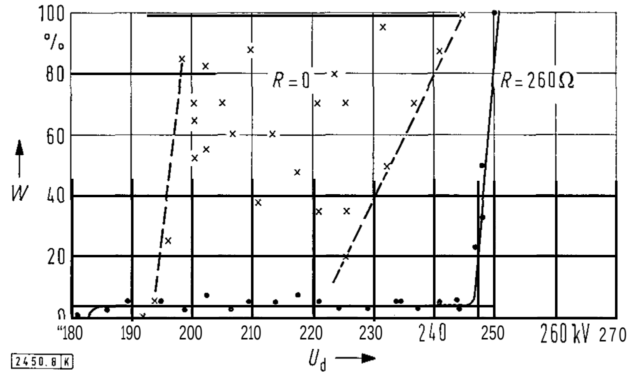
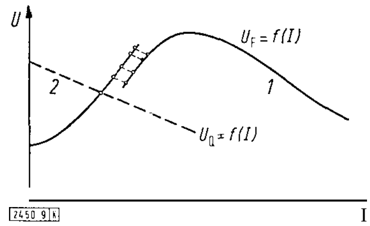


Fig. 8. Breakdown probability W of a negative impulse voltage on a 12.5 cm rod-plane spark-gap in the smaller h. v. hall; 40 shots in each adjustment position.
Impulse voltage shape 1.2150;
Electrode termination: blunt, 0.3 mm round edge radius.



F i g. 9. Current-voltage characteristic curve of spark-gaps.
Curve U_F = f(I) of the spark-gap
Curve U_Q = f(I) of the voltage source

W. *Widmann* [3] also Investigated the influence ot the source impedance at a. c. voltages on breakdown voltage with this type of electrodes. The result was that within certain critical spacing limits, just above the initial voltage (fig. 2), the source impedance influences breakdown voltage. The fact that the softer voltage source shows at first lower breakdown values that those of a rigid voltage source, remained unexplained.

An explanation of this voltage drop is to be found in the variation of the pre-discharge type: the softer voltage source modifies at first the pre-discharge type and this modification into an impulse-shaped streamer discharge results in a voltage break through [8]. This explains the breakdown voltage drop within determined spacing limits and has been confirmed by our own measurements.

A comparison of breakdown voltages with a. c. and d. c. voltages in the transition range of breakdown from glow corona into streamer discharge in a rod-plane system, shows a similar result (f i g. 7). Breakdown voltage of the softer voltage source sinks at first lower that the breakdown value of the rigid source. In both examples however, it is necessary to take into account an influence of the voltage form.

Noteworthy and typical for any arrangement is the fact that breakdown voltage value decreases due to pre-discharge modification within certain spacing limits and is lower than the extension of the following linear function of the breakdown voltage, i. e. the approach to the following function takes place over a less pronounced rise (d u/d a).

Fig. 8 illustrates the breakdown probability of a 12.5 cm rod-plane spark-gap at 1.2150 lightning impulse voltage in function of the breakdown voltage U_d. Pre-discharge is influenced by an outer damping resistance in the transition range of the rod-plane arrangement with negative voltages [14], resulting in various breakdown values. An outer damping resistance favours stabilizing negative glow-brush discharges. This leads, within certain spacing limits (5 cm $\leq a \leq$ 60 cm), to a voltage leap and thus to higher breakdown voltages.

This resistance does not influence, prior to and after the transition range, breakdown probability in function of breakdown voltage.

The source impedance influences also the negative breakdown voltage in the transition range of the rod-rod spark-gap [6].

6. Discussion of the results

Pre-discharge modification under any type of voltage stresses can result in an influence of the source impedance on breakdown voltage. In case of determined pre-discharge conditions and sufficiently rigid voltage sources, breakdown voltage will not be affected by the source impedance.

The load requirement of pre-discharges investigated in the present transaction is mainly covered by stray capacitances of the object under test: the dynamic behaviour of impulse-shaped pre-discharges considered here will not be influenced by the source impedance i. e. pre-discharges can fully develop with the investigated source impedance. The confirmation of this fact can be found in the following literature references: for lightning impulse voltages 1.2|50 and for switching impulse voltages, a capacitance of 400 to 600 pF of test object will suffice for the load requirement of pre-discharges [13, 16]. A test object capacitance of 600 pF will also suffice for a. c. and d. c. voltage [16]. The capacitance value of the investigated arrangements ($C_{Pr} \approx$ 300 pF [4]) lies already in the order of magnitude of the minimum required capacitance, so that no influence of the source impedance on breakdown voltage can be observed under determined pre-discharge conditions. Should a modification of pre-discharge behaviour occur, it will be associated with a voltage break through, excepting the case of positive glow corona and negative glow-brush discharge [14].

A physical explanation for this dependence at any voltage forms can be obtained with the aid of the following results. If one tries to measure the average discharge current in the spark-gap, the result will be successful, provided a steady operational point can de found for the intersection of the characteristic curve U_Q = f(1) of the voltage source with the characteristic curve U_F = $f(I)$ of the spark-gap (fig. 9) [17]. Steady operational points fulfil the condition R + d u/d i > 0, i. e. rising curves always result in steady operational point, as d u/d $i > 0$ [17].

The characteristic curve $U_F = f(I)$ of the spark-gap depends, among other factors, on outer ambient conditions (gas pressure, deleterious products [18], dust, humidity [10, 12], on voltage form, pre-discharge and electrode type). During the breakdown instant, the operational point tilts from low current values over to very high ones, this operational point being nearly exclusively determined not by the spark-gap but by the source impedance [19]. The voltage source curve is characterised by a no-load voltage and a frequency-dependent voltage drop on the source impedance, this voltage drop being due to pre-discharge current. A softer voltage source will be responsible for a bigger voltage drop due to a higher preliminary resistance, i. e. no-load voltage should be higher, in order to maintain the same conditions for the spark-gap.

Should pre-discharge behaviour in the spark-gap change, the characteristic curve $U_F = f(1)$ will show an instability point [12, 17, 18, 20, 21]. *R.* W. *Guck* [20] has measured a sort of hysteresis in that voltage range for the negative voltage on a rod-plane spark-gap at the transition of Trichel impulses to impulse-free discharge. *A. Schwab* [18] has confirmed that in such an arrangement there was a possible jump to either higher or lower current values. With a determined radius of the pin, the U-I-characteristic will show no instability for a determined spacing. According to *Y. Miyoshi* [22], this particular radius becomes smaller if electrode spacing increases. Measurements by *E. Peschke* [12] have shown an unsteady *U-l-characteristic* curve during the transition from a glow corona into a streamer discharge for the positive voltage of a rod-plane spark-gap and also during the transition from glow corona into streamer discharge for the negative voltage of a pin-plane spark-gap. Current values become suddenly higher with a constant voltage. *A. v. Engel* and M. *Steenbeck* [17] have also found an unsteady point in the U-l-characteristic during transition from dark discharge into glow corona; they note that this transition depends not only on discharge length, but also on the values of the test circuit. W. *Hermstein* [23] has also measured a current jump during transition from streamer discharge at positive d. c. voltage, however at lower values.

U-l-characteristics curve of the spark-gap and of the voltage source (f i g. 9) shows very clearly that there can be no influence due to the source impedance in case of determined pre-discharge conditions. There is only a steady operational point and only a modification of pre-discharge behaviour is critical. There are two curves for the spark-gap at these transition points and one of them will be chosen, depending on the voltage curve. Measurements under [20] also show that the rigid voltage source remains longer on the prevailing curve, i. e. that the leap into another pre-discharge type takes place at bigger spacings. Pre-discharge modification is as a rule responsible for a voltage break through, with electrode arrangements investigated here, so that breakdown voltage of a softer voltage source will lie under the rigid voltage source characteristic curve after the modification of pre-discharge behaviour [17].

This behaviour is illustrated most clearly in f i g. 4. A higher value of the damping resistor conditions shorter periods for the modification of pre-discharge behaviour from glow corona to streamer discharge. All the results show that modification of pre-discharge and thus the breakdown voltage are influenced in the transition range by the source impedance eventhough the voltage curve remains practically unchanged by pre-discharges. This fact was discovered in 1911 already by *W. Weicker* [11] with a. c.

voltages. Influence of source impedance in case of unipolar impulses has not been yet investigated.

7. Practical conclusions

In view of the fact that source impedance in case of air spark-gaps has no influence on breakdown voltage, it is by no means necessary that test systems used for air spark-gaps investigation should reproduce the impedance of overhead lines. Care should be taken in dimensioning the voltage source that the load requirement of pre-discharges will be covered by stray capacitances and divider capacitances, whose sum should amount to about 500 to 1000 pF. In this case, pre-discharges will not modify the voltage form. However, a modified voltage form could influence breakdown behaviour [4].

To compare results of measurements performed in various laboratories [6], it is necessary to know all about transition ranges of every circuit arrangement investigated, as breakdown voltage will be influenced by the source impedance during transition from one type of discharge to another. This may be of particular interest with spark-gaps used used as main protection in medium voltage installations.

8. Literature

[1] *Wiesinger, J.:* Funkenstrecken unter Steilstoßspannungen und ihre Bedeutung fiir die Isolationskoordination. Bull. Swiss Union of Electr. Vol. 60 (1969) pp. 672—682.

[2] Feser. K.: Das Durchschlagverhalten von Luftfunkenstrecken mit inhomogenem Feld bei Mischspannungen. Bull. Swiss Union of Electr. Vol. 62 (1971) pp. 320—329.

[3] Widmann, W.: Einfluß der elektrischen Kenngrößen von Hochspannungsprüfkreisen auf die Durchschlagspannung verschiedener Prüflinge in Luft. ETZ-A Vol. 86 (1965) pp. 458—463.

[4] *Feser,* K.: Inhomogene Luftfunkenstrecken bei verschiedener Spannungsbeanspruchung. Diss. Techn. Univ. Munich 1970.

[5] *Prim, H.:* Feuer, Blitz und Funke. Bruckmann, Munich 1965.

[6] *Fcser, K.:* Über das Durchschlagverhalten der negativen Stab—Stab-Funkenstrecke mit Stoßspannungen 1.2|50. ETZ-A Vol. 91 (1970) pp. 321-325.

[7] *Henning,* H. J., und *Wartmann, R.:* Statistische Auswertung im Wahrscheinlichkeitsnetz. Kleiner Stichprohenumfang und Zufallstreubereich. Z. ges. Textilind. Vol. 60 (1958) pp. 19-24.

[8] *Feser, K.:* Einfluß der Spannungsform auf das Durchschlagverhalten von Luftfunkenstrecken mit inhomogenem Feld. Energie & Technik, Vol. 22 (1970) pp. 319-324.

[9] VDE 0433, P&i -1/1. 66: Erzeugung und Messung von Hochspannungen. Part 1: Bestimmungen fiir die Erzeugung und Anwendung von Wechsel- und Gleichsponnungen fiir Prüfzwecke.

[10] *Feser, K.:* Einfluß der Feuchtigkeit auf das Durchschlagverhalten bei Wechselspannung. ETZ-A Vol. 91 (1970) pp. 584—586.

[11] Weickcr, W.: Zur Kenntnis der Funkenspannung bei technischem Wechselstrom. ETZ-A Vol. 32 (1911) pp. 436440 and 460—464.

[12] *Peschke, E.:* Der Durch- und Überschlag bei hoher Gleichspannung in Luff. Diss. Techn. Univ. Munich 1968.

1131 *Markussen,* K. *A.:* Circuit parameters influence on the switching surge flashover voltage. CIGRE report 1968, No. 33-01, Ann. III.

[14] *Fcser, K.:* Einfluß der Vorentladungen auf das Durchschlagverhalten der negativen Stab-Platte-Funkenstrecke bei Normstoßspannungen 1,2|50. Elektrotechn. u. Maschinen-Bau Vol. 88 (1971) S. 347-353.

[15] *Feser, K.:* Inhomogene Funkenstrecken in Luft bei Beanspruchung mit Schaltstoßspannungen. Bull. Swiss Electr. Union Vol. 61 (1970) pp. 711—719.

[16] *Kuccra, J.:* Stromkreisparameter fiir Priifungen mit Stoß- und Wechselspannung. Elektrie Vol. 22 (1960) pp. 464-465.

[17] *Engel, A. v.,* und Steenheck, M.: Elektrische Gasentladungen. Ihre Physik und Technik. Vol. 2, Springer Publ., Berlin 1934.

[18] *Schwab, A.,* und *Zentner,* R.: Der Übergang von der impulsförmigen in die impulslose Koronaentladung. ETZ-A "Vol. 90 (1968) pp. 402—407.

[19] *Woboditsch, W.:* Die Charokteristiken von technischen Funkenstrecken mit stark inhomogenem Feld. Scient. Magaz. Techn. Univ. Dresde Vol. 8 (1959) pp. 869-891.

[20] *Guck, R. W.:* Die negative Koronaentladung an der Spitze—Platte-Funkenstrecke. Diss. Techn. Univ. Karlsruhe 1955.

[21] *Krätzig, E.:* Vorentladungen im Feld Kugel-Platte in Luft bei Gleichspannung. Scient. Magaz. Techn. Univ. Dresde Vol. 16 (1967) pp. 211—221.

[22] *Miyoshi,* Y.: Entladungscharakteristiken und -bereiche in Spitze—Platte-Funkenstrecken in Luft. JIEE Vol. 78 (1958) pp. 1413-1420.

(231 *Hermstein,* W.: Einfluß von Vorentladungen auf das Überschlagsverhalten grundsätzlicher Stützeranordnungen in Luft. ETZ-A Vol. 81 (1960) pp. 413-421.