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From the glow corona into the breakdown

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Abstract: This paper reports about the measurement of the breakdown times of rod-plane spark gaps when resulting from the glow corona. These times were checked against the velocity of the ions by calculation and agreement established. Both the measurement and the calculation reinforced the theory that the space charges, split up into several groups, are displaced one after the other from the rod (anode) and travel to the plane (cathode). According to the calculation, as soon as the first ions are established around the cathode, secondary effects are able to take place. At a separation of 25 cm and at voltages from 115 to 135 kV, breakdown times are 1000 to 2000 us.

1. Introduction

The breakdown of spark gaps in a non-homogeneous field occurs at the bigger distances from the partial discharge. In the literature [1] the different breakdowns, whose areas of existence are dependent on, among other things, the kind of voltage, the polarity of the voltage, the configuration of the electrode, the atmospheric conditions and the'source impedance, are exhaustively described. In the following the breakdown from a positive pre-breakdown (the so-called impulseless glow corona) is to be more closely considered.

W. Hermstein [2] has traced back the existence of the glow corona to the effect of the negative ions. For the transition from the glow corona to the breakdown process qualitative assumptions only are to be concluded from his measurements. In the earlier work [3] the first assessments towards a clarification of this problem were already being investigated. New measurements and, in particular, the attempt to observe with the aid of a digital computer the physical behaviour of the breakdown in the space charged field brought a further insight into the course of the breakdown process. For practical purposes the glow corona is of considerable importance, since the diffused glow, which is confined to the immediate neighbourhood of the anode, is associated with a considerable increase in the strength of the breakdown. The glow corona occurs especially on thin wires or sharp edges and operates so that at these points a possibly damaging impulse pre-breakdown is prevented.

2. Possible development of the breakdown from the glow corona

W. Hermstein [2] has analysed thoroughly the transition from the streamer discharge to the impulseless glow corona. From his measurements it is established that the glow corona results from the constricting effect of the negative ions, which are originated by the resulting discharges in the weak field area. The aim of the present paper is to investigate the possible physical processes which are determinative for the change from the glow corona to the breakdown process and from them to determine the actual mechanism by means of measurements and calculations. For this purpose it is already assumed that a glow corona is built up around the anode, that is to say that a negative space charge in the immediate neighbourhood of the anode increases the field gradient to the anode.

It is assumed that the commencement of the development of the breakdown is when the state of equilibrium of the negative space charge is disturbed. This could, for example, occur by raising the voltage, since it is known that from a certain field strength the negative ions release the negative charge carriers and split themselves into neutral molecules and electrons. The released electrons are able to ionise on their way to the anode by collision and on arriving with sufficient energy at the anode lead to thermo-ionisation [2]. Through the out of equilibrium space charge a positive space charge arises which decisively alters the field distribution. Under the influence of the adjacent field this positive space charge travels to the cathode.

Two mechanisms are possible basically for the final development of the breakdown :

1. The positive space charge drifts as far as the opposmg electrode and there, through secondary emission, releases sufficient electrons to lead to the breakdown. Whilst the positive space charge travels to the opposing electrode. further impulse type pre-breakdowns can arise around the anode, if the field at the anode has increased so much again that conditions for further collision ionisation are attained. In this way it is also possible that, as a result of field emission, an opposing discharge forms against the growing positive space charge immediately around the opposing electrode.
2. The second possible process would be that the breakdown is conducted through a path developing from the anode to the cathode, that is if the positive space charge has lost its destructive effect on the field and has entered into the opposing electrode. This path would then grow rapidly (within a few seconds) in the undistorted field. Any considerable participation of the cathode (I-effects) on the breakdown process would in this case be excluded.

Both processes are linked closely to the velocity of the positive ions, which take a considerable part in the breakdown process [3]. The following results of measurements and calculations should contribute to an explanation of the physical mechanism of the breakdown from the glow corona.

3. Test results

The investigations were carried out on a positive rod-plane spark gap with a hemispherical termination of the rod with a distance between the electrodes of 25 cm. On the rod electrode (Diameter of the rod – 20 mm) a positive d.c. voltage was connected. At an absolute humidity of φa = 6g/m³ the arrangement investigated showed a mean value of breakdown voltage of 162 kV at a constant voltage increase of 5 kV/s. The breakdown always developed from the impulseless glow corona. At a d.c. voltage below the d.c. breakdown voltage, the breakdown was introduced by means of a small impulse voltage which was superposed on the d.c. voltage. The polarity of the impulse voltage did not play any decisive part in the activation of the breakdown process [3]. The breakdown time, that is to say, the time from the start of the impulse voltage up to the breakdown of the spark gap, was recorded with an oscillograph. The negative space charge around the anode was put out of equilibrium through the superposition of the impulse voltage, as the rapid change of voltage could not achieve the generation of new negative ions because of inertia. As the test results in [3] show, the polarity of the impulse voltage can be ignored in the extent of the breakdown time. The destruction of the state of equilibrium is decisive for the starting of the breakdown process. As a mean value of the breakdown times, with 95%-confidence limits, a value of T_d = (2000 ± 600) µs results for a d.c. voltage of 115 kV over which is superposed a negative impulse voltage of 12 kV to release the breakdown. On the other hand with a positive impulse voltage of 12 kV superposed on this d.c. voltage a mean value of T_d = (1500 ± 900) µs is ascertained. For a d.c. voltage of 135 kV the mean value of the breakdown times of T_d = (1150 ± 400) µs results for an superposed negative impulse-voltage of about 12 kV (Fig. 1). The noteworthy fact from the measurements was that at a d.c. voltage of 115 kV only 35% of the impulse voltages has led to the instability of the glow corona with a resultant breakdown. At 135 kV d.c. voltage 95% of the impulse voltages would already lead to a breakdown. Measurement of the "pre-current" on the *severely bent* electrode showed several current impulses at defined intervals between the starting of the impulse voltage and the time of the breakdown. This result indicates that several ionisation processes have taken place in the vicinity of the *severely bent* electrode, whilst the positive space charge travels to the opposing electrode.

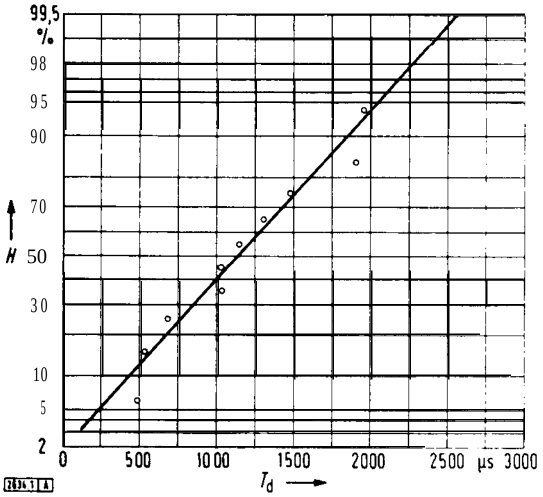

Fig. 1. Total frequency H of the breakdown times T_d of a 25 cm **rod-plane** spark gap with a positive d.c. voltage (U_{Gl} = 135 kV) in the area of the breakdown from the glow corona

At higher absolute humidity ($\varphi a > 6g/m^3$) no glow corona could be observed on the positive electrode with an otherwise unchanged arrangement. Considerably shorter breakdown times (Fig. 2) resulted for the streamer discharge which occurred. The results show an increase of the breakdown time with a relatively greater decreasing overage-voltage $U_ü = (U_{Gl} + u_{Stoss})\ U_{d\ Gl}$ in which under 30% over-voltage breakdown times of a few microseconds are possible. These breakdown times become immediately smaller with increasing over-voltages, so that there exists a distinct transition area which indicates a change in the breakdown mechanism. An explanation of this dependence of the breakdown on the streamer discharge was given in [3]. The breakdown time depends considerably on the space distribution of the pre-discharges leading to the breakdown.

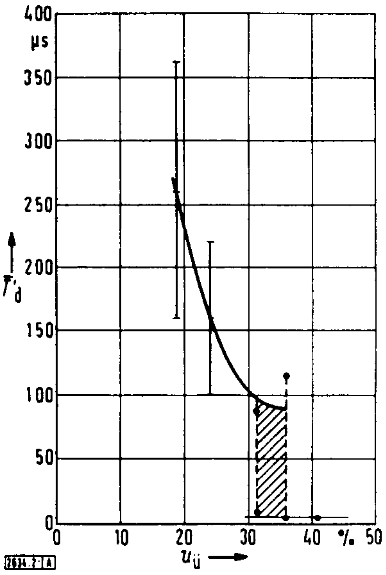

Fig. 2. Mean value of the breakdown times T_d of a 25 cm rod-plane spark gap depending on the relative over-voltage $U_ü = (U_{Gl} + u_{Stoss})/U_{d\ Gl}$ in the area of the breakdown from the streamer corona

4. Calculation of the breakdown process

A simple method for calculation [3] has already been indicated and this permits the approximate calculation of the measured breakdown times. For example following this, for a rod-plane spark gap with a distance of a = 25 cm and a voltage U = 135 kV a mean electric field strength results E_m = 5.4 kV/cm. With a movement of positive ions from b_+ = 1.36 cm²/Vs their average speed is determined as :

$$V_m = b_+ E_m = 7350 \text{ cm/s} \quad (1)$$

The positive ions however require a period

$$t = a/v, = 3400 \ \mu s \quad (2)$$

in order to travel from the anode to the cathode in this arrangement. For a voltage of 115 kV a corresponding time of 4000 μs [3] is obtained. It is possible with the help of the digital computer to determine the actual development of the field for the space charged field. The basis of the method employed works with charges [5]. The charge in position on the surface of the electrode is thus reproduced within the electrode through discrete point, line and ring charges. On the positive electrode (rod) a cloud of positive ions is located, which can be reproduced by point or ring charges (Fig. 3). In the course of the experiments described here ring charges were mainly employed (Fig. 3a to Fig. 3c), as by its nature a ring charge covers a greater volume and therefore fewer ring charges than point charges are sufficient for the reproduction of the ion cloud. Moreover in using ring charges, the calculation can be carried out as a rotationally symmetrical problem, so that relatively little calculation time is required for the digital computer. The form of the ion cloud was varied and is illustrated in Fig. 3 in several forms. The charge of ions and their number were also altered to a great extent, as is still to be explained.

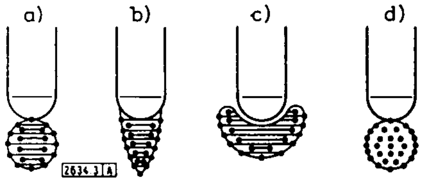

Fig. 3. Ion clouds in their early phase, in the basic form as used in the calculation
a, b, c Reproduction as ring charges
d Reproduction as point charges

The calculations were carried out step by step and proceeded in the following manner:

On any selected ion an electric field strength E occurs (Fig. 4) which originates both from the outer field, as a result of the voltage imposed on the electrode, as well as from the charge of the remaining ions. This field strength, which runs in a certain direction, allows the ion concerned to travel a certain distance further and is presented in these calculations. Calculations are made successively for all ions. The ion which has travelled the longest distance As at that time, is taken as representative and the time of movement established from it:

At = As (b, ·E).

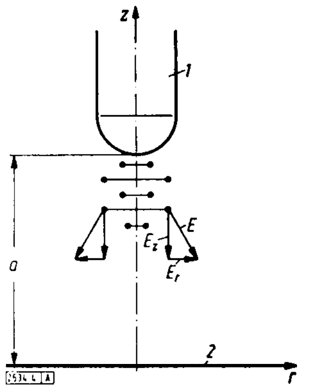

Fig. 4. Dimensions and notations for the calculation of the ion clouds
1 Rod electrode 2 Plane electrode

Thus fixed periods of time are not calculated but the distance, covered by the fastest is assumed. Which ion travels the fastest is only arrived at from the calculation. After each movement the field strength at the time is again calculated and all charge carriers repelled correspondingly. This calculation process is carried through until the first ion has almost reached the opposing electrode. The time which has then elapsed is calculated from the sum of all the times. As a rule 10 to 20 stages are sufficient to reproduce the movement of the charge carriers on their way between the electrodes.

In the greater part of the field area the z-component E_z is negative to the field strength, thus directed on to the plane (Fig. 4). The ions which remain in this area move therefore to the plane electrode. At the starting however when the ion cloud is still near to the anode, it is possible that the ions in a position close to the anode remain in an electric field with a positive field flow, that so the ions are accelerated in the direction of the anode and enter into the anode. This is only possible in the calculation, because the ions cover a certain distance during the period At at a constant speed and during this time are just able to reach the electrode. When this occurs, the experimental calculation ensures that the corresponding ions disappear from the field region. Thus it can be established whether these ions were withdrawn from the anode. In fact the positive ions were repulsed from the anode. As these ions are of no further interest for the calculation, for simplicity they were taken out of the field area.

If the ions travelled away from the anode, the electric field strength E_z at the anode changes its direction and thus becomes negative. As soon as the electric field strength has gone far enough in the new direction, the experiment is started so that a new collision ionisation and a new formation of ions can be produced in the anode area. On the grounds of simplicity of calculation, this ion cloud receives the same charge as the first. This can certainly be achieved approximately, since in amplitude and extent of the charge, the streamer-impulse of the pre-breakdowns remain the same. If these subsequent ions are removed sufficiently far from the electrode, further ions are activated from there. The criteria for collision ionisation and the creation of new positive ions forms the field strength at the anode, measuring 45.5 kV/cm on a hemispherical (1 cm radius) rod end. This represents the initial field strength of the electrode in the field free of space charge. It is an approximation and is taken here, since from the calculation, it is shown that the cycle times for the ions are very much independent of it in a large area of this field strength (25 to 60 kV/cm).

In the same way a field emission is assumed at the electrode opposing the plane, when the electric field strength there reaches a certain figure. This figure is established at 25 kV/cm, that is as large as the breakdown field strength in a homogeneous field at corresponding clearances. As soon as the electric field strength has risen to this figure. an opposing discharge can come into being and results directly to the breakdown. At this time the calculation is interrupted, since the breakdown which then follows expires within a small fraction of the previous time of the ion velocity. For the calculation a constant voltage was chosen. thus leaving open, the way in which the glow corona could be brought out of equilibrium. Thus it is possible to work in a simple manner, in contrast to the measurements, without the small superimposed voltage impulse. This is permissible, since the mean values of the experimental results, which were achieved with a superimposed positive or negative impulse, have achieved no significant difference in the breakdown time.

5. Results of calculations and comparison with the measurements

As basic example of the calculation, a rod-plane arrangement with a gap-distance of 25 cm with a hemispherical end of 1 cm radius of the rod was selected on which was laid a positive d.c. voltage of 115 kV. The velocity of the ions for various forms of space charge distribution were ascertained on this arrangement (Fig. 3a to 3c). In so far as the sum of the space charges is the same in these cases, variations only of 11% are produced in the travelling times. The shortest travelling times occur in the ion distribution in accordance with Fig. 3a, the longest in the form in accordance with Fig. 3c.

The ions cannot optionally be finely divided within the accepted form. In order to maintain the requirement on calculation time and storage for the digital computer the maximum of 100 ring charges was initiated. As was evident from the results, this number was sufficient. One example will confirm this. If the number of charges is raised by a constant charge total of 23 to 46, the travelling time still varies around 15%. On the other hand, no change in the travelling time is established in a further increase from 46 to 70 charges. With 100 charge carriers the space charge is consequently sufficiently exactly reproduced.

The total charge of the ions was selected between 110 and 1150 nC, that is varied in the ratio 1 : 10. This total charge is correct in about the actual ratios. R.T. Waters and others [6] determined, for example, a total charge of 500 nC in a 40 cm rod-plane spark gap with an impulse voltage of 160 kV. The travelling times are lower in the higher space charges than with the lower. The difference adds up to – assuming the same form of ion cloud – relating to the highest figure only 21%. The travelling times therefore are influenced only to a relatively small degree by the total of the charges. The figure which results from 46 charges at 25 nC each will serve as an example. According to the calculation a travelling time of 1775 µs results with the ion distribution from Fig. 3a. The measurement results are quoted as comparison. There the average figures varied (at a separation of 25 cm between rod and plane) between 1500 and 2000 us [3] each in accordance with the polarity of the superimposed impulse. The mean value of interpolation at about 1750 µs conforms very well with the calculation. The number of ion clouds which drifted from the anode to the cathode, varied according to the results of the calculation between two and eight. If the formation of a subsequent ion cloud is not permitted, the calculated travelling times rise from 5000 to 7000 us. These large times figures which were not measured in the experiment showed, on the other hand, that only a single ion cloud travelled to the cathode. In the calculation successive ions were always started for this reason – as soon as the field strength at the rod reached the critical value described above. The further ionisations on the *severely bent* electrode were able to be checked with a qualitative measurement of the current and the second possible process mentioned earlier discarded. It was also established from this, that the field strength at the plane always increased so much, that a field emission developed if the first ions on the plane approached to 0.5 to 1 cm. Since, in this case, calculation is interrupted, times result which are about a few hundred micro seconds less, that is to say, when the ions arrive directly on the plane. This fact indicates that the secondary effects (field emission or r-effects) actually contribute to the breakdown.

If the voltage in the basic example above is raised from 115 to 135 kV, the ion travelling time, according to the calculation, falls from 1775 to 1342 us. The figure occurred, according to Fig. 3a, for an ion cloud with 46 charges at 25 nC each and again on the controls with 70 charges at 16.4 nC each, thus of similar total charge. The travelling time however decreases more strongly in this way, than in the reverse ratio of the voltages. This can also be confirmed by the measurements. The corresponding time lies still lower (Fig. 5) at the breakdown voltage of this spark gap (162 kV). There is good agreement also in this with the figures of the experiment.

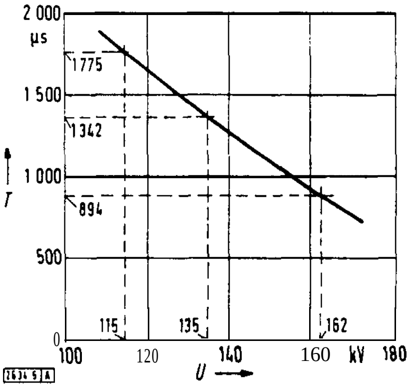

Fig. 5. Calculated ion travelling times T dependent on the voltage U for a rod-plane spark gap with 25 cm distance. The rod end is hemispherical with radius of 1 cm

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