BEHAVIOR OF AIR INSULATING GAPS OF DC SYSTEMS UNDER IMPULSE, DC AND COMPOSITE VOLTAGES

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ABSTRACT

This paper deals with the behavior of air insulating gaps of direct current (dc) transmission systems in the voltage range of ±600 kV to ±1 200 kV. The gaps studied were simulating either a bipolar dc tower or a bipolar rigid bus system. The influence of the terminations of the two ends of the insulator supporting the bus was investigated by using a single bus supported at one end. The breakdown voltage of the gaps was determined for a pure impulse, pure dc voltage or composite voltage formed by a dc on which an impulse was superimposed. The proximity effect of one pole on the pole-to-ground breakdown voltage of the other was also investigated.

INTRODUCTION

For over twenty years now, a considerable amount of work has been devoted to studying problems related to the air insulation of extra high voltage (EHV) alternating current (ac) systems. However, very little work has been done with regard to the air insulation of direct current (dc) systems. To fill this gap, the Electric Power Research Institute (EPRI) has financed an extensive research program concerning UHV dc transmission (±600 to ±1 200 kV). This paper provides an account of tests performed at the Institut de recherche de l'Hydro-Québec (IREQ) at the request of EPRI, to study the air insulation of UHV dc transmission systems.

Overvoltage stresses in dc systems are generally less severe than with ac but have the characteristic of being formed by two components, a switching surge superimposed on a dc voltage (composite voltage). Literature on the behavior of air gaps stressed by composite voltages is very limited[1-4]. The present study consists in an investigation into the response of the air insulating gaps of dc transmission towers and station buses stressed by composite voltages. The influence of the proximity of an adjacent pole on the breakdown voltage to ground was also examined as well as the influence that the shape of the electrodes terminating the insulating gaps can have on the breakdown voltage.

TEST DESCRIPTION

All tests were performed indoors in IREQ's 67 x 82 x 51-m high-voltage hall, most of them under dry conditions. A limited number of tests under artificial rain were also conducted. Actual-size insulating gaps of a real system were tested.

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1. Voltage sources and measuring devices

Two 1.2-MV rectifiers and a 6.4-MV (charging voltage) 400-kWs impulse generator were used as voltage sources. The dc voltage was measured by a resistive voltage divider incorporated into each of the two rectifiers, and a digital voltmeter. The impulse voltage was measured by a 5.4-MV series-damped capacitive voltage divider suspended from the ceiling of the laboratory, and a crest voltmeter. For most of the tests, the time-to-breakdown was also recorded using a signal from the voltage divider and a frequency counter.

2. Test voltages

The following voltage forms were used:
- a pure impulse of 250/6 000 μs;
- a pure dc voltage;
- a composite voltage consisting of a dc component on which a 250/2 500-μs impulse was superimposed, both of positive polarity.

3. Test procedure

In testing with a pure impulse or a composite voltage, the 50% breakdown voltage, $U_{50\%}$, was determined by producing the complete breakdown probability distribution with four to five points, fifty shots per point. For a composite voltage, if a shot was not followed by a breakdown, the dc voltage was maintained and a new shot was applied after ~60 s. Because the dc and impulse components were both of the same polarity, the sum of the two formed the amplitude of the composite voltage applied to the gap.

The dc breakdown voltage was determined as follows: The dc voltage was raised within 10 to 20 s to a certain level where it was maintained for 10 s. Subsequently, the voltage was lowered to zero then raised again to the same level twice more. If less than two breakdowns occurred as a result of three voltage applications at this particular level, the voltage was increased slightly and three additional applications were made. The $U_{50\%}$ was determined as the mean value of two levels, one giving not more than one breakdown and the other not less than two. Usually, the difference between these two levels was less than 2%, which indicates the low dispersion of the dc breakdown voltage.

In testing conductor-to-tower gaps or bipolar buses (gaps a and b below) with a composite voltage, the breakdown probability distribution was determined by simultaneously varying both the dc and the impulse components, maintaining their ratio constant. Contrarily, in testing for the influence of the form of the terminating electrodes (gaps c below), the dc component was maintained constant and the various breakdown probabilities were obtained by varying the impulse component only. The second procedure allowed identical dc corona conditions to be maintained in the gap for all breakdown probabilities, before the impulse was applied.

4. Gaps tested

The present study concentrated mainly on the following topics:

a) determination of the breakdown voltage of conductor-to-tower gaps of a bipolar dc transmission tower;

b) determination of the bus-to-ground or bus-to-bus breakdown voltage of a bipolar bus arrangement;

c) influence on the breakdown voltage of the terminating electrodes of the insulator column of a monopolar bus arrangement;

d) determination of the breakdown voltage of rod-plane gaps.

Conductor-to-tower gaps: The gap was formed by a two-pole tower model (Fig. 1) equipped with two 24-m long conductor bundles, each formed by four 3-cm diameter tubes with a 46-cm spacing. The height of the bundles above the laboratory floor was 17 m. The width of the lattice tower structure which, as it is known, affects the breakdown voltage, was 3 m.

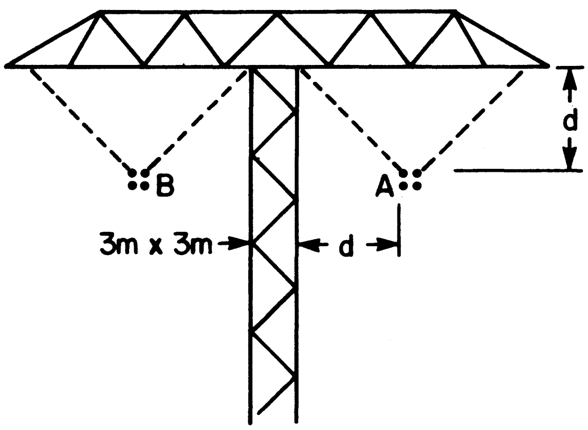

Fig. 1 Two-pole tower model.

Table I

test no.	Tower tests	imp. gen.	casc. rec.	dry	wet	clearances
1	3m, d, + imp. Grounded	X		X		d= 4,6,7.8,9.6m
2	d, + 1.7 imp. - 1d.c.	X	X	X		d= 4m
3	- 1d.c. / + 1d.c.+0.7 imp. Grounded / + 1d.c.+0.43imp. Grounded / + 1d.c.+0.7 imp. Grounded / + 1d.c.+1.0 imp. Grounded / + 1d.c.+1.43 imp. d	X	X	X		d= 4m

The tests, performed with a pure impulse or a composite voltage, are summarized in Table I. The aim of these tests was to determine the conductor-to-tower breakdown voltage. The influence of an adjacent pole on the conductor-to-tower breakdown voltage, was determined by testing with this pole either grounded or polarized by a -1 p.u. negative dc voltage. Throughout this paper the absolute value of the dc component is used as a basis for the per unit expressions.

All tests were performed under dry conditions.

Bipolar buses: The bus-to-ground and bus-to-bus breakdown voltages of a bipolar bus arrangement were determined as functions of the corresponding clearances. The tests performed with this arrangement are summarized in Table II.

In testing bus-to-ground configurations, the two buses consisted of two 24-m long rigid tubes of 15 cm diameter supported at one end only by an insulator column mounted on a metallic pedestal (Fig. 2). Tests with bus heights H = 12 m and H = 15 m were performed. In each test series, while H was maintained constant, the length of the insulator column, D, was varied by short-circuiting a part of it at the lower end. In this series of tests, the second bus served merely to determine the effect of its proximity on the bus-to-

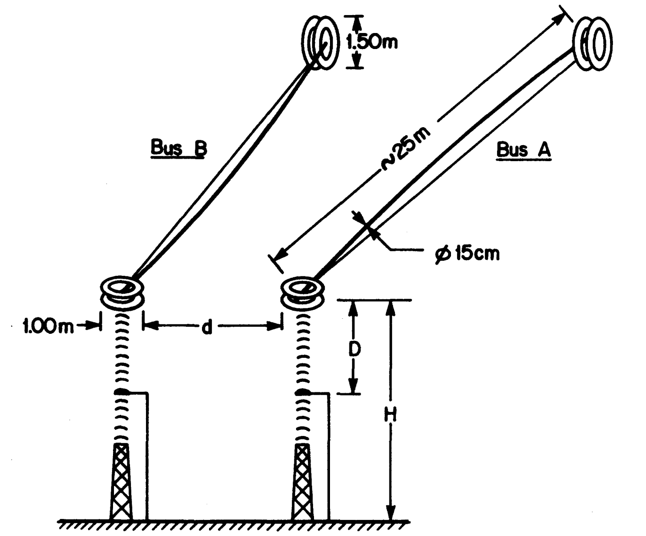

Fig. 2 Bipolar bus arrangement.

TABLE II

test no.	Bipolar bus	imp. gen.	casc. rec.	dry	wet	clearances
4	Grounded, D, H / + imp. - imp. d	X		X	X	D=4,6,7,8m d= 2D H=12,15m
5	- 1d.c., D, H / + 1.7imp. d	X	X	X		D= 4m d = 8,10m H= 12m
6	Grounded, D, H / + 1d.c.+0.7 imp. + 1d.c.+ 1 imp. d	X	X	X		D= 4m d= 8,10m H= 12m
7	Grounded, D, H / + 1d.c.+.43imp. + 1d.c.+1.5 imp. + 1d.c.+2.3imp. d	X	X	X		D= 4m d = 10m H = 12m
8	- 1d.c., H / + 1.7 imp. d	X	X	X		d= 6,7.5,8.25m H= 15m

ground breakdown voltage of the other bus. A distance between the buses d = 2D was maintained throughout in order to avoid bus-to-bus breakdowns. Tests with a pure impulse or a composite voltage were performed with the second bus either grounded or biased with a -1 p.u. negative dc voltage.

In testing for bus-to-bus insulation, the two supports were removed and the two buses were suspended from the ceiling of the laboratory at a height H = 15 m. The two buses were slightly bent in order to reduce the distance of their middle sections so that practically all breakdowns terminated within this section. A -1 p.u. dc voltage was applied on one bus and a +1.7 p.u.

impulse on the other. Tests under rain were also conducted as indicated in Table II.

Testing for the influence of the terminating electrodes: In testing with dc or composite voltages, the terminations of both ends of the gap affect the breakdown voltage. In order to investigate this influence, tests were conducted with a monopolar bus arrangement. The majority of the tests were performed with D = 4 m and H = 12 m. For comparison, a 4-m rod-plane gap was also tested with the full range of composite voltages. For one set of terminations, tests were also performed with H = 12 m and D = 3 and 2 m.

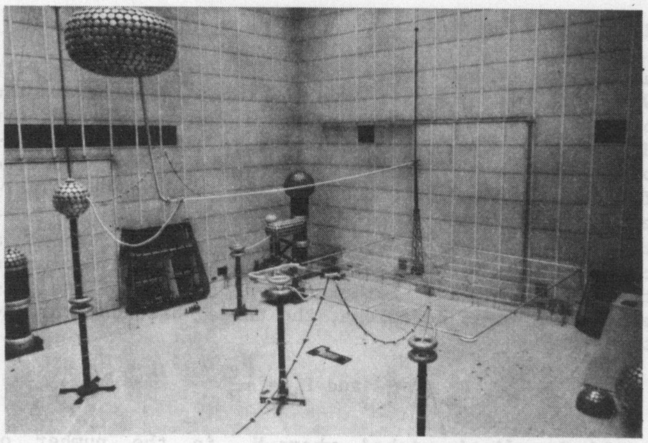

Fig. 3 Photograph of the setup for testing for the influence of the terminating electrodes.

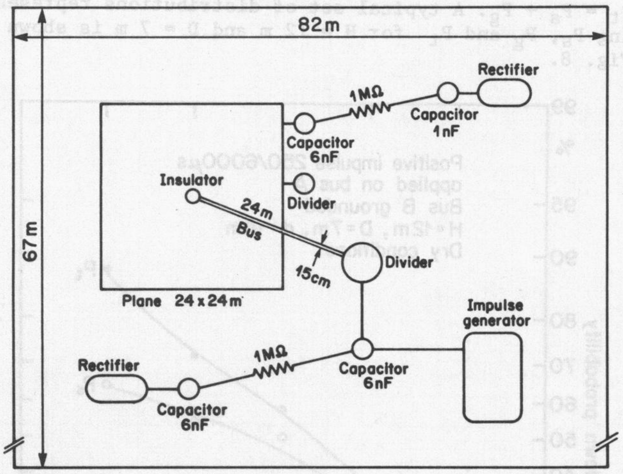

Fig. 4 Setup for testing for the influence of the terminating electrodes (plan view).

Because, in this series of tests, it was judged desirable to test with the entire range of composite voltages, i.e. from pure impulse to pure dc, the 1.2-MV dc voltage available from each of the two rectifiers was not sufficient. It was thus necessary, for certain tests, to polarize the ground plane with a dc voltage of opposite polarity from the bus voltage. For this purpose, a simulated ground plane of 24 x 24 m was formed by a 5-cm wire mesh and suspended with insulating ropes from the laboratory ceiling at a height of 10 m as shown in Figs. 3 and 4.

The detailed dimensions of the three different combinations of terminating electrodes used are shown in Fig. 5 together with a 4-m long rod-plane gap with the rod terminating in a 30° cone. The four gaps are numbered 1 to 4 and these figures are also used to designate the curves obtained with each of them.

The possible effect of the polarization of the ground plane was investigated by inverting the two portions of the total dc voltage applied between the bus and the plane. These tests showed that the use of the polarized simulated ground plane, rather than the laboratory floor, had only a minor effect on the breakdown voltage of the gap.

Rod-plane gaps: Using the suspended-plane arrangement mentioned above, the dc breakdown voltage of rod-plane

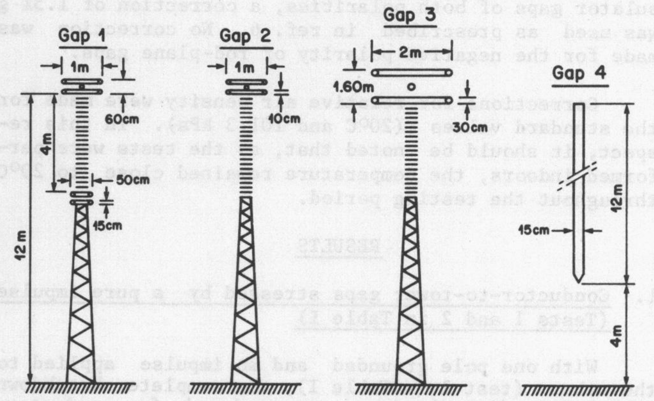

Fig. 5 Detailed dimensions of the four arrangements tested with a 4-m gap clearance and various terminating electrodes in testing for the influence of the terminating electrodes.

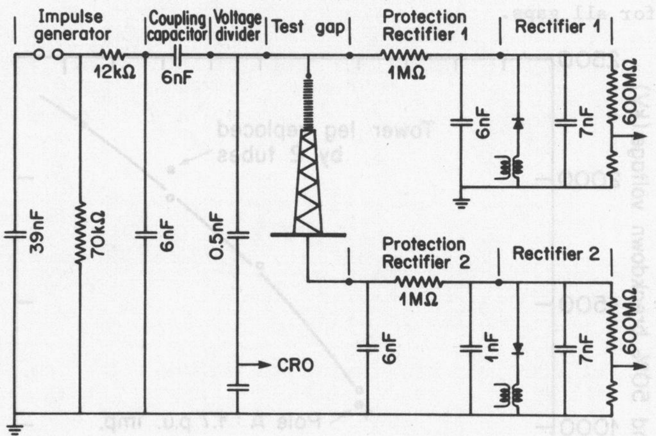

Fig. 6 Test circuit for testing for the influence of the terminating electrodes.

gaps of up to 5 m clearance for positive polarity, and 4 m for negative polarity, was determined.

5. Test circuit

The test circuit used for the general case of a composite voltage applied on one electrode and a polarization voltage on the plane is shown in Fig. 6. The two 1-MΩ resistors, together with the 6-nF capacitors, protected the rectifiers while a 6-nF coupling capacitor prevented dc voltage transfer to the impulse generator. For particular cases not requiring the dc or the impulse component of the composite voltage or the dc polarization of the other electrode, the circuit was modified accordingly.

6. Corrections for atmospheric conditions

Humidity corrections are well-known for their lack of reliability. To avoid large corrections, it was therefore decided to correct not for standard humidity (11 g/m^3) but for the mean value of the humidity variations observed during the testing period. The tests were performed when a mean absolute humidity of 5 g/m^3 was recorded. Hence the correction for humidity was made for this mean value.

For tests with a pure impulse or a composite voltage, the humidity corrections prescribed for impulse voltages in ref. 5 were applied, while for the dc breakdown voltage of positive rod-plane gaps or of insulator gaps of both polarities, a correction of 1.5% g was used as prescribed in ref. 6. No correction was made for the negative polarity of rod-plane gaps.

Corrections for relative air density were made for the standard values (20°C and 101.3 kPa). In this respect, it should be noted that, as the tests were performed indoors, the temperature remained close to 20°C throughout the testing period.

RESULTS

1. Conductor-to-tower gaps stressed by a pure impulse (Tests 1 and 2 in Table I)

With one pole grounded and an impulse applied to the other, (test 1 in Table I), the complete breakdown probability distributions were produced for conductor-to-tower clearances d = 4,6,7,8 and 9.6 m. The $U_{50\%}$ -d characteristic obtained with these distributions is shown in Fig. 7 for the range of clearances tested. For all clearances tested, the breakdown probability distributions obtained were very closely gaussian with a coefficient of variation of c ~4% nearly the same for all gaps.

Figure 7 presents the following additional results:

Point 1: For d = 4 m, energization of one pole by a -1 p.u. dc voltage (instead of being grounded) and a +1.7 p.u. impulse applied on the other, reduces $U_{50\%}$ by ~3%.

Point 2: For d = 7.8 m, replacement of the lattice structure of the tower leg by two tubes simulating the tower corners produced a 6% increase in $U_{50\%}$; this confirms the already known effect that the bulkier and denser the tower structure, the lower the breakdown voltage.

2. Bipolar buses stressed by a pure impulse

a) Bus-to-ground gaps (tests 4 and 5 in Table II): With one bus grounded and an impulse applied to the other (test 4 in Table II), tests were performed for H = 12 m and H = 15 m. With each value of H, the complete breakdown probability distributions were produced for D = 4,6,7 and 8 m. Because the bus-to-bus clearance was adjusted to twice the insulator length, bus-to-bus breakdowns generally did not occur. Above a certain value of D, however, a few breakdowns occurred to the ground plane rather than to the top of the pedestal. On these occasions, the three breakdown probabilities

$$P_s = \frac{N_s}{N}, \quad P_g = \frac{N_g}{N} \quad \text{and} \quad P_t = \frac{N_t}{N}$$

could be distinguished, where N_s is the number of breakdowns to the top of the pedestal, N_g those to the ground plane, $N_t = N_s + N_g$ the total number of breakdowns and N the number of shots applied. By definition, $P_t = P_s + P_g$. A typical set of distributions representing P_s, P_g and P_t for H = 12 m and D = 7 m is shown in Fig. 8.

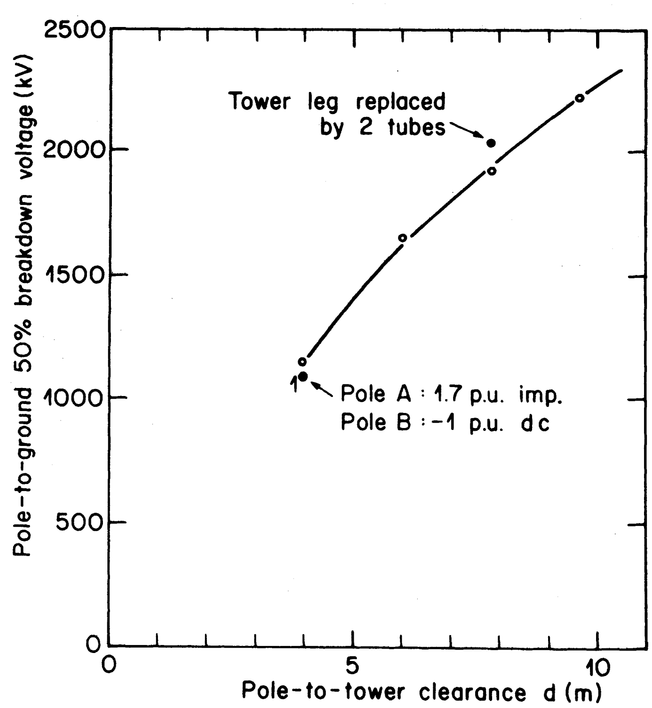

Fig. 7 Switching-impulse 50% breakdown voltage as a function of the pole-to-tower clearance; second pole grounded. Point 1 illustrates the influence of polarizing the second pole with a -1 p.u. dc voltage. Point 2 illustrates the influence of the tower cross section. Results corrected for $\delta = 1$ and $h = 5\ g/m^3$.

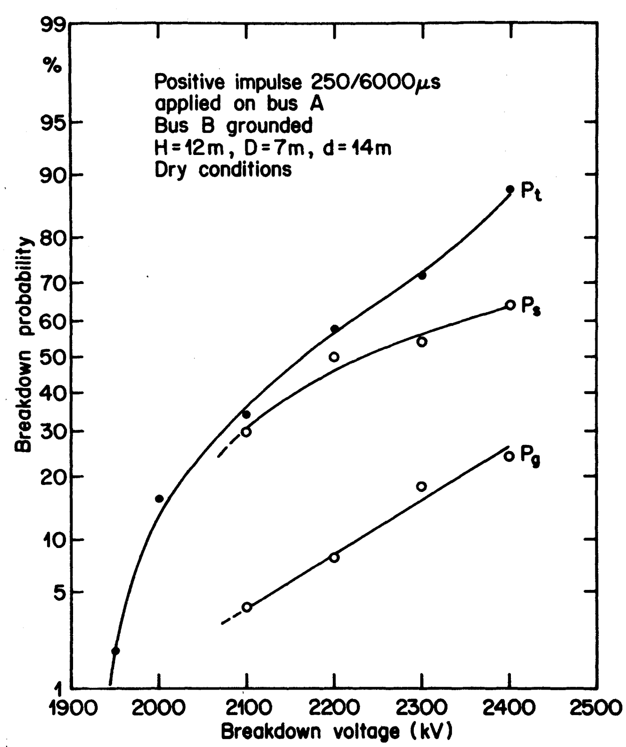

Fig. 8 Breakdown probability distribution of the bus-to-ground gap for two buses supported at one end. P_s and P_g correspond to breakdowns directed to the pedestal top or the ground and P_t gives the total breakdown probability.

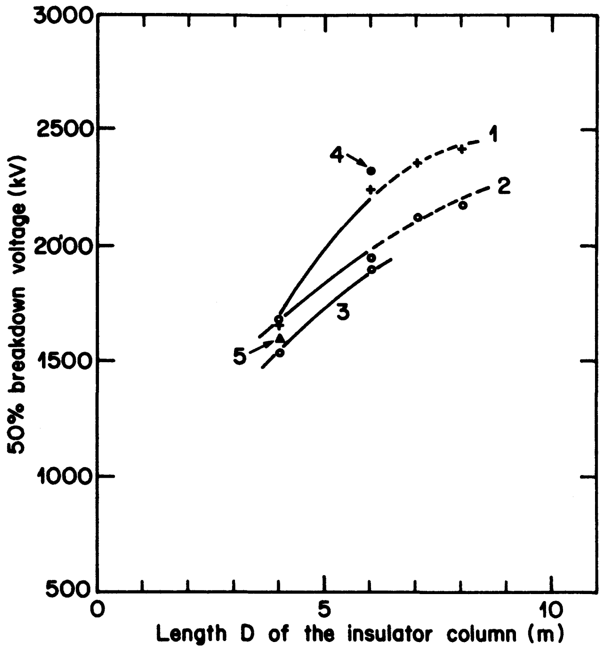

Fig. 9 50% switching-impulse bus-to-pedestal breakdown voltage as a function of the insulator column length D; bipolar bus supported at one end.
Curve 1: H = 15 m, one bus grounded and a positive impulse applied to the other; dry conditions.
Curve 2: H = 12 m; other conditions the same as for curve 1.
Curve 3: Same conditions as curve 2 but under rain.
Point 4: Same as curve 3 but under negative polarity.
Point 5: Same as curve 1 but the adjacent bus polarized with a -1 p.u. dc voltage instead of being grounded.
Results corrected for δ = 1 and h = 5 g/m³.

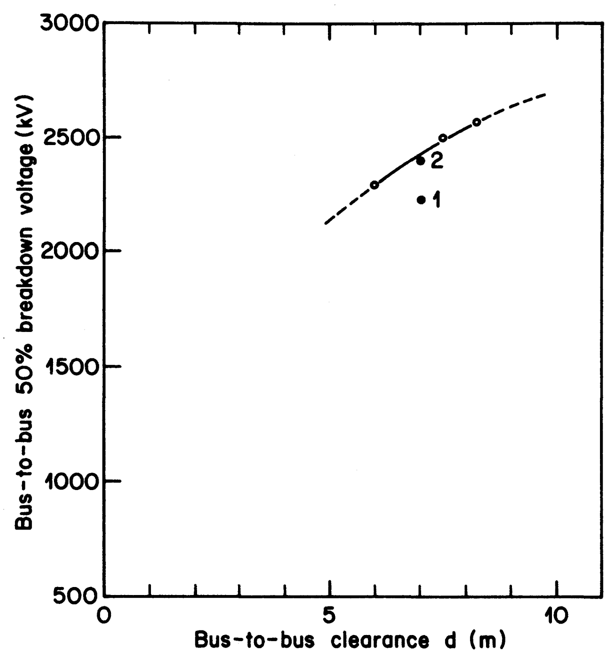

Fig. 10 Bus-to-bus 50% breakdown voltage as a function of the bus-to-bus clearance d. Positive impulse 250/6 000 µs on bus A, -1 p.u. dc voltage on bus B, H = 15 m.
Point 1 is for bus B grounded and H = 12 m;
Point 2 is for H = 12 m and a 1 200/8 000 µs negative impulse on bus B.
Results corrected for δ = 1 and h = 5 g/m³.

By determining the $U_{50\%}$ value corresponding to the total breakdown probability, P_t, for various values of D, the $U_{50\%}$ - D characteristics for H = 12 m (curve 1) and H = 15 m (curve 2) are produced (Fig. 9). The part of the curve corresponding to D values above which breakdowns to the ground plane occurred is shown by a dashed line. The following additional results are superimposed on Fig. 9:

Curve 3: For H = 12 m one bus grounded and a positive impulse on the other, rain reduces $U_{50\%}$ by ~7%.

Point 4: For H = 12, D = 6 m, one bus grounded and a negative impulse on the other, the $U_{50\%}$ under rain is appreciably higher than the positive breakdown voltage under dry conditions; consequently negative polarity under rain is not a critical situation.

Point 5: For H = 12 m and D = 4 m, polarization of one bus by a -1 p.u. dc voltage and a positive impulse of +1.7 p.u. on the other reduces $U_{50\%}$ by ~4%. A more detailed discussion of this effect is provided later in the text.

b) Bus-to-bus gap (test 8 in Table II): Removing the bus supports (insulator and pedestal) and suspending the two buses with insulating ropes from the ceiling of the laboratory at H = 15 m above the floor, the bus-to-bus breakdown voltage was determined as a function of the clearance d. For this purpose, a -1 p.u. dc voltage was applied on one bus and a +1.7 p.u. impulse on the other. The sum of the absolute values of the dc voltage and the impulse was considered as the bus-to-bus voltage. The characteristic $U_{50\%}$ - d obtained in this way is shown in Fig. 10 where the following additional results were superimposed:

Point 1: One bus grounded (instead of being energized by a -1 p.u. dc voltage of negative polarity) and an impulse applied on the other. Grounding of the previously polarized bus reduces $U_{50\%}$ by ~8%. This illustrates the fact, well-known from phase-to-phase studies, that a fraction of the total voltage applied between the two electrodes of a gap is more effective in producing breakdown if it is applied at the positive rather than the negative side of the gap.

Point 2: When the -1 p.u. dc polarization was replaced by a 1 200/8 000-µs negative impulse, $U_{50\%}$ remained practically unaffected. Physical considerations lead the authors to believe, however, that for values of the polarization voltage high enough to produce corona, the effect of an impulse should not be identical to that of a dc voltage.

3. Conductor-to-tower gaps and bipolar buses stressed by a composite voltage (tests 3 in Table I and 6 and 7 in Table II)

These tests refer to pole-to-ground breakdowns and were performed with one pole grounded and the composite voltage applied to the other. Certain tests, performed with one pole energized by a negative-polarity dc voltage (instead of being grounded), have shown that this has the effect of slightly reducing the composite break-

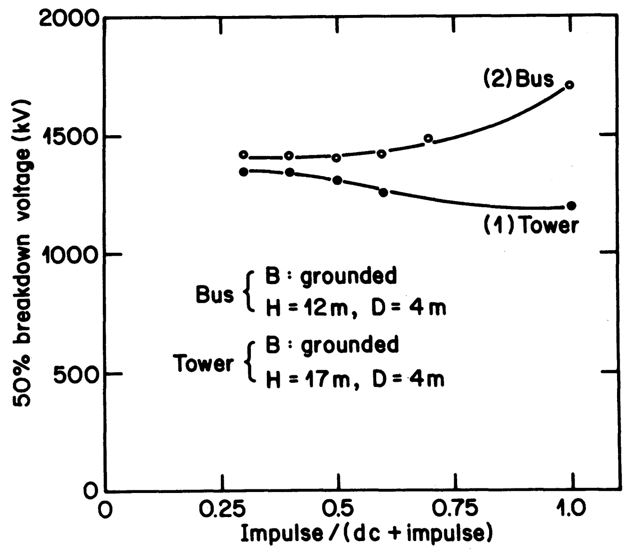

Fig. 11 Influence of the impulse-to-dc ratio of a composite voltage on the pole-to-ground 50% breakdown voltage of a bipolar tower or a bus. Results corrected for $\delta = 1$ and $h = 5\ g/m^3$.

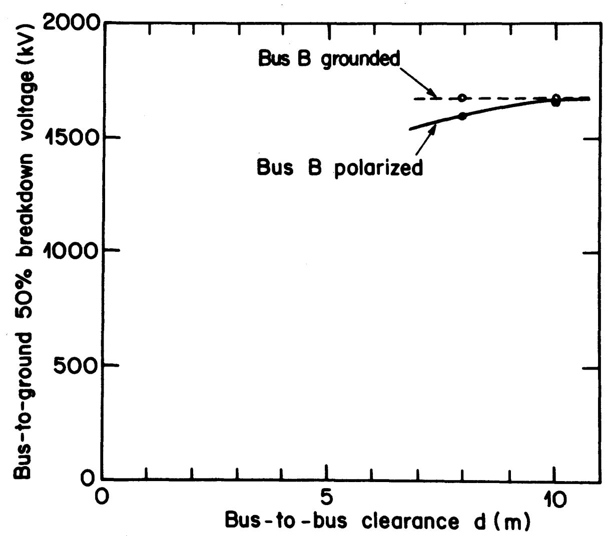

Fig. 12 Influence of dc polarization of bus B on the bus-to-ground 50% impulse breakdown voltage of bus A as a function of the bus-to-bus clearance d.
H = 12 m, insulator column length D = 4 m, ratio impulse-to-dc: 1.7/1.

down voltage to ground as was also the case for a pure impulse.

The characteristic curves giving $U_{50\%}$ with a composite voltage as a function of the ratio impulse/impulse + dc, obtained with a 4-m conductor-to-tower gap (in the case of the tower) or a 4-m insulator column (in the case of buses), are illustrated in Fig. 11. The two curves show an opposite tendency; in the case of the tower, $U_{50\%}$ decreases as the ratio impulse/impulse + dc increases (and consequently dc decreases) while for the bus arrangement the opposite occurs. As shown below, both tendencies are justifiable, depending on the terminations of the two ends of the gap.

4. Influence of the polarization of one pole on the pole-to-ground breakdown voltage of the other

Because of capacitive coupling, the proximity of an adjacent pole influences the electric field around the other pole. If the adjacent pole is grounded and a positive voltage is applied to the other, this influence has the effect of enhancing the field around the energized pole and presumably reduces the breakdown voltage. This effect intensifies if the adjacent pole, instead of being grounded, is energized with a negative-polarity voltage and, also, as the distance between the two poles decreases.

In order to determine the importance of this effect, the $U_{50\%}$ to the ground of bus A (see Fig. 12) stressed by a pure impulse was determined as a function of the bus-to-bus distance with bus B either grounded or energized with a -1 p.u. dc voltage. Figure 12 shows that when the adjacent bus is grounded, its effect on the breakdown voltage to the ground of the energized bus is negligible. However, when the adjacent bus is energized with a -1 p.u. dc voltage, for large bus-to-bus clearances the effect is still negligible but becomes noticeable as the bus-to-bus clearance decreases. It should be noted that the tests were only performed for bus-to-bus clearances exceeding those giving a large number of bus-to-bus breakdowns. These results are in line with the theoretical considerations made above.

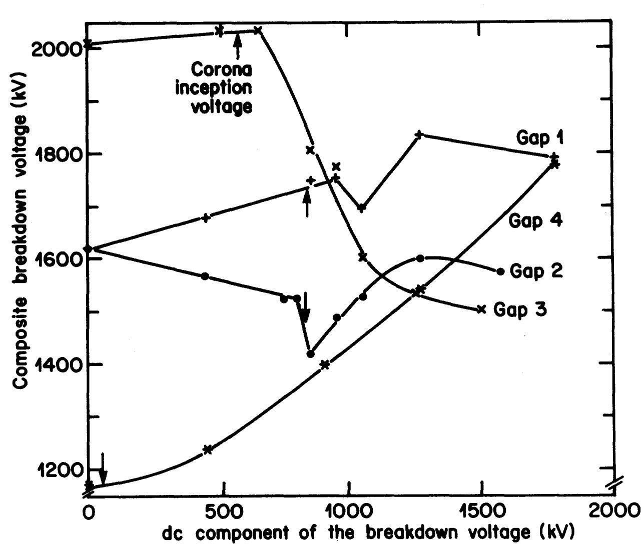

Fig. 13 Composite breakdown voltage as a function of the dc component for three bus arrangements with a 4-m long insulator column and a 4-m rod-plane gap. Numbering of curves corresponds to numbering of gaps in Fig. 5.
Results corrected for $\delta = 1$ and $h = 5\ g/m^3$.

5. Influence of the shape of the terminating electrodes

a) Tests with a composite voltage on 4-m gaps with various terminating electrodes: Four types of 4-m long gaps were tested: three monopolar bus arrangements with a 4-m long insulator and various terminating electrodes and a 4-m rod-plane gap with the rod terminating in a 30° cone. Details of the dimensions of these gaps and their terminating electrodes are shown in Fig. 5 and the characteristics giving the composite breakdown voltage of each of these gaps as a function of the dc component are illustrated in Fig. 13 where they bear the same numbers as the gaps. The idea behind the use of various terminations for the two ends of the insulator column was to vary the level of the dc component at which corona starts at the upper or the lower end of the column before the application of the impulse.

For gap 1, corona started at the upper end of the insulator column at ~840 kV of the dc component while at the lower end no corona occurred for any of the dc voltage components used. Curve 1 of Fig. 13 shows that the positive-impulse $U_{50\%}$ of the gap is 1 620 kV. With an increasing dc component, before corona inception, $U_{50\%}$ increases linearly. A little after corona inception at the upper end of the column, $U_{50\%}$ dropped abruptly forming a narrow valley after which it increased again up to the dc breakdown voltage of the gap. The general trend of the breakdown characteristic was to increase as the dc component increased.

For gap 2, corona started quasi-simultaneously at the upper and the lower end of the insulator column at ~840 kV of the dc component. The impulse $U_{50\%}$ of gap 2 was the same as for gap 1, as expected in fact because this voltage depends mainly on the electric field around the positive electrode and this field is affected very little by the termination of the lower end of the column. With an increasing dc component, before corona inception, $U_{50\%}$ decreased linearly up to corona inception (instead of increasing as in gap 1) whereupon it dropped to form a narrow valley in much the same way as for gap 1. The effect of corona inception at the lower end of the column, however, was a general downward trend of the breakdown characteristic and a dc breakdown voltage ~15% lower than gap 1.

The results obtained with gaps 1 and 2, shown in Fig. 13, now provide an explanation for the opposite tendencies observed with the tower and bus gaps shown in Fig. 11. This difference in tendencies should be attributed to the fact that, for the bus gap, corona is generated from the lower (negative) side of the gap whereas for the tower gap corona was not generated from this side of the gap. Thus, the tower gap behaves like gap 1 of Fig. 13. On the other hand, curves 2 of Figs. 11 and 13 are similar because they refer to the same gap. It should be noted that in order to compare Figs. 11 and 13, the two figures must be brought to a common abscissa scale.

Gap 3 had the same lower termination as gap 2 but the upper end of the column terminated in a much larger electrode with the result that, with the increasing dc component, corona started only at the lower end of the column at ~580 kV. The larger electrode of the upper end of the column then had the effect of producing a higher positive-impulse breakdown voltage, as was expected. Up to the corona-inception level, or a little above it, the breakdown voltage remained practically constant and then dropped abruptly to terminate — for the positive dc — at practically the same value as gap 2.

For a rod-plane gap (curve 4), the breakdown voltage remained practically constant for a dc component below 200 kV while for higher dc values the breakdown voltage increased quasi-linearly. It is interesting to note that the dc breakdown voltage of the rod-plane gap coincided with that of gap 1.

b) Tests with a composite voltage on 2- and 3-m gaps: For the same terminations of the insulator column as for gap 2 of Fig. 5, the composite breakdown voltage was determined as a function of the dc component for 2- and 3-m lengths of the insulator columns. The results are illustrated in Fig. 14 where curve 2 of Fig. 13, corresponding to a 4-m long insulator column, is also reproduced. Figure 14 shows that the pattern of the breakdown voltage for the three different lengths of

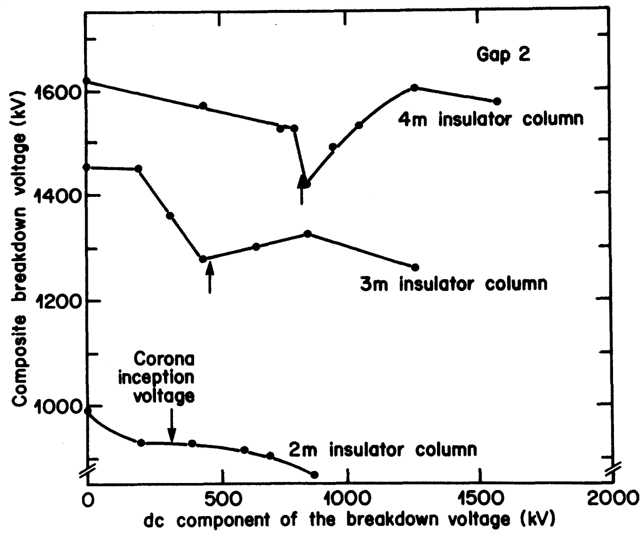

Fig. 14 Composite breakdown voltage as a function of the dc component for three bus arrangements with insulator columns of 2, 3 and 4 m. Terminations of the column ends as gap 2 of Fig. 5. Results corrected for $\delta = 1$ and $h = 5$ g/m^3.

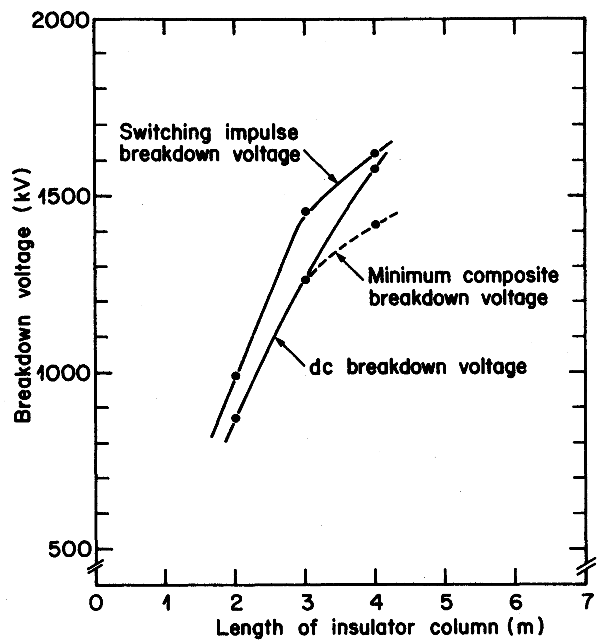

Fig. 15 Impulse, dc and minimum composite breakdown voltage of a rigid bus arrangement (gap 2) as a function of the insulator column length.

the insulator column was more or less maintained, which confirms that this pattern is mainly determined by the column terminations.

In Fig. 15, the positive-impulse and the positive dc breakdown voltage of gap 2 are given as a function of the length of the insulator column. It may be seen that, for the range of insulator lengths considered, the dc breakdown voltage, while in linear relation with the insulator length, is slightly lower than the impulse breakdown voltage. For insulator columns longer than 3 m, however, the impulse breakdown voltage showed a pronounced nonlinearity, which suggests that for longer insulator columns the impulse breakdown voltage would be lower than for dc.

In Fig. 15, the minimum composite breakdown voltage obtained for gap 2 is also shown by a dotted line as a function of the clearance and can be seen to follow the same type of nonlinear characteristic as the impulse breakdown voltage, although remaining clearly below it. It should be noted that the pattern of curves shown in Fig. 15 is representative of gap 2 only, and the conclusions drawn from this figure should not be generalized.

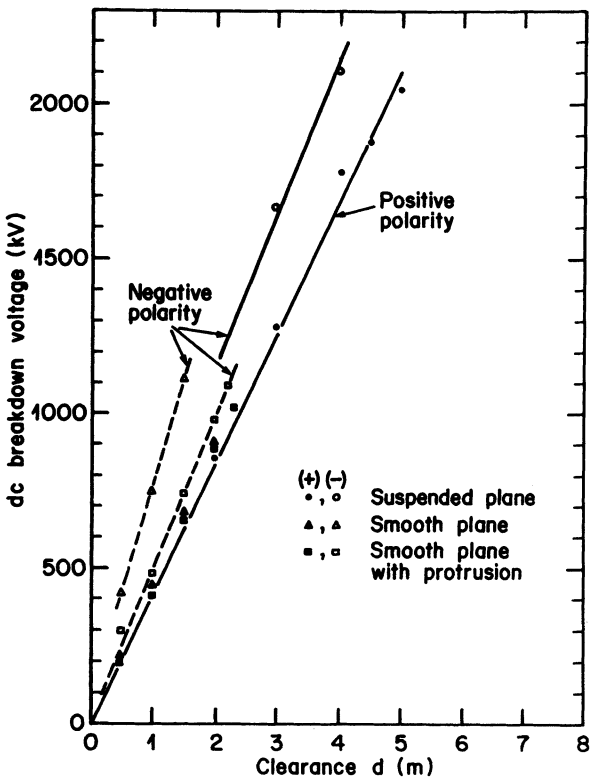

Fig. 16 Positive and negative dc breakdown voltage of rod-plane gaps as a function of the gap clearance.

Figure 16 shows that the curve giving the positive breakdown voltage approaches a straight line with a mean slope of ~4.2 kV/cm. In fact for gaps shorter than 2 m the slope is slightly steeper (~4.35 kV/cm) than for longer ones (~4.00 kV/cm). The mean positive breakdown gradient found by the present tests is lower than that given in ref. 6 (~5 kV/cm) but this difference can be partly attributed to the fact that the present results are corrected for an absolute humidity of only 5 g/m^3 instead of the normal value of 11 g/m^3.

The negative breakdown voltage is also given by lines approaching a straight one but not going through the origin. Their slope is dependent on the surface conditions of the plane; it is ~4.5 kV/cm for the suspended plane, ~7 kV/cm for the smooth plane and ~5 kV/cm for the smooth plane with a protrusion.

6. Positive and negative dc breakdown voltage of rod-plane gaps

Using the same suspended plane as for the bus arrangement and a vertical 12-m long rod terminating in a 30° cone suspended from the ceiling of the laboratory, the positive and negative dc breakdown voltage of the rod-plane gap formed in this way was determined as a function of the gap clearance. The results of this test are shown in Fig. 16 as a solid line. Comparing these results with those of refs. 2 and 3, fairly good agreement was observed for the positive breakdown voltage while for the negative one the values obtained were appreciably lower than those found in the same references. The hypothesis was then made that this difference was due to the surface roughness of the plane; it should be remembered that the surface of the suspended plane consisted of a 5-cm wire mesh. To check this hypothesis, tests were performed using as the ground plane the laboratory floor covered with a smooth aluminum plate. Since it was impossible to polarize the ground plane with this arrangement, only one rectifier was used and thus the test voltage could not exceed 1 200 kV.

Tests with the smooth plane showed that, whereas the positive-polarity breakdown voltage remained practically the same, the negative one was appreciably higher. The tests with the smooth plane were then repeated, this time with a small protrusion consisting of a vertical rod of 6-mm diameter, with a pointed end and only 5 cm in height, installed at the plane below the rod. While the positive breakdown voltage was practically not affected by this protrusion, the negative one was reduced by ~30% with respect to the smooth plane. This shows that the negative dc breakdown voltage of a rod-plane gap is sensitive to surface irregularities of the plane while the positive one is not. The results of the tests with the smooth plane — with and without the protrusion — are shown by the dotted lines in Fig. 16.

7. Switching impulse and dc, positive and negative, 50% breakdown voltage

The $U_{50\%}$ for positive and negative switching impulses and dc of the various configurations tested are given in Table III below corrected for normal air density and 5 g/m^3 absolute humidity. No correction was made for the negative polarity of the rod-plane gap.

TABLE III SWITCHING IMPULSE AND DC, POSITIVE AND NEGATIVE, 50% BREAKDOWN VOLTAGE OF VARIOUS GAPS TESTED

			S.I. Breakdown Voltage kV	dc Breakdown Voltage kV
Bus Configuration	gap 1 4-m insulator column	pos.	1620	1800
		neg.	2385	1790
	gap 2 2-m insulator column	pos.	990	870
		neg.	-	965
	gap 2 3-m insulator column	pos.	1455	1260
		neg.	-	1505
	gap 2 4-m insulator column	pos.	1620	1575
		neg.	2190	1995
	gap 3 4-m insulator column	pos.	2010	1505
		neg.	2220	1865
	gap 4 4-m rod-plane gap	pos.	1160	1780
		neg.	-	2100

DISCUSSION

1. Effect of the proximity of an adjacent pole on the pole-to-ground breakdown voltage

The results reported in Fig. 12 show that the breakdown voltage to the ground plane of one pole is practically unaffected by the proximity of an adjacent pole if this is grounded. However, if the adjacent pole is energized with a -1 p.u. dc voltage and when the pole-to-pole clearance becomes sufficiently small, it does start to have an effect. Figure 12 shows that this influence is ~4% for a bus-to-bus clearance of d = 8 m and an insulator length of D = 4 m. This d/D ratio seems to be close to the one that would have to be used in an actual bus arrangement. The isolated point 1 of Fig. 7 shows, on the other hand, that the effect of an energized pole on the pole-to-tower breakdown voltage of the other pole, is of the order of 3%. These results suggest that when pole-to-ground insulation is considered, the proximity of the adjacent pole, if energized, cannot be disregarded.

2. Coordination of the bus-to-pedestal top and bus-to-ground plane gaps

In testing with the rigid station bus arrangement, it was observed that, when the insulator exceeded a certain length, breakdowns directly to the ground plane (and not to the pedestal top) also occurred. This happened for insulator lengths exceeding 6 m for both bus heights H = 12 and 15 m.

With regard to station operation, breakdowns directly to the ground plane constitute a risk for personnel entering the station. Wherever such situations are encountered, design engineers tend to coordinate the clearances involved so that the risk of a breakdown to an undesirable point — in the present case, the ground — is much lower than the risk of a breakdown to a position where it could be tolerated, even reluctantly. Similar conditions exist with phase-to-ground and phase-to-phase insulation or the phase-to-ground insulation of an open disconnect switch and across its contacts. Upon closer examination of this philosophy, however, one realizes that the main design parameters are the risk of a discharge terminating at the undesirable position, in the present case represented by P_g, and the total risk, P_t, which determines the reliability of the system. These two risks could be treated independently, however, without necessarily introducing the restriction $P_g \ll P_t$. If P_g is sufficiently low to satisfy the relevant requirements (safety of personnel, for example), P_t would be selected solely in terms of system reliability and thus could be close to P_g or even equal to it. This dispenses with the requirement of coordination of the two gaps involved and simplifies insulation design.

3. Bus-to-bus insulation

The tests for bus-to-bus insulation were performed with one bus energized with a -1 p.u. dc voltage and a positive impulse of 1.7 p.u. applied to the other. The $U_{50\%}$ values determined in Fig. 10 correspond to the sum of the two components, 2.7 p.u. A test performed with one bus grounded and all the voltage applied to the other bus as a positive impulse (point 1 on Fig. 10) yielded a substantially lower $U_{50\%}$. This illustrates the well-known fact noted in phase-to-phase studies that, with bipolar stresses, the total breakdown voltage depends to a considerable extent on the ratio of the individual stresses applied to the two electrodes. The ratio -1 to +1.7 p.u. used in the present test is, however, representative of the actual stresses of a dc system.

It should be noted that, in an actual system, the bus is stressed by a composite voltage rather than the pure impulse used in the tests described here. This is an aspect which is not investigated in the present study but which is expected to have an additional effect on the bus-to-bus breakdown voltage.

4. Influence of the terminating electrodes on the dc breakdown voltage

The positive and negative breakdown voltages of the four gaps of Fig. 5, stressed either by a pure impulse or by a pure dc voltage, are summarized in Table III corrected for $\delta = 1$ and $H = 5\ g/m^3$. It may be seen that for gaps 1, 2 and 3, which have a similar general geometry, both the positive and the negative impulse breakdown voltages depend only on the electrode terminating the positive side of the gap, as expected.

Under dc voltage, gap 1 has the same breakdown voltage for both polarities which is also approximately equal to the positive breakdown voltage of the rod-plane gap. As stated in ref. 6, this behavior is typical of a rod-rod gap. In the same reference, however, it is claimed that the dc breakdown voltage of a rod-rod gap is also independent of the terminations of the two rods. In this respect, gap 2, differing from gap 1 by the lower termination only, has a lower positive and a higher negative dc breakdown voltage than this one and, differing from gap 3 by the upper termination only, has a lower breakdown voltage of both polarities than the latter. Consequently, for the insulator gap tested, the dc breakdown voltage of both polarities depends on the two terminations of the gap and this gap therefore does not fully conform with the typical behavior of a rod-rod gap as determined in ref. 6. This deviation is probably due to the fact that the size of the terminations used is too big compared with the gap clearance.

5. Time-to-breakdown

Figure 17 gives the mean time-to-breakdown, T_B, of the four gaps of Fig. 5 as a function of the dc component with the latter not exceeding ~80% of the total breakdown voltage; T_B is measured from the beginning of the impulse component. It may be seen that up to the above-mentioned value of the dc component, T_B does not exceed a few hundreds of microseconds for any of the gaps tested. This suggests that, for any of these gaps, the breakdown mechanism does not involve the transfer of heavy ions from one electrode to the other, as was observed in ref. 7.

With an increasing dc component, T_B decreases for all gaps tested irrespective of the fact that for some of the gaps the breakdown voltage increases (gaps 1 and 4) whereas for others it decreases (gap 3). Figure 17 shows further that for gaps 1,2 and 4 the difference in their mean time-to-breakdown does not exceed 20%. Only gap 3 shows an appreciably longer time-to-breakdown for values of the dc component below the corona-inception level.

CONCLUSIONS

1. The proximity of an adjacent energized pole generally causes a decrease in the pole-to-ground breakdown voltage. In an actual dc system, if the adjacent pole is not energized, this effect is negligible.

2. By replacing the lattice tower-structure (comprising diagonal members) with two tubes, representing only the corners of the tower, the pole-to-tower positive-impulse breakdown voltage increased

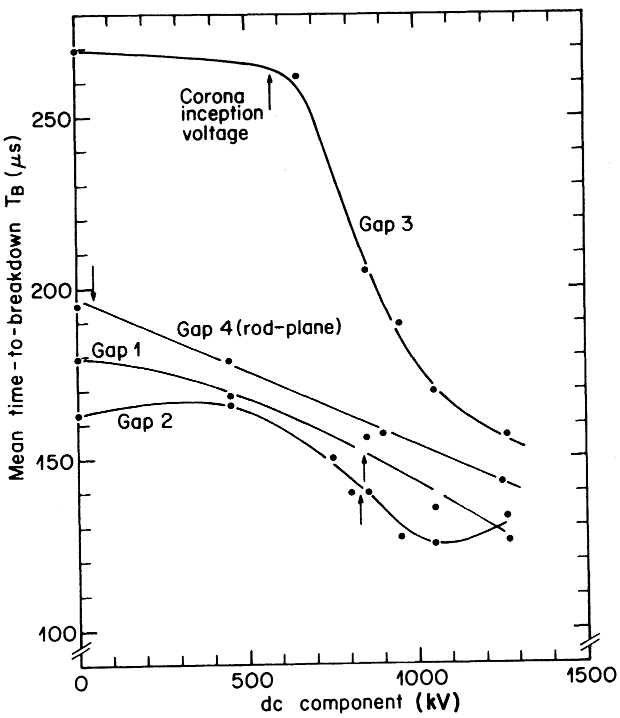

Fig. 17 Mean time-to-breakdown, T_B, of the four gaps of Fig. 5 as a function of the dc component.

by 6%. This illustrates the influence of the bulkiness of the tower structure on the conductor-to-tower breakdown voltage.

3. The pole-to-pole breakdown voltage depends on the voltage components applied to each of the two electrodes.

4. Rain reduces the positive bus-to-pedestal breakdown voltage of a supported bus by ~7%.

5. In a station bus arrangement, while the positive impulse breakdown voltage to ground depends almost entirely on the positive electrode only, the composite as well as the dc breakdown voltages of both polarities depend on the terminations of the two ends of the gap.

6. The positive dc breakdown voltage of a bus arrangement may be equal to or lower or higher than the positive impulse breakdown voltage of the same arrangement depending on the terminations of the two ends of the insulator column.

7. The composite breakdown voltage of a supported bus may be lower than either the positive dc or the positive switching impulse of critical front. This minimum would occur for a dc component close to the one generating corona at either end of the insulator column. The value of this minimum, as well as the corresponding ratio of voltage components, depend on the terminations of the insulator column. If these terminations are properly modified, it is possible either to shift this minimum outside the range of components — ratio occurring during system operation or even to eliminate it.

8. Even before corona inception at either end of the insulator column, the dc component, however small, generally affects the positive composite (i.e. both components, dc and impulse, positive) breakdown voltage of the arrangement. This influence increases linearly with the amplitude of the dc component until corona inception at either of the electrodes, whereupon a sharp, significant drop occurs in the breakdown voltage.

9. Up to the investigated clearance of 5 m, the positive and the negative dc breakdown voltage of rod-plane gaps are quasi-linear functions of the gap distance.

10. The positive dc breakdown voltage of a rod-plane gap is scarcely, if at all, affected by the surface conditions of the plane and it corresponds to a mean breakdown gradient of ~4.2 kV/cm (for normal air density and 5 g/m^3 absolute humidity).

11. The negative dc breakdown voltage of a rod-plane gap is sensitive to roughness or small protrusions on the plane surface. For a smooth plane, a negative dc breakdown voltage was measured, corresponding to ~7 kV/cm, while for a small protrusion formed on the plane surface the mean breakdown gradient dropped to ~5 kV/cm which is only ~20% higher than the mean positive breakdown gradient of the same gap.

12. For all of the configurations tested, the dispersion of the dc breakdown voltage of both polarities is extremely low (below 2%), although with positive composite voltages, a much higher dispersion was observed in many cases.

ACKNOWLEDGMENTS

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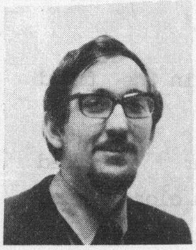
Christos Menemenlis (M'70-SM'73) was born in Athens, Greece on June 11, 1926. He received the M.Sc. degree in electrical engineering and the Ph.D. degree from Athens Technical University in 1952 and 1963 respectively. He did post-doctoral studies at the Eidgenossische Technische Hochschule, Zurich, Switzerland, from 1963 to 1965.

In 1952 he joined Solomos Company, in Athens, where he worked in data processing systems, from 1953 he was employed by the Public Power Corporation of Greece, from 1954 to 1963 he held the position of Stations Superintendent, and from 1965 to 1967 he belonged to the staff of the Planning Department and participated in the design of the 400 kV network of Greece. In addition, from 1954 to 1967 he was an Assistant with the High Voltage and Electrical Measurements faculty at Athens Technical University. He was active in Athens as a Consultant Engineer during 1967–1969. Since 1969 he has been with the Hydro-Quebec Institute of Research, Varennes, P. Q., Canada where he participated in the design and supervision of the High Voltage Laboratory. Since 1971 he has been Senior Researcher and is leader of several projects related to the insulation of EHV and UHV lines.

Dr. Menemenlis is the author of numerous papers related to insulation problems and other topics of the engineering science.



Germain Harbec (S'73) was born in St-Jean, Quebec, Canada on March 3, 1950. He received the B.Sc in Science from Sherbrook University in 1971, and the M.Sc. from INRS-Energie in 1973.

As a M.Sc. and subsequently D.Sc student of INRS, he is collaborating since 1971 with the staff of IREQ in the programe related to the air insulation of EHV and UHV systems.

Laurie Snider (B. C. Hydro and Power Authority, Burnaby, B. C., Canada): Some of the results presented in this paper may also lead us to a more accurate determination of the risk-of-flashover of a.c. lines. For example, the risk-of-flashover of a conductor to tower, following a reclosing operation on a line may be higher then currently predicted owing to the presence of the other charged phases. This is perhaps another argument in favour of considering the total composite insulation structure, along with the magnitudes and shapes of all the voltage stresses, when predicting the risk-of-flashover of a.c. lines.

Manuscript received March 1, 1979.

M. Abdel-Salam (Assiut University, Assiut, Egypt): The authors should be commended for their study of the behavior of air gaps under impulse, dc and composite voltages.

It has been reported (A) that in atmospheric air the breakdown voltage is independent of the curvature radius of the stressed anode. This was observed (A, B) also in highly electronegative gases such as SF_6 and C_3F_8 at atmospheric pressure where the applied field nonuniformity appears to have a little, if any, influence upon the positive breakdown voltage. Have the authors experienced the same behavior in their rod plane gaps? Could they explain a physical reason to which this behavior can be attributed?

It is well known that negative feathers appear (C) only at very nonuniform field configuration and can thus be observed only at large electrode spacings and very high voltages. They develop from at the negative electrode (rod) and extends toward the anode (plane). The transition to spark, or to full breakdown occurs when the negative feathers approach the anode plane and retrograde anode streamers are produced from at the anode. In this paper, the authors gave an evidence that the surface roughness of the anode plane only affects the negative breakdown voltage. Does this confirm that the surface roughness of the anode plane defines the conditions necessary for triggering the retrograde anode streamers which fulfill the full negative breakdown? The discussor is interested to have the authors express their opinion on this matter.

Recently, the transition from negative pulseless corona to spark (full) breakdown on a laboratory scale was confirmed (D) to start trom at the anode plane through the observation of the luminosity in its vicinity. Also at the spark breakdown, the field intensity in the vicinity of the anode plane was observed to be constant at 33 v.cm^{-1}. torr^{-1} for all the gap lengths studied in air. Therefore, it was concluded that the transition from pulseless negative corona to spark breakdown occurs on satisfying a field intensity to 33 v.cm^{-1}. torr^{-1} (i.e. the ionization coefficient $\alpha \geqslant$ the attachment coefficient η). The discussor finds this conclusion conforms with the findings of the present paper, namely, the surface conditions of the plane anode significantly affect the negative breakdown voltage.

In an attempt, the discussors have checked the feasibility of the above condition to give an estimation to the negative breakdown voltage in air and SF_6 at atmospheric and subatmospheric pressures. This in turn needed by necessity to account the effect of space charge filling the gap on the field value at the plane anode. The results of preliminary predictions of the negative breakdown voltages are about $\pm 8\%$ of those measured in air (E) and SF_6 (F). Comments of the authors in this regard are appreciated.

The discussor would like to ask the authors to give specific dimensions of the rod in Fig. 16 of the paper, namely, tip radius, height of the conical head, .. etc., as well as the specific dimensions of the protrusion being chosen to simulate the roughness of the anode plane. This can help in a continuous check of the above condition to predict negative breakdown voltages for long gaps.

Finally, the authors are commended again for this interesting paper.

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Manuscript received March 5, 1979.

C. Menemenlis and **G. Harbec:** The authors would like to thank the discussers for their interest in the paper. They agree with Mr. Snider that a systematic study of the total composite insulation structure could contribute to predicting the risk-of-flashover on both ac and dc lines. With regard to Mr. Abdel-Salem's discussion, it is true that the breakdown voltage is not always sensitive to the curvature radius of the stressed anode; as reported in Ref. 1, there exists a critical curvature radius of the anode below which the corona pulse cannot prevent the development of the successive stages of the impulse. Taking Mr. Abdel-Salem's second point, related to the breakdown of rod-plane gaps of negative polarity, it is known that streamers developing from a negative electrode require a higher voltage than if the electrode were positive. The authors believe, therefore, that in the case of a negative rod-plane gap, the plane may be considered perfectly smooth—as long as there is no discharge activity from the anode (plane) until the streamers from the cathode (rod) reach the final stages of breakdown. However, in the event of surface roughness of the plane in the early stages of discharge, it is possible that streamers will develop from such irregularities, which can be equivalent to positive rods. In fact for very rough surfaces, the breakdown voltage could even be as low as with positive rod-plane gaps. The authors did not perform negative breakdown calculations but found the $\pm 8\%$ agreement obtained by the discusser very interesting; further research in this field is obviously required. In reply to the discusser's request for dimensions, the rod used in Fig. 16 was cylindrical, 12 m long, 15 cm in diameter, terminating in a 30° pointed cone, a 5 cm pointed rod, 6 mm in diameter, was used as the protrusion on the plane.

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