Influence of impulse waveshape on breakdown voltage of a nonuniform-field gap in compressed gases

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Abstract

Investigations were made into the influence of the impulse waveshapes, gas pressure p and polarity on t e breakdown voltage V_s of a sphere–plane gap in compressed air and nitrogen. The pressure was vari d from 0lbf/in^{2}gauge to 150lbf/in^{2}gauge, the gap spacings from 6·35mm to 102mm and the risetimes of t e impulse voltages from 2·1μs to 189μs. For an impulse voltage of either polarity, certain gap lengths exhibit d a critical-pressure effect, and the gap lengths and pressure at which this effect was observed depended on t e risetime of the impulse voltage. Observations of the dependence of V_s on the risetime showed that ${}_s$ decreased with increasing risetimes, for risetimes of 16μs or 40μs, beyond which it increased again to rea h a maximum at risetimes of the order of 100μs. For risetimes longer than 100μs, V_s again decreased wi h increasing risetime. This behaviour was similar for both nitrogen and air. Possible mechanisms are suggest d to explain this behaviour.

1 Introduction

It is well known that the impulse breakdown voltage V_s of a nonuniform field gap such as exists between a point and a plane is higher than that for steady-state voltage. While considerable data are available on V_s for steady-state voltage, particularly in uniform electric fields,[1,2] very few investigations have been made into the influence of the impulse waveshape on V_s in compressed gases. The earlier measurements of McConnell[3] in compressed air were confined to a single waveshape, 1·5 × 50μs, while the data of Crouch and Whitman[4] were obtained in nitrogen at atmospheric pressure. The voltages used in their investigation had risetimes of 0·5–550μs, and the time taken to reach 50% of the crest on a tail of a wave was 10–9000μs.

For a nonuniform-field electrode configuration, V_s does not increase with pressure continually. A peak in the breakdown voltage/pressure characteristics (V_s against p) has been observed at a pressure p_m, and, for higher pressures up to a critical pressure p_c, V_s decreased. For pressures beyond p_c, V_s increased again. This effect was known as the 'critical-pressure effect', and was reported only for a positive polarity voltage.[5–7] Recently, Govinda Raju and Lakshminarasimha[8] have confirmed, in compressed air, the earlier results of Steiniger,[9] who showed that, in sulphur hexafluoride, the critical-pressure effect occurred both for positive and negative polarity voltages. Lakshminarasimha and Govinda Raju[10] have reported on the dependence of V_s of a point–plane gap on the impulse risetime in compressed air.

Because of our interest in compressed gases as a possible insulating medium, we have measured the impulse-breakdown voltage of compressed air and nitrogen and investigated the influence of the impulse waveshape, gas pressure and polarity on V_s. The waveshapes used had risetimes of 2·1–189μs (1·67 × the time required to rise from 30% to 90% of peak value), and the time taken to decline to half the crest value was in the range of 1000μs (±10%). Sphere–plane gaps with a high-voltage sphere of 11mm diameter and a plane of 230mm diameter having a Rogowski profile were studied at gap spacings in the range of 6·36–102mm. The pressure was varied from 0lbf/in^{2}gauge to 150lbf/in^{2}gauge. Before admitting the gases into the pressure vessel, they were dried by a column of calcium hydroxide, and, as an additional precaution, a thick layer of silica gel was spread on the floor of the compressed-gas chamber. The highest voltage used, which was only limited by the high-voltage bushing of the experimental chamber, was 300kV, and this voltage was derived by a Marx-type impulse generator. The waveshape of the voltage was varied by the standard technique of varyi g the circuit parameters of the impulse generator. Details of t e experiment are given elsewhere.*

2 Breakdown voltages

2.1 Sphere–plane gaps with positive-polarity impulse

The determination of the 50% breakdown volta e was tedious because of a considerable conditioning effe t. Such conditioning behaviour has been observed by seve l workers with steady-state voltages. Frequently, there we e instances when a higher voltage caused a smaller percenta e of breakdowns than a lower voltage. This was attributed o the insufficient conditioning of the electrodes and the -herently statistical nature of breakdown. An attempt o determine the number of impulses that were required to giv a reasonably good accuracy in determining the 50% brea -down voltage proved too laborious. Therefore, it was decid d to check whether ten impulses at each voltage level we e sufficient by adopting the following procedure. Ten sets of t n impulses per set were applied at a constant voltage. For each t and for the ten sets as a whole, the percentage breakdown w s calculated. Fig. 1 shows the plots of percentage breakdo n against impulse-set number for a given pressure and g p setting. The breakdown percentage did not differ by mo e than 20% between individual sets in almost all the ca s (Fig. 1*a*). This procedure, when repeated over several spacir s and pressures, led to the following conclusions: (*a*) fo a given spacing and pressure, the variation in percentage brea -down between individual sets decreased with increase n voltage, (*b*) for a given pressure, and with a voltage causi g approximately 50% breakdown, the variation in percenta e breakdown between individual sets increased with the -crease in gap distance, (*c*) for a given gap distance, and witl a voltage causing approximately 50% breakdown, the variati n in breakdown percentage between individual sets decreas d with increasing pressure, and (*d*) the conditioning effect d not show any consistent dependence on the impulse wa -shape. Consequently, it was decided to apply between 5 – 100 conditioning pulses (sometimes 200pulses), at the end f which, consistent dependence of the percentage breakdown on the applied voltage was obtained. Then, ten pulses were applied at each voltage level, and the 50% V_s was determined in the usual way, by determining the percentage breakdown at each voltage level. The absolute accuracy of voltage measurement is within ±5%, but the relative accuracy is better than this, within ±2%.

Fig. 2 shows the V_s–p curves for 2·1 × 1000μs positive-polarity impulses at various constant gap spacings. The

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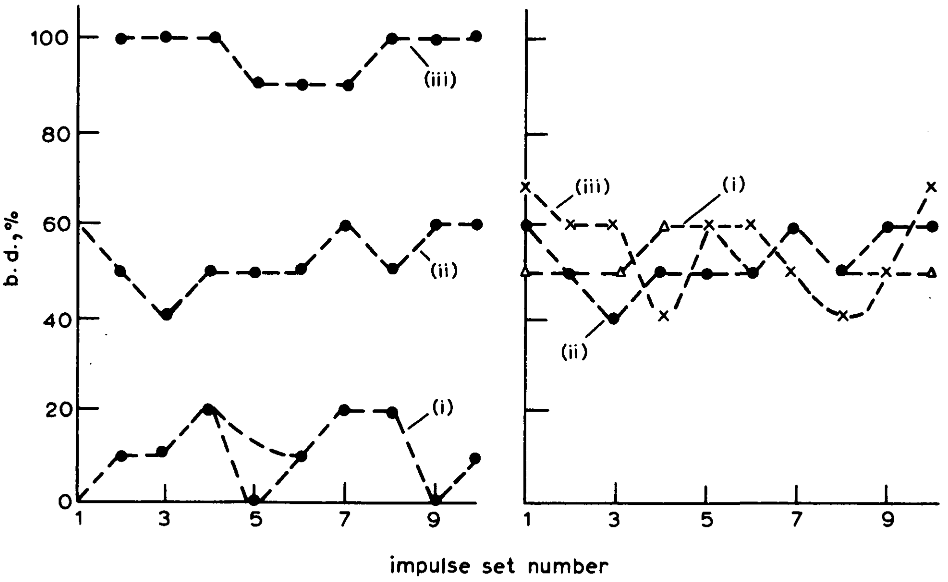
critical-pressure effect was observed for 6·36mm, 12·7mm and 25·4mm (not included in the Figure) gaps. For larger gap lengths of 38mm and 51mm, the critical-pressure effect disappeared completely, and V_s increased with p continually. This was unexpected. When the gap length was increased still further, to 76mm, there was some evidence for the critical-pressure effect, but this was not considered to be conclusive. However, at 102mm gap length, the effect was pronounced. From Fig. 2, the V_s/p curve for each gap length may be classified into one of three groups; (*a*) at certain gap lengths, the critical-pressure effect is very clearly seen, as for 6·35, 12·7, 25·4 and 102mm gaps, (*b*) gaps at which the critical-pressure effect disappeared and V_s increased monotonically with p, as at 38mm and 51mm, or (*c*) gaps which showed an intermediate behaviour, that is, there is some, but not conclusive, evidence for the critical-pressure effect. This type of behaviour is seen for the 76mm gap. V_s/p curves obtained at other waveshapes confirmed that this classification is generally valid. We suggest that the behaviours (*a*) and (*b*) are associated with different mechanisms of breakdown, and the behaviour under (*c*) represents an intermediate stage between the two mechanisms. Fig. 3 shows the V_s/p curves for 189/1100μs impulses, and Table 1 gives a summary of the results.



a *b*

Fig. 1

Percentage breakdown as a function of impulse set number

(*a*) Curves (i), (ii) and (iii) are for successively higher voltages at 50lbf/in² gauge pressure and 25·4mm gap length
(*b*) (i) 6·35mm gap length, 70kV; (ii) 25·4mm, 85kV; (iii) 51mm at 120kV at 50lbf/in² gauge pressure

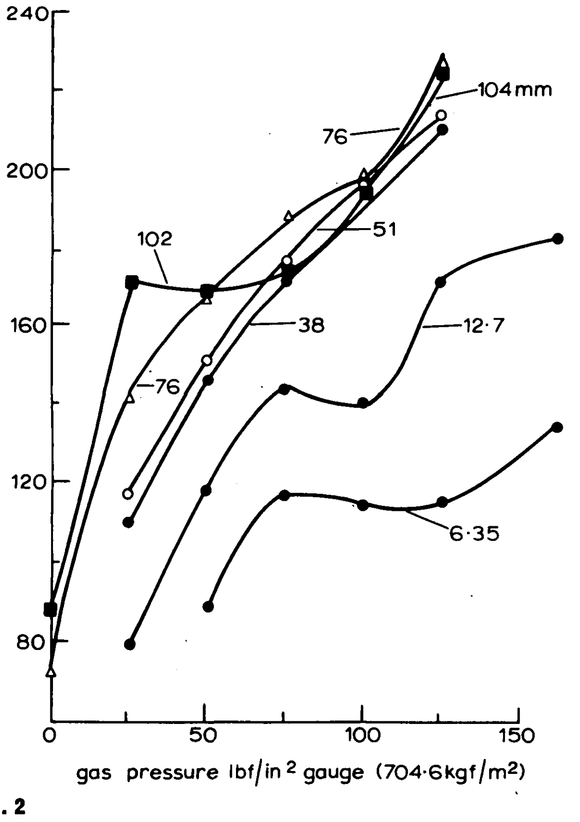


Fig. 2

50% V_s/p curves in compressed air at various spacings for 2·1/1000μs positive-polarity impulse

Table 1

Impulse risetime	Gap lengths investigated	Gap lengths showing mechanisms		
		a	*b*	*c*
μs	mm	mm	mm	mm
2·1	6·35, 12·7, 25·4, 38, 51, 76, 102	6·35, 12·7, 25·4, 102	38, 51	76
16·0	6.35, 12·7, 25·4, 38, 51, 76, 102	12·7, 76, 102	25·4, 38, 51	6·35
40·0	6·35, 12·7, 25·4, 38, 51, 76, 102	102	12·7, 25·4, 38, 51	6·35, 76
79·0	6·35, 12·7, 25·4, 38, 51, 76, 102	102	6·35, 12·7, 25·4, 38, 51	76
129·0	6·35, 12·7, 25·4, 38, 51, 76, 102	76, 102	6·35, 12·7, 25·4, 51	76
189·0	51, 76, 102	102		51, 76

The table shows that each gap length investigated showed any one of the three mechanisms, depending on the duration of the wavefront. 12·7, 25·4, 38 and 102mm gap lengths did not show mechanism *c* at all, while the 102mm gap length showed only mechanism *a*, for all waveshapes.

Fig. 4 shows the variation of V_s as a function of risetime for 25·4mm gap length. Fig. 4 also includes the results for negative polarity, and will be discussed in Section 2.2. The general pattern of the plots is a fast decrease in V_s as the risetime is increased, reaching the lowest V_s at a critical risetime. Beyond the critical risetime, up to a time t_m, V_s increased again, but at a slower rate. For risetimes longer than t_m, V_s decreased again. The critical risetimes observed for all gap lengths had a definite value, either 16 or 40μs. t_m was about 80–100μs for all gap lengths and pressures.

Fig. 5 shows results for a 25·4mm gap in nitrogen, and the behaviour is similar to that in air. Again, the critical risetime is 16μs or 40μs, as in the case of air, and the possible significance of this is given in the discussion.

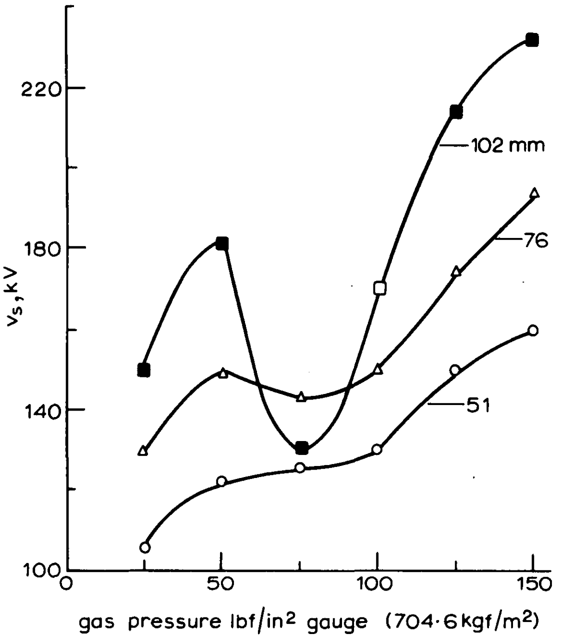


Fig. 3

50% V_s/p curves in compressed air at various spacings for 189/1100 μs positive-polarity impulse

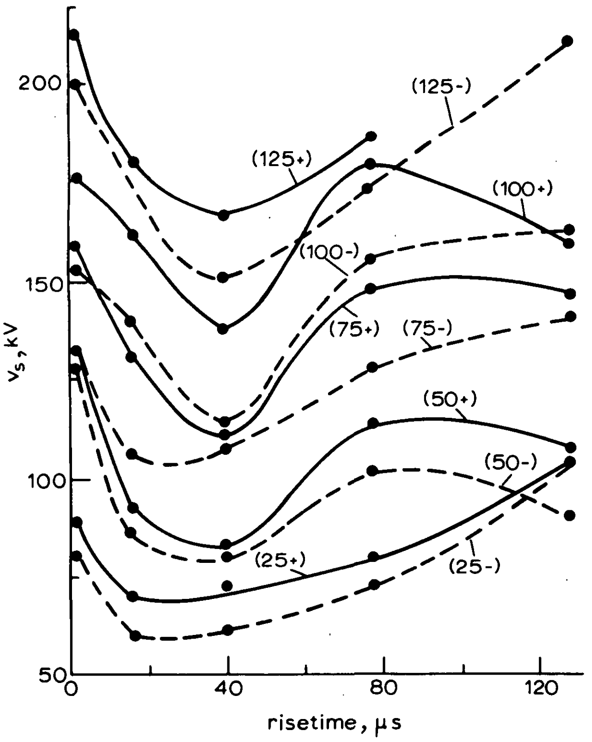


Fig. 4

Influence of impulse risetime on the 50% V_s for a gap spacing of 25·4mm in compressed air

Number on each curve denotes gas pressure and polarity

2.2 Sphere–plane gaps with negative-polarity impulse

In a previous paper, Govinda Raju *et al.*[8] have shown that the V_s/p characteristics of a point–plane gap in compressed air showed the critical-pressure effect for a negative-polarity impulse also. The only other gas in which such a behaviour was reported[9] was SF_6, which is also highly electronegative. It was not clear whether the critical-pressure effect for the negative polarity would be observed for a sphere–plane gap, and, therefore, V_s/p characteristics were obtained in air for various diameters of high-voltage electrodes and gap spacings. Fig. 6 gives typical results. When the diameter of the high-voltage electrode was 10mm, no critical-pressure effect was observed for a gap length of 12·7mm or lower. When the spacing was increased to 25·4mm, the critical-pressure effect was pronounced. Similarly, spheres of 20mm and 40mm diameter exhibited the critical-pressure effect for gaps longer than 38mm and 76mm, respectively. In the case of positive polarity, the critical-pressure effect was not observed for gases which are not electron-attaching. Thus, in nitrogen, hydrogen and argon, Pollock[5] reported that V_s increased with pressure continually, even up to pressures as high as 28atm. To check whether this was true for the negative polarity also, we measured V_s in nitrogen and mixtures of nitrogen and air. Fig. 7 shows that, in pure (commercial cylinder grade) nitrogen, and in nitrogen

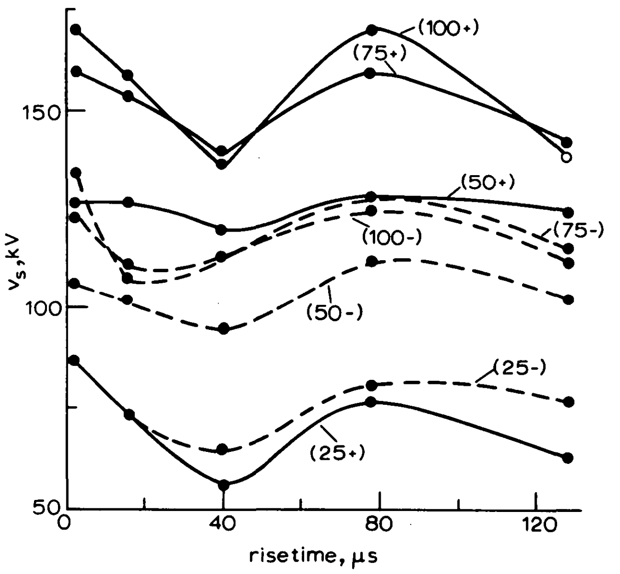


Fig. 5

Influence of impulse risetime on the 50% V_s for a 25·4mm gap in compressed nitrogen

Number on each curve denotes gas pressure and polarity

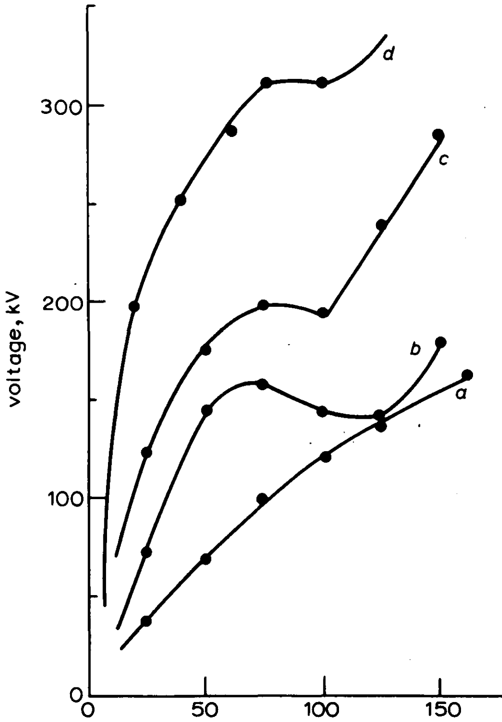


Fig. 6

Breakdown voltage as a function of pressure for various constant electrode radii and spacings for 1·2 × 50μs negative impulse voltage contaminated with a very small percentage of air, the critical-pressure effect was not observed, even at the highest voltage investigated, but the addition of 50% air to nitrogen resulted in the critical-pressure effect. It was found that about 5% oxygen, calculated on the basis of air content, resulted in the peaks in the V_s/p curves. The highest breakdown voltage was observed for pure nitrogen, and the lowest for air.

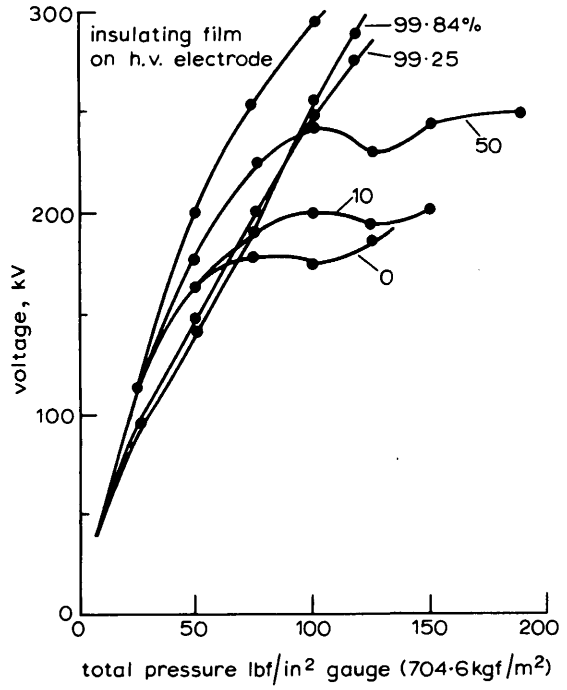


Fig. 7

Breakdown voltage as a function of pressure for air and mixtures of air and nitrogen

10mm-diameter electrode, 25·4mm gap length

For the negative polarity, it is likely that field emission is a major contributing factor for the sudden decrease of V_s at pressure P_m. The field gradient for field emission in a high vacuum with highly degassed electrodes is 10^6V/cm, but Jones *et al.*[11] have shown that the threshold may be reduced to 10^5V/cm if the cathode is oxidised. The electric-field gradient at the sphere was calculated for all the electrode diameters using the formula[12]

$$E_y = \frac{2\delta\{\delta^2(f+1) + y^2(f-1)\}}{\{\delta^2(f+1) - y^2(f-1)\}^2} V$$

in which V = applied voltage, $f = \frac{1}{4}\{(2P-1) + \sqrt{(2P-1)^2 + 8}\}$, $P = 1 + \delta/R$, δ = gap length, R = electrode radius and y is the distance along the axis of the gap at which the field is required. The following table shows the field at the sphere at voltages corresponding to a pressure p_m. Table 2 shows that field emission is a possible mechanism responsible for the critical-pressure effect. To obtain further confirmation, the V_s/p curve was obtained for an electrode which was coated with a thin layer of epoxy resin. As expected, the critical-pressure effect disappeared (see Fig. 7). An experimental difficulty was that the insulating film was ruptured after a few impulses, and, for the next impulse, V_s was unusually lower, because breakdown occurred at a point where the film was ruptured. This necessitated the frequent renewal of the film. In spite of this uncertainty, we suggest that the film suppressed field emission, and, therefore, the critical-pressure effect disappeared.

Table 2

R	δ	V	E	Gas
mm	mm	kV	V/cm	
5	25·4	156	$3{\cdot}85 \times 10^5$	air
10	37·0	195	$1{\cdot}13 \times 10^5$	nitrogen
20	76·0	272	$1{\cdot}58 \times 10^5$	air
20	100·0	220	$2{\cdot}54 \times 10^6$	SF_6^9

Figs. 4 and 5 also show the influence of impulse risetime on the negative breakdown voltage in air and nitrogen, respectively. The behaviour is similar to that under positive polarity, but, surprisingly, V_s, for negative-polarity voltages in air with longer risetimes, is lower than that for positive polarity (Fig. 4).

3 Discussion

The breakdown of compressed gases in a nonuniform field has been studied by several workers, using mainly a steady-state voltage, and the critical-pressure effect is reproducible. It is important to note that the critical-pressure effect is not observed in a nonattaching gas or when the electric field in the gap is uniform. Berg and Works[13] have shown, by an interesting experiment, that the critical-pressure behaviour in electron-attaching gases can be explained on the basis of a mechanism known as 'corona stabilisation'. The breakdown voltage of a sphere–plane gap was measured by superimposing an impulse voltage on a steady-state bias voltage. It was observed that the breakdown voltage, which was the sum of the two voltages, increased with increasing bias voltage. It was suggested that the corona which was formed before the application of the impulse voltage modified and reduced the nonuniformity of the electric field, thereby increasing the total voltage required to cause breakdown. Since a steady-state voltage was used as a bias, it was not possible to determine the time required for the build up of space charge of a density sufficient to modify the electric field. The present investigation shows that, for a given gap, the critical-pressure effect is observed for certain risetimes only, while for other risetimes the voltages increased rather uniformly with pressure. We suggest that this behaviour is consistent with the theory which postulates the modification of the electric field by the space charge, and the critical-pressure effect disappears when the nonuniformity of the field in the gap is reduced because of the drift of charge carriers. A possible explanation for the variation of V_s with impulse risetime in air has been given by Boylett *et al.*,[14] and we suggest that a similar mechanism explains the behaviour of gaps in compressed gases. According to this model, the usual mechanism is obtained at small risetimes. An electron occurring within a certain distance of the point causes the initiation of an electron avalanche towards the point. This will lead to secondary avalanches, and corona filaments are built up until the electric field is too weak to allow further avalanche propagation. It was suggested that, for a filament to propagate across the entire gap, the applied voltage has a unique value. The speed with which the position of the boundary of the limiting field for avalanche propagation moves away from the point is governed by the risetime of the impulse voltage. Depending upon the risetime, four conditions are obtained.

(*a*) *Short-risetime impulse*: in this case, the minimum field E_c in which an avalanche can propagate moves very rapidly away from the point. For breakdown to occur, an applied voltage is needed of such a magnitude that a field of at least E_c is produced everywhere in the gap. Consequently, a high V_s is obtained.

(*b*) *Medium-risetime impulses corresponding to the minimum-breakdown voltage*: for certain slower risetimes, there will be time for space-charge fields to form because of ionisation produced in the avalanche. If the positive space charge drifts across the gap at the same rate as the rise of voltage, the field due to the applied voltage will always be enhanced by the space-charge field. Thus, the field E_c can be produced by a smaller applied voltage, under these conditions rather than in the absence of space charge. The breakdown voltage will be less than in case *a*. The positive-ion space charge drifts across the gap in times of the order of 10–50μs, and the risetime at which the minimum V_s is obtained is of the same order of magnitude. The variation of V_s with risetime was identical both for compressed nitrogen and air, providing support to the theory that positive-ion space charge influenced the V_s risetime curves.

(*c*) *Long-risetime pulses*: in this case, the space-charge field will drift away from the point faster than E_c. Hence, the space-charge field will reduce the electrostatic field, and hence quench the discharge. Consequently, a higher applied voltage is needed to cause breakdown than in case *b*.

(*d*) In addition, our results show that a maximum V_s is obtained at a particular risetime, beyond which V_s decreased again. At these very long risetimes, we suggest that the positive-ion space charge traverses the gap completely, and, therefore, the applied voltage alone would be responsible for production of E_c everywhere in the gap. Consequently, V_s would be lower for longer risetimes, because more time is available for various ionisation processes. This suggests that the 50 Hz breakdown voltage is lower than the impulse-breakdown voltage of any risetime, and this has been confirmed experimentally.

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