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Volt-Time Characteristics of Short Rod-Rod Gaps

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ABSTRACT. In this paper volt-time or V-t characteristics for rod-rod air gaps are determined experimentally using positive and negative standard lightning impulses for gap spacings in the range of 5 to 25 cm. The rods were of cylindrical shape with hemispherical ends and had tip radii in the range of 1 to 5 mm. From the measurements, the effect of rod tip radius, gap spacing and impulse polarity on V-t characteristics is examined and empirical equations for predicting the V-t characteristics of short air gaps are proposed. The values of breakdown voltage predicted by the proposed equations are compared with measurements reported in the literature and a good agreement is observed between the two sets.

Surge overvoltages occur in power systems due to lightning and switching actions. The surge breakdown voltage level (V) of a given gap is related to time duration (t) of the applied surge up to the breakdown instant. This relationship is expressed as a V-t curve for a given insulation system. V-t curves are essential design data when air gaps are employed as overvoltage protective devices or as high voltage measuring devices. A survey of the available literature (Abdullah and Kuffel (1965), IEEE (1974), Meek and Craggs (1978), Harada *et al.* (1979) and Yamamoto *et al.* (1985)) indicates that V-t curves are not well known and cannot be predicted for short air gaps of less than 20 cm in length. Therefore, this work is aimed to study the V-t characteristics of such short air gaps. Such air gaps are of considerable importance for overvoltage protection of overhead power distribution lines.

Experimental Set up and Procedures

Fig. 1(b) shows the schematic of the experimental set up which consisted of a 10 stage, ± 1 MV, Marx impulse generator along with its voltage divider and measuring instruments. The test object was connected across the divider. The impulse generator was adjusted to produce standard lightning impulse of 1.2/50 μs waveform. The test object was a rod-rod air gap with identical rod electrodes, each being 70 mm long and having hemispherically terminated ends of 1 to 5 mm tip radii (r) as shown in Fig. 1(a). The gap spacing (G) used varied from 5 to 25 cm. For a given gap, impulses of a fixed polarity and magnitude were repeatedly applied to measure the values of V and t. The voltage measurements were carried out using a damped R-C divider (Haefely, Model CR 1000) and a precision impulse peak voltmeter (Haefley, Model 64) and had an accuracy of better than 1%. The breakdown time was measured by using a time to breakdown meter (Haefely, type 66) which had a resolution of 0.1 μs. By adjusting the peak value of the applied impulse, enough measurements were made to derive the V-t curve for a given gap. The measured voltages were corrected for changes in the atmospheric parameters *i.e.* pressure (P), temperature (T) and absolute humidity (H), following the procedure adopted by IEC (1973) and IEEE (1978). Thus, the results given in this paper correspond to the standard atmospheric conditions of P = 1013 m bar, T = 20°C and H = 11 g/m^3.

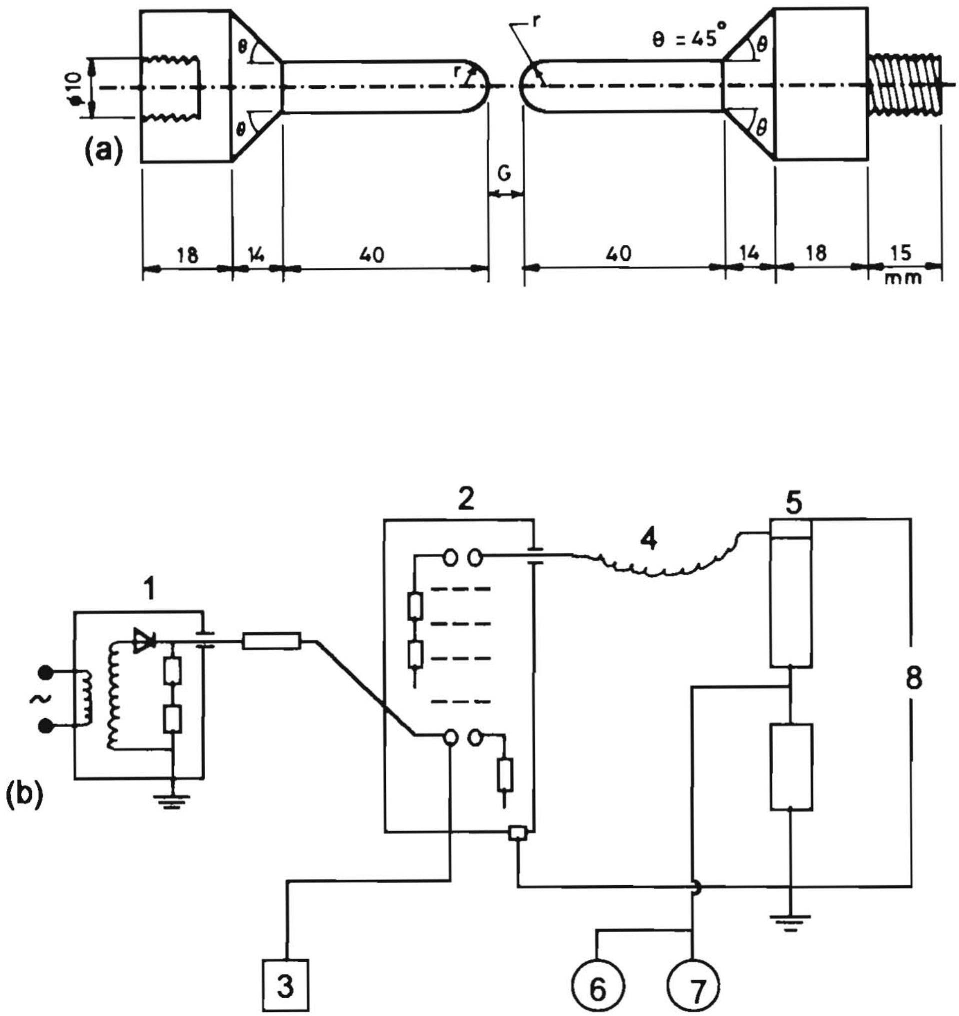
Results and Analysis

The V-t characteristics of rod-rod air gaps under positive and negative standard lightning impulses are shown in Fig. 2 for a few selected cases. In this figure, the measured data points are plotted. Moreover the curves through these data points which give the best fit of the experimental data as a relationship between breakdown voltage V (in kV) and the time to breakdown t (in μs) are also shown. Consequently, the following relationship is applicable for V-t characteristics over most of the range:

$$V = AT^{-B} \qquad (1)$$

where A and B are constants. The constant A depends upon various experimental parameters such as the gap spacing, the voltage polarity and the rod tip radius. However, the constant B is approximately independent of most of these parameters.

Fig. 2 shows that, as expected, when impulse voltage of a given polarity is applied, there is a limiting value of the breakdown voltage (V_{min}) for each gap length and rod radius below which no breakdown occurs. Associated with this voltage, there is also a maximum time to breakdown (t_{max}) above which no breakdown time



1. DC supply
2. Impulse generator
3. Trigger pulse generator
4. External resistor
5. Damped voltage devider
6. Time to breakdown meter
7. Impulse peak voltmeter
8. Test electrodes (shown in (a))

Fig. 1. Experimental Set up and electrodes.

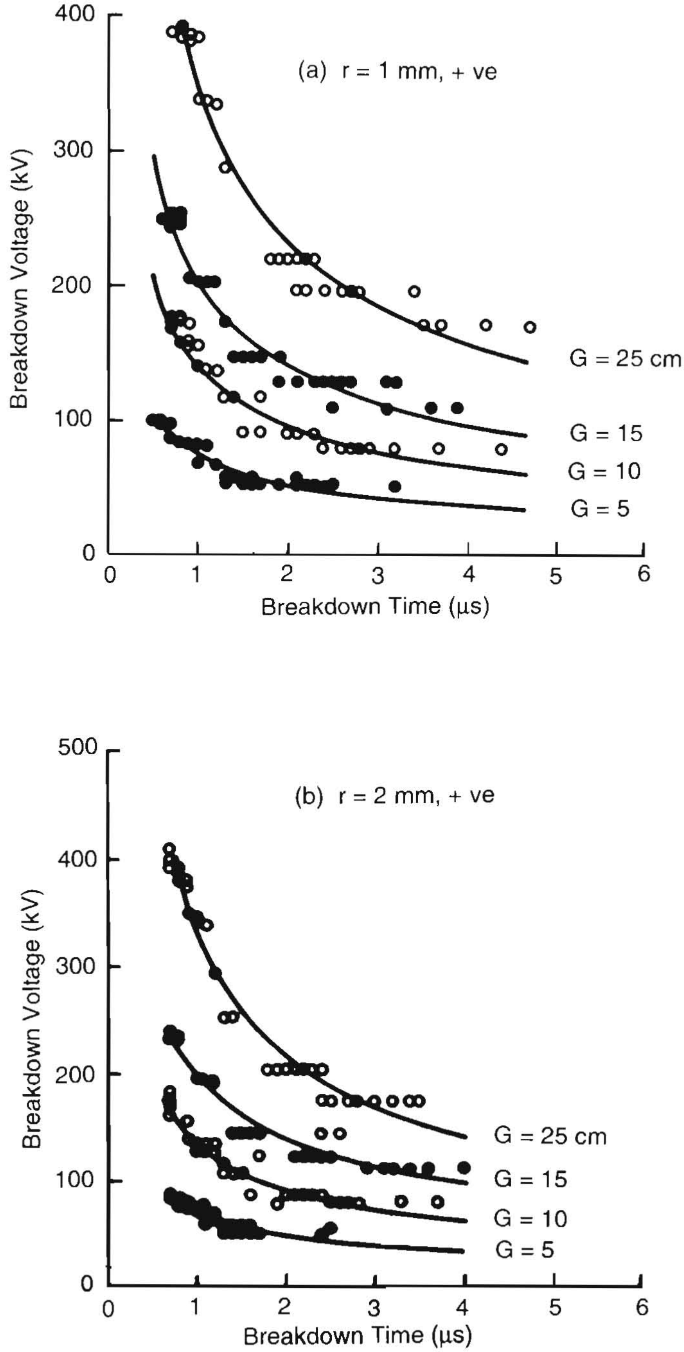


Fig. 2(a,b). V-t characteristics for rod-rod gaps.

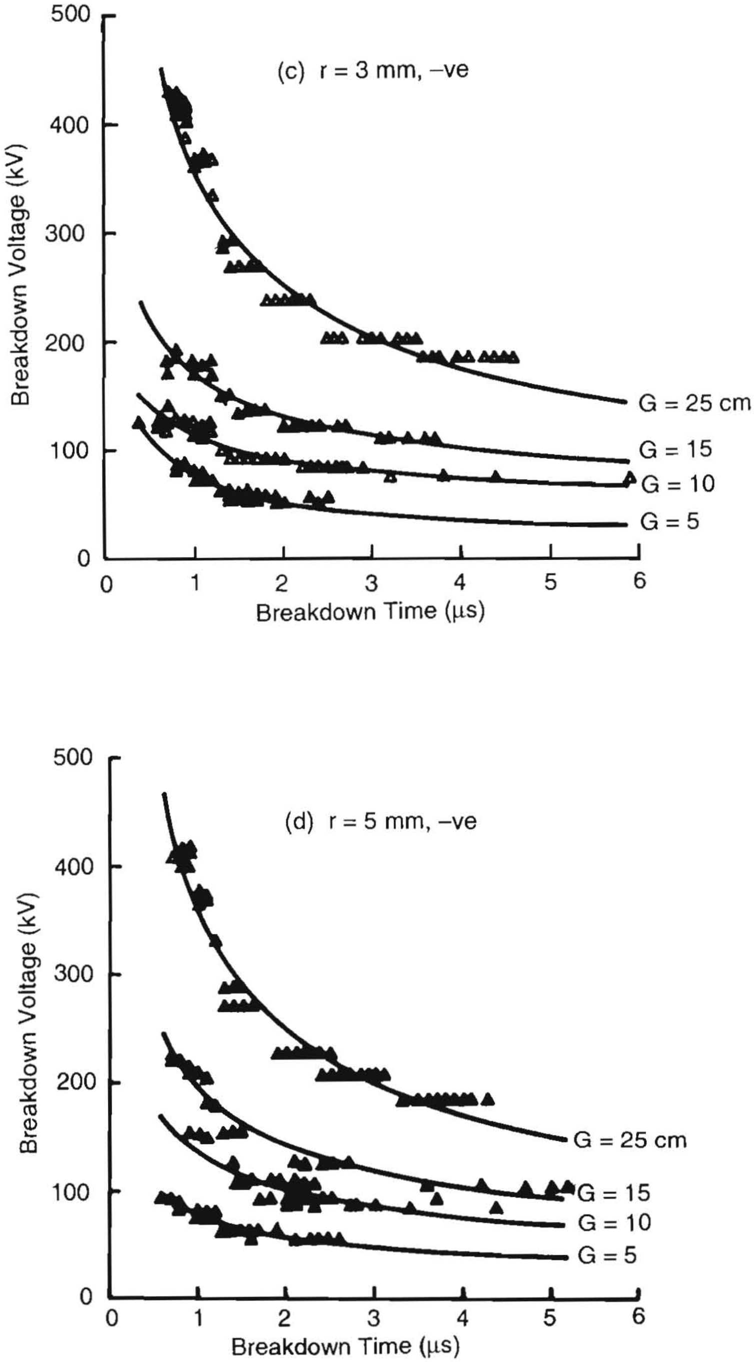

(c) r = 3 mm, –ve
Breakdown Voltage (kV)
Breakdown Time (μs)
G = 25 cm
G = 15
G = 10
G = 5
(d) r = 5 mm, –ve
Breakdown Voltage (kV)
Breakdown Time (μs)
G = 25 cm
G = 15
G = 10
G = 5

Fig. 2(c,d)

was recorded in this study. V_{min} and t_{max} are influenced by the gap length and the voltage polarity. Depending upon the gap spacing, t_{max} was in the range of 2 to 6 μs for negative impulses whereas its value was 2 to 7 μs for positive impulses. Generally, the lower values of t_{max} were observed for 5 cm gap whereas the higher t_{max} values were associated with longer gaps. Variation of V_{min} (in kV) with gap spacing G (in cm) in the range of 5 cm $\leq$ G $\leq$ 25 cm can be approximated with the following linear relation:

$$V_{min} = 19.75 + 6.45\,G \quad \text{(2)}$$

There are many factors such as gap spacing, electrode configuration, rod geometry, polarity and waveform of the applied voltage, air pressure, temperature and humidity, *etc.*, which may affect the V-t characteristics. The influence of some of these factors on V-t curves will be discussed here.

The effect of gap spacing is clear from Fig. 2 from where it can be noticed that, as expected, the breakdown voltage increases with the gap spacing. This is true for all values of breakdown time. The polarity of the applied voltage has some effect on the V-t curves as shown in Fig. 3. It can be seen from this figure that the breakdown voltages of negative polarity are usually somewhat higher than the corresponding values for the positive polarity. Generally, the different between the two voltage corresponding to a given breakdown time is a function of the breakdown time. At lower end of the time scale, the V-t curves for the two polarities tend to merge. This behavior is consistent with results compiled by IEEE (1978) and can be attributed to the asymmetry in the field distribution produced by the grounding of one of the electrodes and by the differences in the discharge development mechanism (Matthews and Saint-Arnand (1971)).

Usually, even for symmetrical electrodes, the field at the tip of the high voltage electrode is somewhat higher than its corresponding value at the grounded electrode (Pillai and Hackam (1983)). Thus, for a given value of applied voltage, the maximum field at the cathode will be somewhat higher when negative impulses are applied than the corresponding value under positive polarity impulses. Similarly, the anode fields for the two polarities will also be different even for the same value of the applied voltage. Such differences are influenced by the electrode shape and size as well as the gap length. Influenced by such field differences, there will be some variations in the discharge initiation process under the two polarities.

Once the discharge initiates in the form of streamers, it transforms into a leader discharge before the occurence of the breakdown. There are also differences in the leader formation mechanism under the two polarities. These differences in the discharge initiation and its propagation mechanism are responsible for the polarity related effects observed in V-t curves of Figs. 2 and 3.

According to Abdullah and Kuffel (1965) under positive impulses, a leader forms at the anode and travels along the gap to the cathode. Then the main stroke sweeps the gap from the cathode to the anode along the pre-ionized path formed by the leader discharge. However, under negative impulse voltages, the mechanism is different. The negative leader starts from the cathode to propagate towards the anode but does not cross the entire gap. In the meantime, a positive leader starts from the anode and propagates towards the cathode and the two leaders meet somewhere in the gap. The main stroke then follows within a certain time. This process makes the negative breakdown voltage somewhat higher than the corresponding positive breakdown value. The difference between the two voltage levels is influenced by the electrode gap configuration as well as the overvotlage value. For highly overstresed gaps, which correspond to smaller values of breakdown times, the differences between the breakdown voltages under the two polarities become progressively small and the V-t curves for the two polarities tend to merge as shown in Figs. 2 and 3.

From the result of Figs. 2 and 3, it is also clear that for a given V, t has some scatter. Consequently, the measured data points display piece-wise behavior corresponding to the time scale. There are several possible reasons for this observation. The most important of these are the statistical nature of the breakdown process, the possible variations in statistical and formative time lags even under apparently identical experimental conditions and the dependence of these time lags on the overvoltage factor.

As shown in Fig. 4, the rod tip radius in the range of 1 to 5 mm has no significant effect on the V-t curves. It can be noticed that the difference in breakdown voltages for the two extreme values of r is very small and can be neglected. Thus, the breakdown voltages of rod-rod gaps employing hemispherically terminated rods do not depend significantly upon the tip radius as long as the gap length to rod tip radius ratio is more than 50 to ensure significant field enhancements at the electrodes. For less nonuniform field gaps, the electrode radius is expected to be an important factor governing the breakdown characteristics.

Breakdown Formula

As mentioned earlier, the breakdown voltage for both polarities can be represented by eqn. (1) where the constant A varies with the gap spacing and the impulse polarity whereas, the constant B lies in a narrow range and is approximately the same for all the cases studied. By expressing the constant A as a function of gap

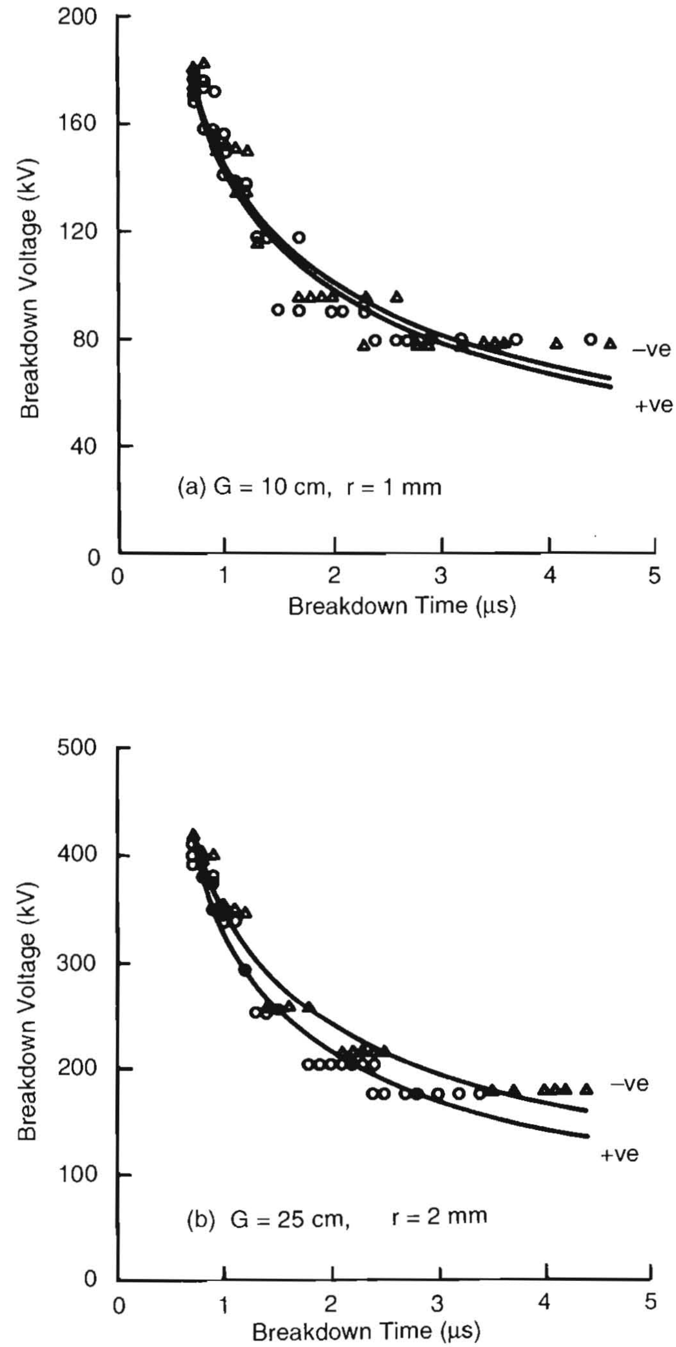


Fig. 3(a,b). Effect of polarity on V-t curves.

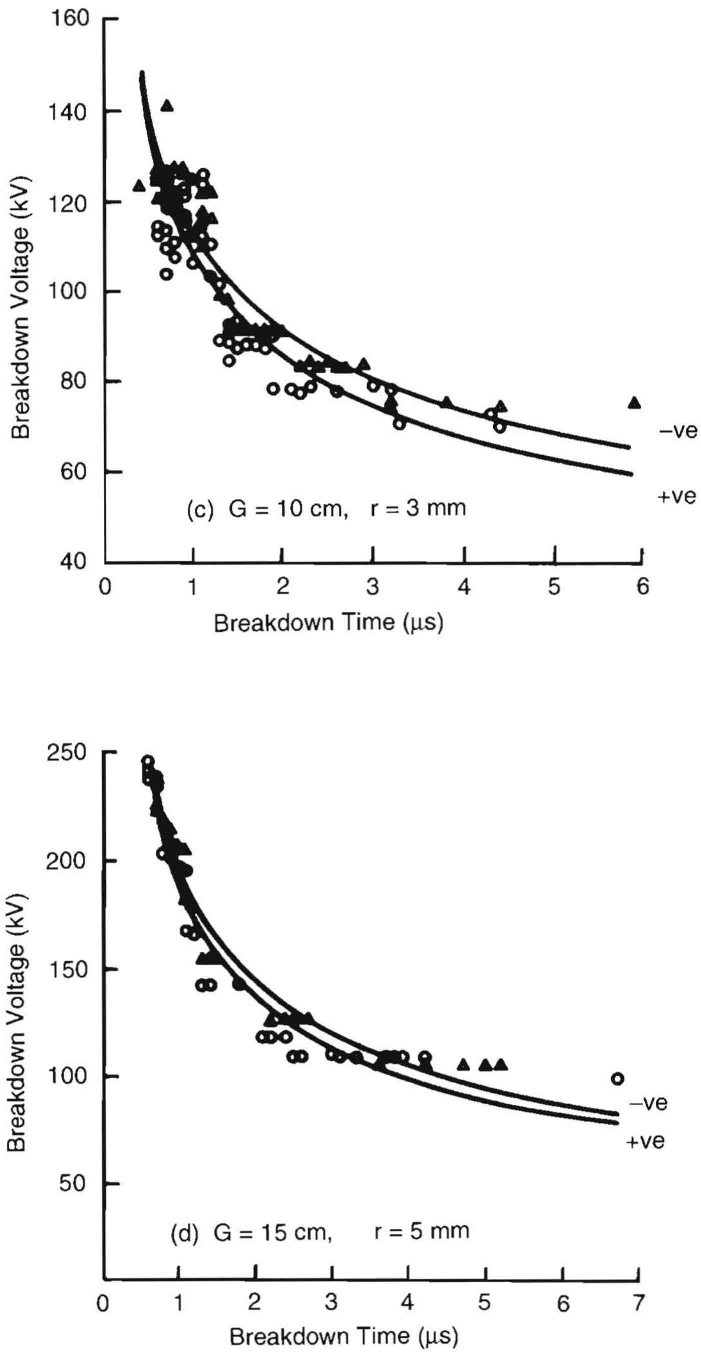

160
140
120
100
80
60
40
Breakdown Voltage (kV)
0
1
2
3
4
5
6
Breakdown Time (μs)
(c) G = 10 cm, r = 3 mm
–ve
+ve
250
200
150
100
50
Breakdown Voltage (kV)
0
1
2
3
4
5
6
7
Breakdown Time (μs)
(d) G = 15 cm, r = 5 mm
–ve
+ve

Fig. 3(c,d)

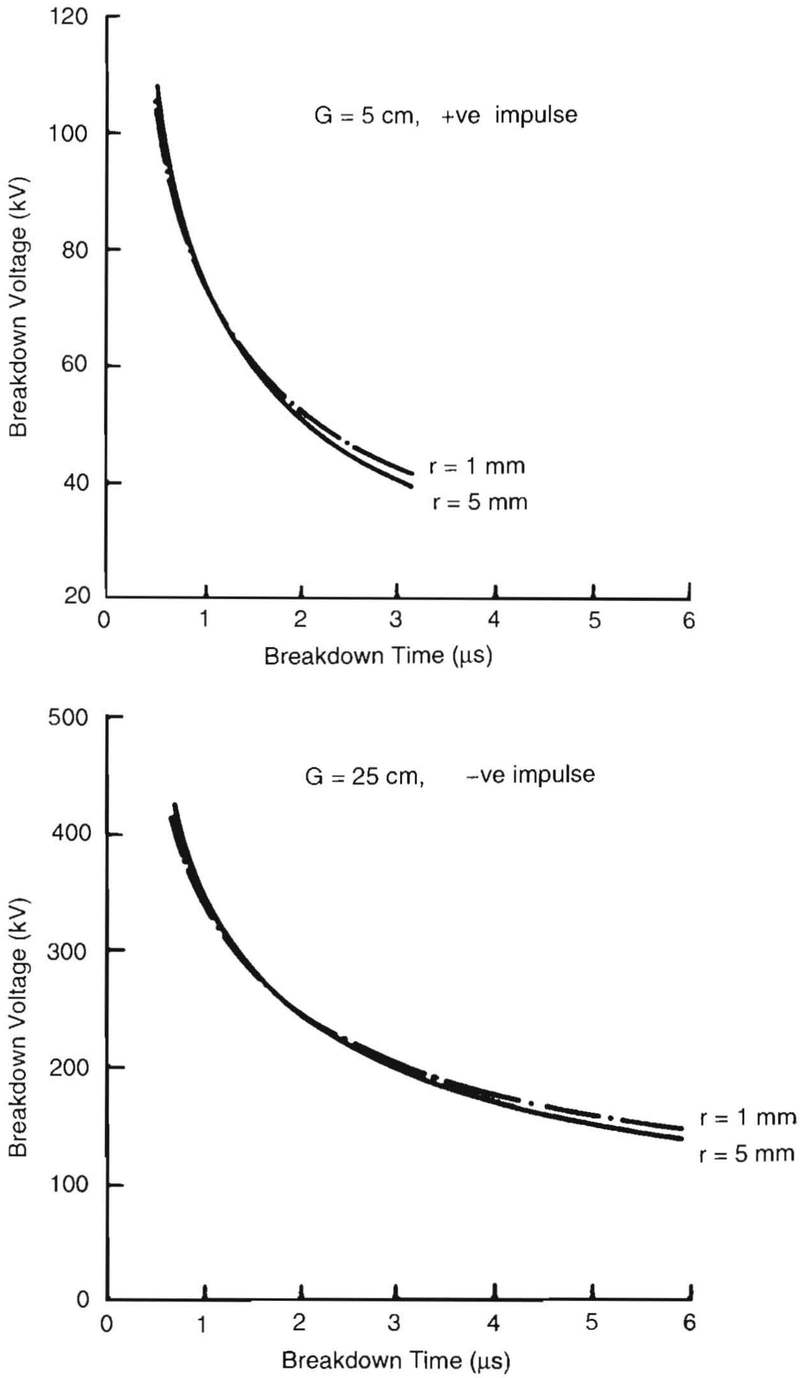


Fig. 4. Effect of tip radius on V-t curves.

spacing G and by obtaining the average value of the constant B for each polarity, the following empirical equations are obtained for the V-t curves.

For positive impulse voltages;

$$V = 13.7\ Gt^{-0.5} \quad \text{.......} \quad (3)$$

For negative impulse voltages;

$$V = 13.9\ Gt^{-0.49} \quad \text{.......} \quad (4)$$

Since eqns. (3) and (4) are very close, an approximate general equation for both positive and negative lightning impulses can be obtained by using the average from eqns. (3) and (4). This leads to the following empirical relations;

$$V = 13.85\ Gt^{-0.495} \quad \text{.......} \quad (5)$$

Equations (3) to (5) are valid for $0.6\ \mu s \leq t \leq t_o$ and for $5\ cm \leq G \leq 25\ cm$. For $t_o \leq t \leq t_{max}$, the breakdown voltages are constant and equal to V_{min} as given by eqn. (2). The time t_o up to which breakdown voltage decreases with time and at which it becomes constant and equal to V_{min} is a function of the gap length and can be approximated by the following equation:

$$t_o = -0.122 + 1.21\ \ln(G) \quad \text{.......} \quad (6)$$

where t_o is given in μs and G is given in cm. To the best of the authors knowledge, no simple empirical formula exists for predicting V-t characteristics of short gaps of less than 50 cm spacing. For large gaps, IEEE working group (1974) have presented the following empirical relation for calculating the breakdown voltages of rod-rod gaps in the range of $50\ cm \leq G \leq 200\ cm$.

$$V = a.G + b \quad \text{.......} \quad (7)$$

where a and b are constants which depend upon different experimental parameters and the breakdown time. Similarly, different models for leader propagation have been used by several researchers to derive V-t curves. Some researchers have used integration methods or equal area criterion to obtain V-t curves (Darveniza and Vlastos (1988), Coldwell and Darveniza (1973)). However, none of these papers propose a simple empirical formula which can be readily applied by design engineers for estimating V-t curves of air gaps in general and for short air gaps in particular.

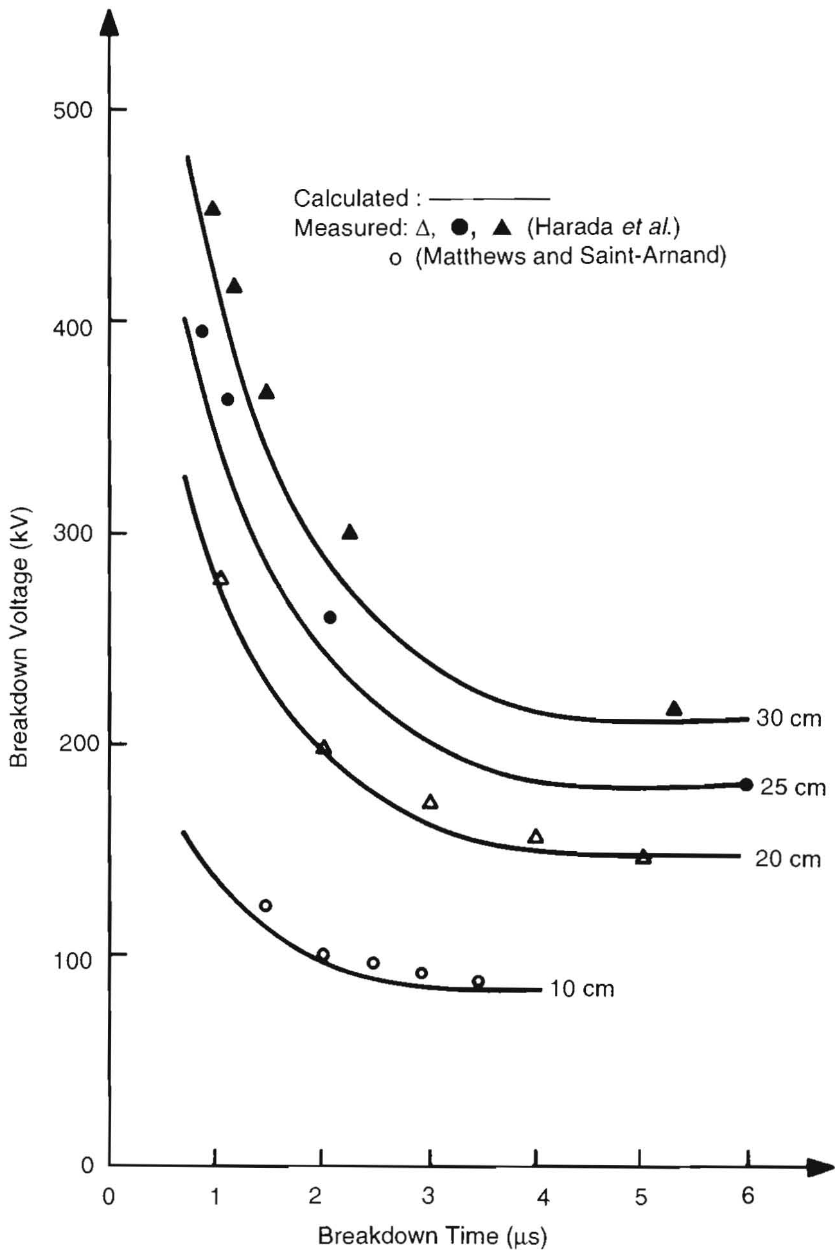


Fig. 5. Comparison between the V-t characteristics predicted by equation (5) and measured by Harada *et al.* (1979) and Matthews and Saint-Arnand (1971)

A comparison between the experimental results of Harada et al. (1979) and the calculated values using eqn. (6) is given in Fig. 5 for 20, 25 and 30 cm long rod-rod gaps from where it is clear that there is a reasonably good agreement between the two set of results. The small differences between the experimental results of Harada *et al.* (1979) and the calculated values using the proposed formula may be attributed to the differences in the waveforms of the impulses used. The impulses used for experimental measurements by Harada *et al.* (1979) had waveforms of 0.82/38 μs and 1/40 μs as compared to 1.2/50 μs impulse used for the present study. According to equal area criterion of impulse breakdown, the impulse used in the present study should result in somewhat lower breakdown voltage. Moreover, the differences between the breakdown voltages corresponding to the above mentioned two impulses should decrease with larger values of breakdown time which can be clearly observed from the results of Fig. 5.

Fig. 5 also shows a comparison between the breakdown voltages estimated for a 10 cm rod-rod gap and the experimental values reported by Matthews and Saint Arnand (1979) for a 10 cm irradiated rod-rod gap using square cut rod electrodes of 1.27 cm x 1.27 cm cross-section and an impulse votlage of 1/50 μs waveform. It is clear that there is a reasonable agreement between the two sets of results. Thus, the proposed equations can be used to estimate V-t characteristics of rod-rod gaps with a reasonable degree of accuracy. Hence in designing the protective gaps for power distribution lines of up to 33 kV with a BIL of 170 kV, equation (5) can be used to estimate the required clearances.

Conclusions

V-t characteristics are studied for 5 to 25 cm long rod-rod gaps using positive and negative standard lightning impulses. Empirical equations are proposed to predict V-t characteristics of such gaps. A comparison of the predicted breakdown voltage values and the results available in the literature indicates a reasonable agreement.

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علاقة جهد الإنهيار مع زمن الإنهيار (v-t curve) لثغرات هوائية محصورة بين قضيبين

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تتعرض شبكات القوى الكهربائية لموجات عابرة ذات جهد فائق تحدث أضراراً في الشبكة إذا لم تتوفر الحماية اللازمة . مصدر هذه الموجات إما الصواعق الرعدية من السحب أو التحويلات الكبيرة في الأحمال بصورة مفاجأة . وتستخدم الأقطاب ذات قضيبين بينهما ثغرة هوائية كأدوات حماية لمكونات الشبكة الكهربائية من تلك الجهود الفائقة . الوقت اللازم لإنهيار الثغرات الهوائية من جراء هذه الموجات (t) يرتبط بصورة مباشرة بقيمة جهد الإنهيار (v) . وهذه العلاقة تسمى منحنى v-t ومعرفتها ضرورية من أجل تنسيق الحماية . وفي الماضي درست بصورة مفصلة هذه العلاقة للثغرات الهوائية الواسعة (من ٥٠ سم فأكثر) . ولا توجد دراسة مماثلة للثغرات الصغيرة والتي عادةً ما تستخدم في حماية مكونات شبكات التوزيع الكهربائية .

هذه الورقة تلخص الدراسة المعملية التي عملت عن علاقة الجهد بالوقت (v-t) لقضيبين بينهما ثغرة هوائية بإستخدام نبضة صاعقية تتراوح ما بين ٥ إلى ٣٠ سم وكل قضيب مكون من إسطوانة ذات رأس نصف كروي

تتراوح أنصــاف أقطاره من ١ إلــى ٥ سم . وقــد درس تـأثـير طــول الثغــرة وقطــبيه المــوجــة وقيمــة نصـف قطــر رأس القضــيب علــى علاقــة الجـهـد - الــوقـــت (v-t curve) حيث إستخلصت معادلات في هـذا الخصوص أهمـها العلاقة العامة بين جهد الإنهيار (v) ووقت الإنهيار (t) وهي :

$$V = 13.85\ Gt^{-0.495}$$

حيث أن (G) هي طول الثغرة (سم) وهذه المعادلة صالحة لثغرات أطوالها مــا بين ٥ سم و ٢٥ سـم ولأوقـات تتــراوح ما بين ٦ , ٠ ميكروثانية و (t_o) حيث (t_o) يمكن إيجادها بالمعادلة الآتية :

$$t_o = -0.122 + 1.21\ \ell n\ (G)$$

وقد تحقق من صحة هذه المعادلة بتطبيقها على عدة نتائج منشورة في أبحاث سابقة وتبين أن هناك توافق جيد .