Sparkover Characteristics of Sphere-rod Gaps under Standard Impulse Voltages

P. N. MIKROPOULOS, C. A. STASSINOPOULOS, I. KATARACHIAS and A. TSETOGLOU
Department of Electrical and Computer Engineering
Aristotle University of Thessaloniki
Thessaloniki GR-54124
GREECE

Abstract: - The sparkover behaviour of sphere-rod gaps under standard impulse voltages is investigated by assessing the influence of gap spacing, voltage waveshape and polarity, and atmospheric conditions on the distribution of the sparkover voltage. A new correction procedure for atmospheric conditions is introduced and the related IEC standard is discussed. The feasibility of using the sphere-rod gap as measuring substandard, replacing the conventional more expensive sphere gap, is examined.

Key-Words: - Sphere-rod gaps, Impulse voltage, Sparkover voltage

1 Introduction

Sphere gaps are most commonly used for calibrating and measuring purposes. The recent revision of the relevant IEC standard suggests that in high voltage laboratories their use will always be a reference calibrating method. The sphere-rod electrode arrangement is much cheaper and simpler in construction than the sphere gap; therefore examining the feasibility of using such a gap configuration as measuring substandard appears an interesting subject.

For this purpose the sparkover characteristics of sphere-rod gaps has been investigated. Under standard impulse voltages stressing the sphere the influence of gap spacing, voltage waveshape and polarity, and atmospheric conditions on the sparkover behaviour has been studied.

It is shown that the breakdown mechanism of the sphere-rod gap depends on the type of the voltage applied at the sphere and upon the atmospheric conditions. A new accurate correction procedure for atmospheric conditions is introduced, based on experimental data; the relevant IEC standard [1] is discussed. The sphere-rod gap configuration can be used under certain conditions as measuring substandard.

These experiments form part of a larger project concerning the use of air gaps as measuring standards. Part of this work has been published before [2, 3] and a similar attempt was carried out by Allibone and Allen [4] for positive direct voltages.

2 Experimental Setup

The gap configuration consisted of a brass sphere 15 cm in diameter and an earthed cylindrical brass rod 23 mm in diameter with a square cut end. The axis of the sphere - rod gap was always horizontal to the ground and the distances above the ground and to the nearest objects were as is stipulated by IEC for sphere gaps.

A 2-stage, 280 kV, 1 kJ Marx generator produced impulse voltages with the standard waveshapes: 1.2/50 μs '*LI*' and 250/2500 μs '*SI*'. The Marx generator was located at a distance of 3 m from the sphere - rod gap, thus the radiation from the auxiliary gaps of the generator was regarded as having negligible influence. The voltages were measured via a capacitive divider and a digital oscilloscope [5]. The atmospheric conditions were not artificially controlled.

3 Experimental Results

3.1 General

Breakdown probability curves '$p(U)$' were obtained through the "multiple level test" method and from each $p(U)$ curve, the values of the 50% sparkover voltage 'U_{50}' and the standard deviation 'σ' were computed in accordance with IEC [1]. The voltage levels were taken for breakdown probabilities ranging from 0 to 100%. Each voltage level was higher 1÷2% from the previous one and consisted of 10 impulses applied at time intervals of around 30s.

The values of the 50% sparkover voltage referring to normal atmospheric conditions 'U_0' were calculated using the following expression:

$$U_{50} = U_0 \cdot \delta^{\mathrm{m}} \cdot k^{w} \quad (1)$$

where δ and k are given by IEC [1]. The exponents m, w were computed so as to ensure best fit to the experimental data.

3.2 Influence gap spacing and voltage type

Fig. 1 displays the variation of U_0 with gap spacing for all cases studied. The first result to be drawn is that the sphere-rod gap configuration suffers from a remarkable polarity effect, stronger with increasing gap spacing.

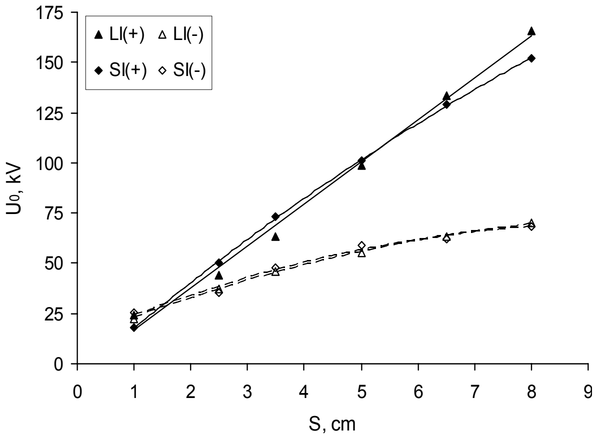
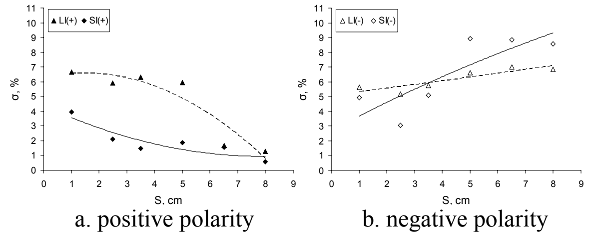


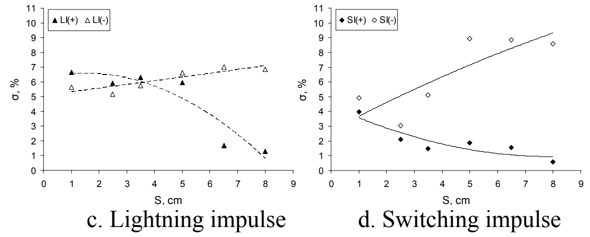
Fig. 1: Variation of U_0 with gap spacing

With the exception of the shortest gap length tested, U_0 is higher under positive than under negative polarity. The effect of gap spacing on U_0 is stronger under positive polarity, sparkover voltage increases linearly with gap spacing. Under negative polarity the corresponding curves saturate as the gap length increases (Fig. 1).

Concerning the influence of the waveshape on U_0, the trend is for *SI* to exhibit higher values than *LI* for short gap lengths whereas for the longest gap lengths the opposite is true (Fig. 1).



a. positive polarity b. negative polarity



c. Lightning impulse d. Switching impulse

Fig. 2: Variation of σ with gap spacing

Fig. 2 displays the variation of σ with gap spacing with the polarity and waveshape of the applied impulse as parameters. Under positive polarity (Fig. 2a) for both waveshapes σ tends to decrease with gap spacing approaching a value of ~1% for the longest gap lengths. Under negative polarity (Fig. 2b) the opposite is true as σ tends to increase with gap spacing.

The polarity of the impulse voltage applied at the sphere has a marked influence on the values of σ especially for long gap lengths. For both waveshapes σ displays similar values for short gap lengths, up to 5 cm for *LI* (Fig. 2c) and up to 2.5 cm for S*I* (Fig. 2d), but for long gap lengths σ is considerably higher under negative than under positive polarity.

It is also noteworthy that under both polarities and for short gap lengths σ is higher for *LI* than for *SI*, especially under positive polarity (Fig. 2a). For long gap lengths under positive polarity σ displays similar low values for both waveshapes (~1%) whereas under negative polarity σ is higher for *SI* than *LI*.

3.3 Influence of atmospheric conditions

Air density and absolute humidity are considered as the main physical parameters influencing on breakdown behaviour of air gaps. With the aid of equation (1), the values of the sparkover voltage corrected for air density were related to the corresponding values of k so as to study the effect of absolute humidity. In a similar way, the effect of air density was studied by relating the values of the sparkover voltage corrected for humidity to the corresponding values of δ. Examples of this procedure are shown in Fig. 3.

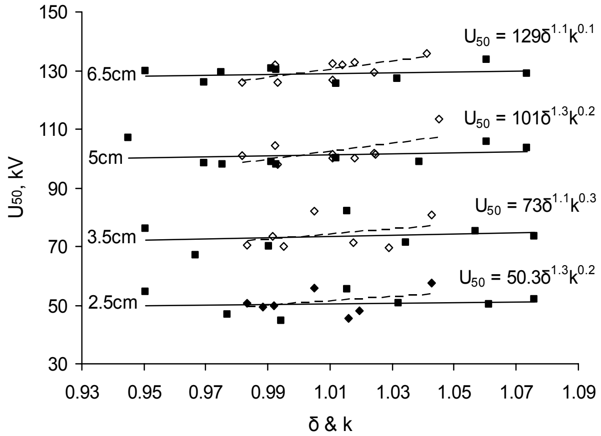
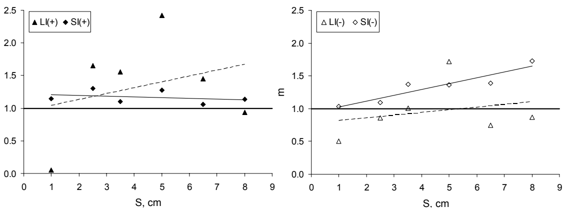
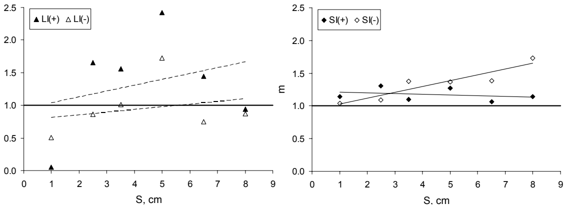


Fig. 3: Variation of U_{50} with δ and k; positive *SI*

Analysis of all the cases examined showed that the effect of air density on the sparkover voltage is for the latter to increase with δ whereas the effect of humidity is either negative or positive varying considerably with the gap configuration. To demonstrate better these effects the experimental values of m and w were plotted against gap spacing in Figures 4 and 5 respectively with the polarity and waveshape of the applied impulse as parameters.

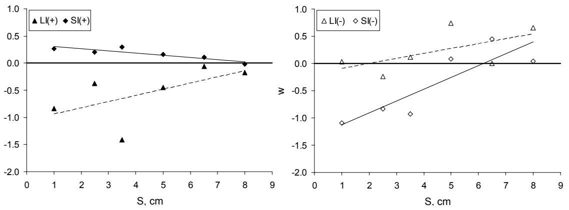


a. positive polarity b. negative polarity

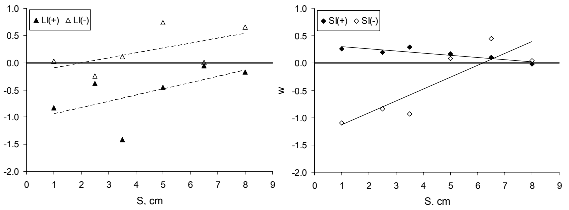


c. Lightning impulse d. Switching impulse

Fig. 4: Variation of exponent *m* with gap spacing



a. positive polarity b. negative polarity



c. Lightning impulse d. Switching impulse

Fig. 5: Variation of exponent *w* with gap spacing

For all the cases studied *m* displays positive values around or greater than 1 with the only exception of the shortest gap length (Fig. 4). The exponent *w* displays either positive or negative values (Fig. 5). From Figures 4 and 5 it is evident that under positive polarity and for all gap lengths *w* is negative for *LI* whereas positive for *SI*. Another clear conclusion to be drawn is that under positive *SI* and for all gap lengths *m* and *w* take roughly constant values around 1.1 and 0.2 respectively.

4 Discussion

The sphere-rod gap is a highly non-uniform field configuration therefore, the electric field values were found much higher in the vicinity of the tip of the rod than of the sphere. This results in sparkover to initiate by a corona discharge emerging from the earthed rod instead from the stressed sphere. The same was also found by Allibone and Allen [4] and by Water and Jones [6] in similar electrode arrangement for relatively short gap spacing.

Consequently, when the sphere is stressed with positive impulses sparkover starts by a negative corona from the rod whereas stressing the sphere with negative impulses results in sparkover to initiate by a positive corona. However, to study the breakdown mechanism it is important also to elucidate whether discharges of both polarities are present as well as their extend of development up to sparkover.

An indication of the type of predischarges occurring in any air gap is the average field gradient required for breakdown. For the same purpose the parameter *g*, firstly introduced by Pigini et al. [7], as defined by IEC [1] can be used. The parameter *g* is expressed by equation (2) in terms of the positive streamer propagation gradient of 500 kV/m, corrected for the conditions of δ and k:

$$g = \frac{U}{500L\,\delta\,k} \tag{2}$$

where L is the minimum discharge path in meters and U is the 50% breakdown voltage at the actual atmospheric conditions in kV.

The result of application of equation (2) on the experimental data is shown in Fig. 6. From this figure it is evident that under positive polarity *g* is roughly constant, around 4 times the positive streamer propagation gradient, suggesting that the same breakdown mechanism applies for all gap lengths examined. On the contrary, under negative polarity *g* displays significantly lower values that reduce with gap spacing in a non-linear way.

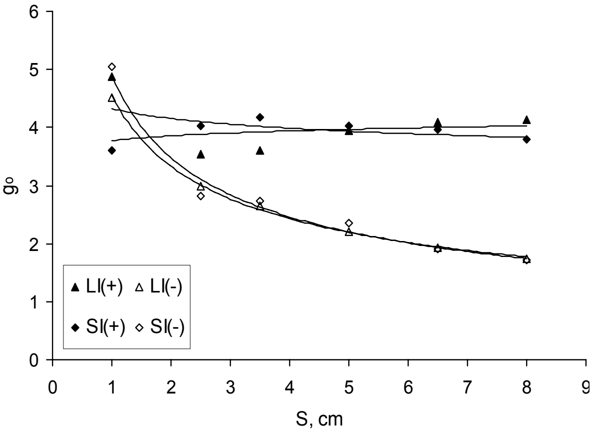


Fig. 6: Variation of *g* with gap spacing

As the gaps are relatively short in length for a significant leader to develop, the above analysis suggests that under positive polarity sparkover is effectuated by a single negative corona and the gap is mainly bridged by negative streamers.

Under negative polarity breakdown starts from a positive corona at the rod that gives rise to a negative corona from the sphere; thus, the gap is bridged partly with positive and negative streamers. It is well established that negative streamers require for propagation around 3 times higher average electric field value than positive. Since under negative polarity lower average electric field is required for breakdown with increasing gap spacing (Fig. 6) it follows that the part of the gap bridged by positive streamers increases with gap spacing.

These can explain the findings of Fig. 1 concerning the strong polarity effect observed on the sparkover voltage. The almost linear increase of sparkover voltage with gap spacing under positive polarity (Fig. 1) confirms the notion of a fairly uniform breakdown mechanism for all gap lengths examined. The saturated curves of sparkover voltages against gap spacing under negative polarity (Fig. 1) can be attributed to the bigger part of the gap bridged by positive streamers for longer gap spacing. The latter can also explain the higher values of *w* obtained with increasing gap spacing (Fig. 4b) since it is well recognized that positive discharges are more influenced by humidity than negative discharges.

Since the gap spacing examined is relatively short the value of σ is determined by both the initiation and the development of the discharge. The higher values of σ under negative polarity than under positive (Fig. 2) can be explained by the complexity of the breakdown mechanism for the former case since it requires for breakdown the emergence and development of both positive and negative coronas.

According to the IEC atmospheric correction procedure the values of the exponents *m*, *w* in expression (1) are arrived at using the parameter *g* as calculated with the aid of equation (2). The parameter *g* takes values bigger than 2 for the majority of the cases examined (Fig. 6). The only exceptions are the longest gap lengths of 6.5 and 8 cm under negative polarity where *g* takes values around 1.9 and 1.7 respectively. Thus, according to figure 4 of the IEC Standard [1] the values of the exponents *m*, *w* are found constant and equal to 1 and 0 respectively.

The experimental values of *m* and *w* that were computed so as to provide best fit to the experimental data are plotted against *g* Fig. 7. These values of *m* and *w* ensure a correction of U_{50} for normal conditions with minimal errors.

There is no clear relation between the exponents *m*, *w* and *g*; The spread in their values is quite large, especially for *w*, deviating in some cases considerably from the standard values of 1 and 0 respectively. Thus, the application of the IEC standard atmospheric correction procedure may result in significant errors in the values of the sparkover voltages.

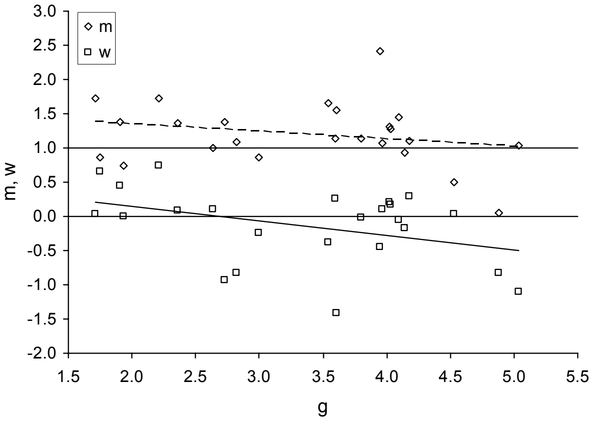


Fig. 7: Variation of exponents *m, w* with *g*

In order to test the accuracy of the IEC correction procedure for atmospheric conditions the values of U_{50} were corrected accordingly, 'U_{iec}'. If that correction procedure is accurate a parallel line to X-axis should be observed when plotting U_{iec} as a function of the ratio of humidity over δ h/δ. An example is shown in Fig. 8 where the dashed lines fit the values of U_{iec} and the solid lines the values of U_0 computed according to equation (1) with values of *m* and *w* giving best fit to the experimental data.

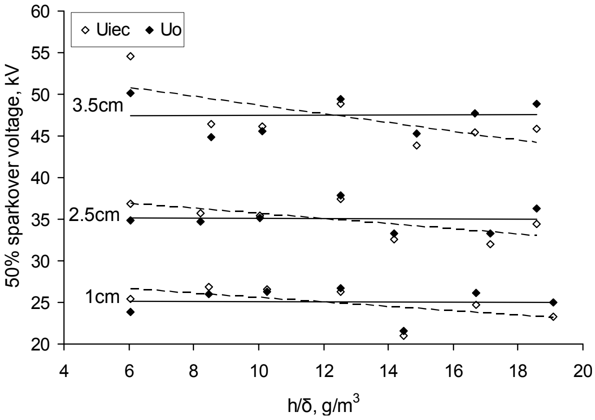


Fig. 8: 50% breakdown voltages corrected for normal atmospheric conditions as a function of *h/δ*, negative SI

From Fig. 8 it is clear that attributing to each case the proper correction factors the correction procedure becomes more accurate, associated with smaller errors, than using constant values as the IEC correction procedure suggests. This calls for further work in order to test the applicability of this procedure to other gap configurations.

Concerning the use of sphere-rod gap as substandard for calibrating and/or measuring purposes, under positive switching impulses and for relatively long gap spacing breakdown is associated with low values of σ (Fig. 2d) and is relatively insensitive to atmospheric conditions variation (Fig. 4 and 5). The same result was also found in previous work [2].

5 CONCLUSIONS

The sphere - rod gap displays a strong polarity effect especially with increasing gap spacing. With the sphere as the stressed electrode, breakdown under positive polarity occurs through a uniform mechanism involving negative discharges, while under negative polarity it occurs through one involving both positive and negative discharges.

The variability of the atmospheric correction factors with the gap configuration contrast with the IEC standard suggesting constant values for the gaps tested. A more accurate correction procedure has been introduced, based on a step by step calculation, attributing to each case the proper correction factors.

Under positive switching impulses the sphere-rod gap of relatively long gap spacing, bigger than the half of the sphere’s diameter, can be used as substandard for measuring impulse voltages.

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References:

[1] I.E.C.: ‘High-voltage test techniques, Part 1: General definitions and test requirements’. Publication 60600-1, 1989

[2] Gourgoulis D.E., Mikropoulos P.N., and Stassinopoulos C.A.: ‘Analysis of sphere-rod gaps under standard lightning and switching impulse voltages'. *IEE Proc.-Sci. Meas. Technol.*, Vol.144, No.1, 1997, pp. 11-16.

[3] Gourgoulis D.E., and Stassinopoulos C.A.: ‘Influence of irradiation on impulse breakdown of sphere gaps and sphere-rod gaps'. *IEE Proc.-Sci. Meas. Technol.*, Vol. 145, No.4, 1998, pp. 147-151.

[4] Allibone T.E., and Allen N.L.: ‘The sphere/rod and the rod/sphere gaps as possible substandards for measuring high direct voltages.’ *Proc. 8th I.S.H*, Yokohama, 1993.

[5] Gourgoulis D.E., Mikropoulos P.N., and Stassinopoulos C.A.: ‘Sparkover voltage of sphere gaps under standard lightning and switching impulse voltages'. *IEE Proc.-Sci. Meas. Technol.*, Vol.143, No.3, 1996, pp. 187-194.

[6] Waters R.T., and Jones R.E.: ‘The impulse breakdown voltage and time-lag characteristics of long gaps in air'. *Philosophical Transactions of the Royal Society of London*, Vol.256, No.1069, 1964, pp. 185-234.

[7] Pigini A., Sartorio G., Moreno M., Ramirez M., Cortina R., and Garbanati E.: ‘Influence of air density on the impulse strength of external insulation'. *IEEE Trans.*, PAS-104, (10), 1985, pp. 2888-2900.