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Evaluation of Electrical Performance on High Voltage Glass Suspended Insulators

J. Alles[1,2], A. Beroual[1], J-M. George[2], E. Brocard[2]

[1] Ecole Centrale de Lyon, University of Lyon, AMPERE CNRS UMR 5005,
36, Avenue Guy de Collongue, 69134 Ecully, France
[2] SEDIVER, 46 Avenue de Thiers, Saint Yorre
*Email: Abderrahmane.Beroual@ec-lyon.fr

Abstract - This paper is aimed at the comparison of performances of different types of glass insulators in dry conditions, under different types of voltage waveforms namely DC, AC and lightning impulse voltages. It is shown that the arcing distance is the main parameter influencing the flashover voltage. However, the difference between flashover voltages for the different voltage waveforms reduces when the arcing distance of insulators is increased. A comparison between experimental results with those obtained by using the streamer criterion as well as those given by empirical formulas, is presented.

Keywords: glass insulator; high voltage; DC; AC; lightning impulse voltage; electric field; arcing distance.

I. Introduction

Overhead line insulators are one of the key elements in transmission lines. They ensure both mechanical and electrical functions: attaching the power lines to the transmission towers and insulating this mechanical link in all environmental conditions. Glass insulators are, next to porcelain and polymeric types, one of the available options to electric grid markets. These insulators are exposed to numerous stresses and their failures can lead to transmission line outages, thereby reducing system reliability. One form of insulator failure is flashover, the unintended disruptive electric discharge over around the insulator. The flashover voltage depends on many parameters such as the physicochemical properties of insulator and its geometry (profile and leakage length), the contamination layers including the type of contaminants and their distribution, the evolution of the deposits, the atmospheric conditions (mist, fog, rain, sleet or melting snow or ice,…) and the waveform, polarity, amplitude and application time of the voltage. Thus, the choice of given kind of insulator depends on the voltage and the operating conditions.

Glass insulators are available on the commercial market since the first half of the 20th century. They appeared after porcelain but well before polymeric/composite insulators. Their electrical performance in polluted conditions has been widely investigated [1, 2]. But there are few studies on glass insulators in dry conditions [3].

This paper is devoted to the comparison of performances of three kinds of glass insulators in dry conditions, under different types of voltages namely DC (positive and negative polarities), AC (50 Hz) and lightning impulse voltages (positive and negative). The influence of different insulator parameters namely the outer diameter, arcing distance, electrode size and glass thickness are investigated.

II. Insulators types

Glass suspended insulators have as main characteristic the presence of tempered glass as dielectric medium, being the form and shape of the insulator similar from the porcelain counterpart. There exists a plethora of different types of insulators, responding to a range of different requirements.
Apart of the glass shell and its form, an insulator has more than 15 parameters that can adopt various values, therefore enabling for the existence of thousands of permutations. Manufacturers have in their catalogs more than a hundred types of insulators, with some insulators displaying only minor changes and others completely different. Most of these parameters have not a direct consequence on the electrical performance in dry conditions. Figure 1 depicts the different parts of a glass insulator

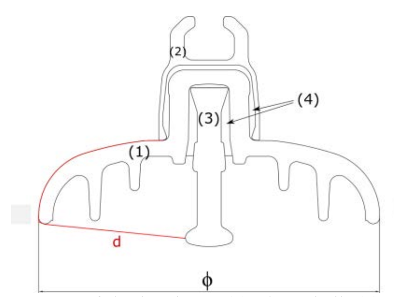

Fig. 1. Different parts of the insulator: (1) glass shell, (2) cap, (3) pin, (4) mortar. The outer diameter of the insulator is notated as ϕ and the arcing distance as d.

Three types of glass insulators considered as representative enough were selected for comparison; these are described hereinafter (Figures 2 - 4):

Insulator 1

This insulator has a high diameter and high arcing distance.

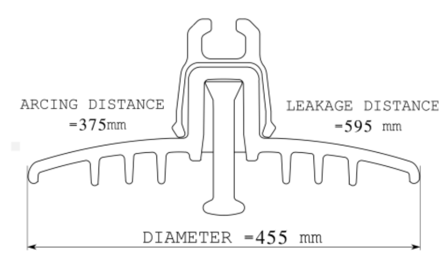

Fig. 2. Scheme of insulator UF300AN195

Insulator 2

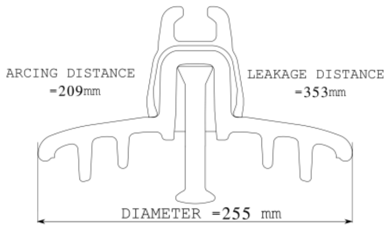

Fig. 3. Scheme of insulator UF120CB146

This insulator represents a variety of insulators with small diameter, leakage distance and arcing distance.

Insulator 3

Insulator of type 3 has an intermediate diameter and arcing distance between type 1 and type 2.

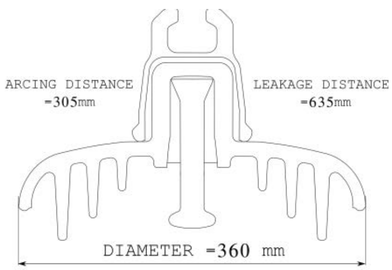

Fig. 4. Scheme of insulator UF300PU195

III. Computation of flashover voltage

A. Empirical Approaches

The flashover voltage, FOV, is defined as the voltage at which an air spark occurs along the surface of the insulator. In addition to parameters previously indicated, FOV is influenced by many physical phenomena including mainly the interaction dynamic between the discharge and the slippery surface of the solid dielectric, the accumulation of electric charges on the surface, changing ionization and attachment coefficients and the phenomenon of distortion of the electric field in the presence of such charges.

For a system corresponding mainly to a uniform electric field, the flashover voltage is slightly lower than the breakdown voltage of air alone, for the same electrode gaps. The decrease in the flashover voltage is due to the presence of small air pockets between the electrodes and solid dielectric, the influence of moisture and the non-uniformity of the electric field resulting of the difference between the permittivity of both the solid and that of air. The non-uniformity of electric field increases with the voltage because of the surface charging that takes place in this situation.

The flashover voltage for given insulator and voltage wave form, is generally estimated from empirical formulas established for the breakdown voltage of long air gaps in non-uniform electric field and more especially in a point-to-plane electrodes arrangement. Different empirical formulas have been proposed to compute FOV depending on the type of voltage and the surface state of insulator (clean/dry/polluted/wetted).

One of these formulas that is often found in literature for clean and dry support insulators subjected AC voltage is [4]:

$$V_{FOV}[kV] = 3.16 * l(cm) + 14 \quad (1)$$

where l is the arcing distance.

For DC voltage, some investigators use [4]

$$V_{FOV}[kV] = 4.47 * l(cm) + 19.8 \quad (2)$$

For insulators submitted to positive lightning impulse voltage, one often uses [5]

$$V_{FOV}[kV] = 5.1 * l(cm) + 19 \quad (3)$$

Or [4]

$$V_{FOV}[kV] = 5.36 * l(cm) + 23.8 \quad (4)$$

To compute the V_{FVO} for switching impulse voltages, Paris et al [6] proposed the following equation

$$V_{FOV,50\%}[kV] = 500 * l^{0.6} \quad (5)$$

And Les Renardières Groupe [7]

$$V_{FOV,50\%}[kV] = 3400/(1 + (\frac{8}{l})) \quad (6)$$

Also another formula that is recommended for switching impulse is [8]

$$V_{FOV,50\%}[kV] = 1080 \ln(1 + 0.46\, l) \quad (7)$$

Note that in equations (5, 6 and 7), l is in m.

All these empirical formulas give FOV values that are more or less consistent with the measured ones.

B. Approach using streamer criterion

The streamer criterion is a well-known explanation of the flashover mechanism [6, 8]. Some methods have been derived from it to calculate the flashover in non-uniform electrode air gaps [9, 10]. Larry Warne et al [10] proposed an approach that uses an ionization coefficient for the modeling of breakdown of non-uniform electrode geometries. This offers a good procedure for calculating the breakdown of air gaps.

The application of this method to glass insulators raises the problem of the influence of the dielectric surface onto the flashover process. A surface flashover implies that electrons will collide with the surface generating secondary electrons or sticking into it. Due to the inert nature of glass these phenomena can be neglected if a bigger error is tolerated.

Although the method cannot provide a very accurate estimation of the flashover voltage of glass insulators in power frequency, it allows the analysis of the influence of parameters as arcing distance, electrodes shape or glass thickness.

The procedure is based on the integration of the first Townsend coefficient through the path of the discharge. To calculate the integral, it is necessary to solve first the voltage distribution of the system (geometry, permittivity and conductivity of the materials must be known, as well as the voltage between electrodes).

The expression chosen for approximating the first Townsend coefficient is $\frac{\alpha}{p} \approx A\, e^{-\frac{B\,p}{E}}$ where p is pressure in Torr; E is the electric field in $\frac{V}{m}$; α is the first Townsend coefficient; and A and B are coefficients for adjustment per the intensity

of the field. Their value is: $A \approx 7.79 \frac{1}{cm\ Torr}$ and $B \approx 246.85 \frac{V}{cm\ Torr}$.
The field is non uniform around an insulator and the values of the field and pressure (1 atm) allow using the approximation of the first Townsend coefficient.
The integral over the streamer path is, once calculated, compared to an empirical expression of the form $F = 17.7 + \ln(d)$ where d is the arcing distance in centimeters and $\ln(d)$ the natural logarithm of d [10].

Because originally the flashover voltage is not known, an iterative process is repeated until the integral provides the same result as F. For each iteration the voltage must be changed and potential distribution is recalculated.

To perform the integrals over non trivial paths, we used the simulating software COMSOL. This software enables solving the capacitive and conductive electric field problem and afterwards calculating integrals over an arbitrary path. Figure 5 shows a COMSOL window during the calculus. The electric field has been solved for the system for a certain voltage between the electrodes, and the integral over the path allows the calculation if the voltage used is high enough for a flashover to occur.

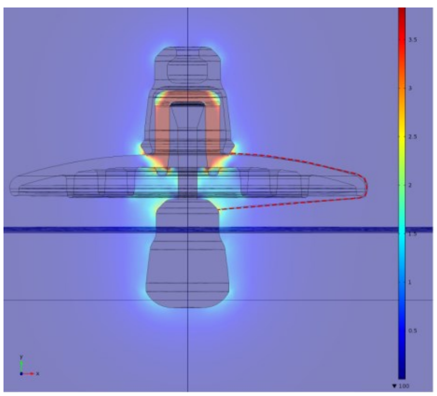

Fig. 5. The image shows the electric field solution in color grading and the path (red in dashed line) used for integrating. All other paths between the electrodes produce a higher flashover voltage.

For each insulator various arcing paths have been calculated, defining the optimum path as the one showing the lowest voltage between electrodes necessary to accomplish the equality:

$$p \int_L \frac{\alpha}{p}\, dL = 17.7 + \ln(d) \qquad (8)$$

Table 1 gives the computed results for the three insulators using equations (1) and (8).

Table 1: Flashover voltage estimated according to equations (1) and (8).

	Flashover voltage (kV)	
	Equation (1)	Equation (8)
Insulator 1	132	90
Insulator 2	80	100
Insulator 3	110	135

IV. Comparison between Insulators for different voltage wave forms

All data has been gathered according to IEC 60060.

A. Comparison between Insulators in AC voltage

Table 2 gives the AC flashover voltage of the three types of insulators.

Table 2: Results for the AC case

	Average [Peak-kV]	Std. Deviation
Insulator 1	130	1
Insulator 2	106	3
Insulator 3	145	3

It appears that although insulator 2 only has half the arcing distance of insulator 1, it has a flashover voltage 18 percent less. Thus the flashover voltage is not directly proportional to arcing distance.

Figure 6 clearly indicates that the arcing distance cannot be the only parameter. Insulator 1 has a longer arcing distance than insulator 3 but a lower flashover voltage.

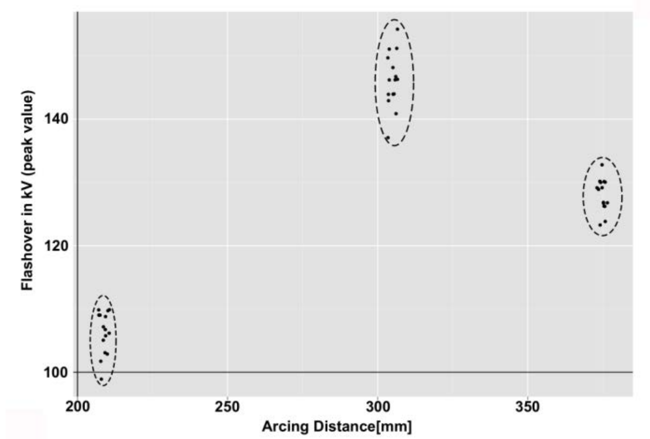

Fig. 6. Plot of the flashover voltage versus the arcing distance.

The comparison between the peak values of AC flashover (Table 2) and the values expected according to the streamer model (Table 1) are similar, with an average error of 15 %. The empirical formulas present a lower accuracy and are only valid for very specific geometries.

B. Comparison between Insulators in DC voltage

For the case of DC voltage, both positive and negative polarities are evaluated. During the tests, the voltage was applied at 500 V/sec until flashover occurred. The steepness of the voltage is critical for DC tests, also it has been observed that air currents modify the results.
As a result it is possible to observe that the variance of the tests for DC voltage is much higher than that for AC voltage as shown in Table 3. This could be due to dust particles and air currents that affect the charge distribution and hence the electric field.

Table 3: Results for DC case

	Average [kV]	Std. Deviation
Insulator 1	211(+) / 251(-)	7/10
Insulator 2	144(+) / 162(-)	13/6
Insulator 3	199(+) / 218(-)	10/8

Figure 7 plots the results according to arcing distance for both polarities.

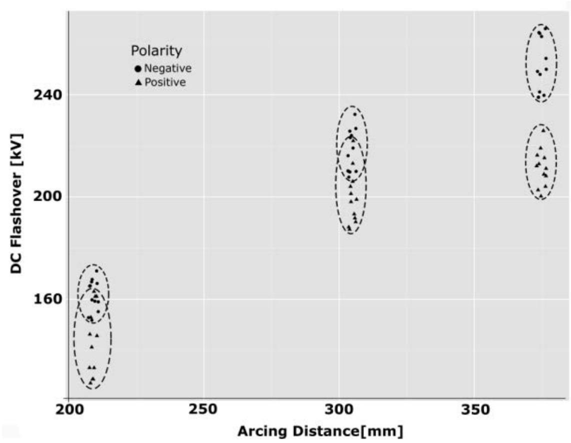

Fig. 7. Results for the DC case: vertical line is the flashover and the horizontal line is the arcing distance.

The results show that negative flashover is usually higher than positive flashover. This fact has also been reported by others [11, 12].
For the DC case, the relation between flashover and arcing distance is more linear than for the AC case.

C. Comparison between Insulators in Lightning Impulse Voltage

The fifty percent flashover voltage ($V_{FOV,\ 50\%}$) is the highest for Insulator 3 while it is the lowest for insulator 1 as shown in Table 4.

Table 4: Results for the lightning case

	Average [kV]	Std. Deviation
Insulator 1	137(+) / 151(-)	3/3
Insulator 2	116(+) / 115(-)	3/2
Insulator 3	187(+) / 190(-)	5/7

The results for the lightning voltage display much lower variance.

V. Performance in function of the steepness

In the previous sections, the performance of insulators have been evaluated in an individual excitation mode basis. The objective of this section is to compare how the same insulator presents different characteristics for different applied voltage waveforms.

It is a fact that for uniform electric fields in air gaps (no surface flashover) the value of DC, AC and negative lightning voltage are the same, as attested by the standard air gap tables [13]. Note that in these tables positive lightning values are tabulated apart. Unfortunately, in non-uniform air gaps these no longer holds true. The results clearly indicate a difference in the disruptive discharge values between the different voltage waveforms (Figure 8).

According to the laboratory experience in insulator testing and IEC60060 (section 7.1) standards, the fastest the rising time of the voltage, the higher the flashover voltage is.
This is not the case for DC case in non-homogeneous electric fields. Indeed, the DC flashover voltage is higher for all three tested insulators than the lightning flashover voltage. This is likely due to the pre-discharge phenomena that are quite different for the three cases in non-uniform fields.

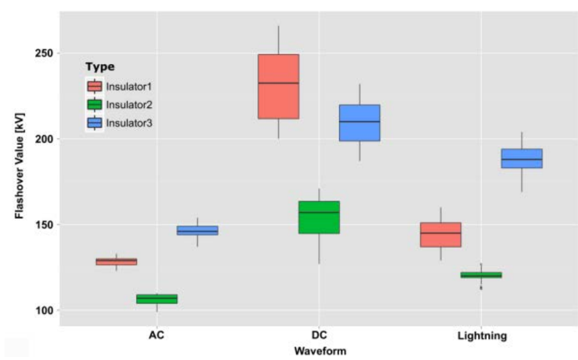

Fig. 8. Flashover voltage depending of the excitation mode. Positive and negative polarities are joined for DC and lightning.

VI. Conclusion

A comparative study of the surface flashover voltages of three types of glass insulators submitted to different voltage waveforms has been performed. The experimental results show that the flashover voltages are different depending upon voltage waveforms. Especially, the DC flashover voltage is the highest one.

A comparison of laboratory results with those obtained by using the streamer criterion (neglecting surface reactions) as well as those given by empirical formulas, has been presented.

Some hypothesis explaining the results and the polarity effect for DC and lightning voltage waveforms have been discussed.

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