Dielectric behaviour of polluted porcelain insulators

F.V.Topalis, I.F.Gonos and I.A.Stathopulos

Abstract: The dielectric behaviour of polluted porcelain insulators is investigated by means of experimental tests and simulation methods. The elaboration of the experimental results, using well known mathematical models of polluted insulators, leads to the identification of the arc constants. It was found out that the arc constants are independent of the insulator type and of the experimental pollution procedure (salt fog or solid layer cool fog method). This allows the formulation of a generalised simulation model of polluted insulators. The critical parameters for the flashover (voltage, current and gradient) are computed by means of the developed model, using only the geometric dimensions of the insulator, the pollution severity and the arc constants. Different types of porcelain insulators are investigated and the variation of the critical parameters upon the density of the pollution layer is determined. The influence of the geometrical dimensions and of the shape of the insulator to the critical parameters is also investigated. Furthermore, analytical relations are defined, between the computed critical parameters and the salt deposit density as well as the dimensions, the shape and the type of the insulator.

1 Introduction

A major problem of insulation systems is the accumulation of airborne pollutants due to natural, industrial or even mixed pollution, during the dry weather period and their subsequent wetting, mainly by high humidity. This problem was the motivation for the installation of a test station to perform laboratory tests on artificially polluted insulators. The experiments carried out, using either the salt fog method or the solid layer cool fog method, gave numerous experimental data (maximum withstand voltage against pollution, ratio between leakage distance and minimum flashover voltage against pollution, maximum withstand salinity at a given applied voltage, leakage current, etc.) for several insulator types.

The experimental results permitted a highly accurate evaluation of the arc constants of the insulator by means of a mathematical procedure. It has been proved that the computed values of the arc constants are independent of the insulator type and the kind of pollution.

Although the mentioned experiments are indispensable for the study of the insulator behaviour under pollution, they take a long time. For this reason, it would be very useful to predict the performance of insulators under pollution conditions, with a satisfactory accuracy, using analytical expressions according to the polluted insulator model.

2 Mathematical model

The most simple model [1, 2] for the explanation and the evaluation of the flashover process of a polluted insulator consists of a partial arc spanning over a dry zone and the resistance of the pollution layer in series (Fig. 1). The applied voltage U across the insulator is expressed as

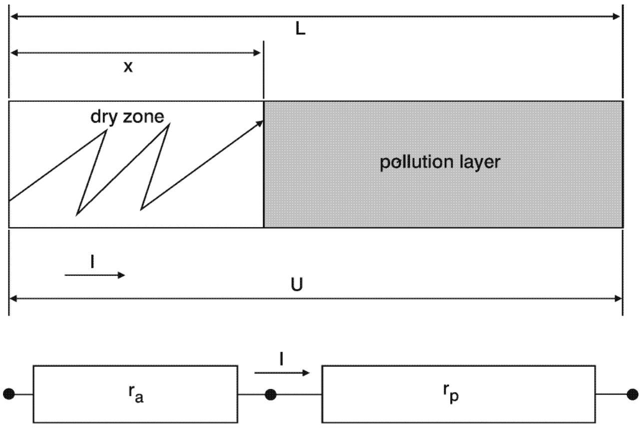

Fig. 1 *Equivalent circuit of polluted insulator*

$$U = I \cdot (r_a \cdot x + r_p \cdot (L - x)) \qquad (1)$$

where x is the length of the arc, L is the leakage distance of the insulator and I is the leakage current. The resistance r_a per unit length of the arc is defined as

$$r_a = A \cdot I^{-(n+1)} \qquad (2)$$

where A and n are the arc constants. On the other hand, the resistance r_p per unit length of the pollution layer is

$$r_p = \frac{l}{\pi \cdot D_{eq} \cdot \sigma_s} \qquad (3)$$

where D_{eq} is the equivalent diameter of the polluted insulator and σ_s is the surface conductivity, which is given [3] for the equivalent salt deposit density C (ESDD), by

$$\sigma_s = (369.05 \cdot C + 0.42) \cdot 10^{-6} \qquad (4)$$

σ_s is obtained in Ω^{-1} and r_p in Ω/cm, for C expressed in mg/cm^2. The equivalent diameter D_{eq} of the insulator, which is expressed in centimetres, is defined [4] as

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$$D_{eq} = \frac{L}{\pi \cdot F} \tag{5}$$

where F is the form factor of the insulator:

$$F = \int_0^L \frac{d\ell}{\pi \cdot D(\ell)} \tag{6}$$

$D(\ell)$ is the diameter of the insulator, varying across its leakage length L.

At the critical condition, when the partial arc is developed into a complete flashover, the current I obtains its critical value I_c which is given by

$$I_c = \left(\frac{D_m \cdot A}{D_{eq} \cdot r_p}\right)^{\frac{1}{n+1}} \tag{7}$$

where D_m is the maximum diameter of the insulator disc. A and n are the arc constants. Furthermore, the above equation results in the following formula, according to eqn. 3:

$$I_c = (\pi \cdot A \cdot D_m \cdot \sigma_s)^{\frac{1}{n+1}} \tag{8}$$

The respective critical value ℓ_c of the arc length x is given [5] as

$$\ell_c = \frac{L}{n+1} \tag{9}$$

At the critical condition, eqn. 1 becomes:

$$U_c = I_c \cdot (r_a \cdot \ell_c + r_p \cdot (L - \ell_c)) \tag{10}$$

where K is the coefficient of the pollution layer resistance with consideration of the current concentration at the arc foot point. In the case of cap-and-pin insulators a simplified form of K is given [6] as

$$K = 1 + \frac{n+1}{2 \cdot \pi \cdot F \cdot n} \cdot \ln\left(\frac{L}{2 \cdot \pi \cdot R \cdot F}\right) \tag{11}$$

where R is the radius of the arc foot, given by [7]

$$R = \sqrt{\frac{I}{\pi \cdot 1.45}} \tag{12}$$

and according to eqn. 8:

$$R = 0.469 \cdot (\pi \cdot A \cdot D_m \cdot \sigma_s)^{\frac{1}{2(n+1)}} \tag{13}$$

In the case of stab-type insulators, K is defined [6] as follows:

$$K = \frac{N \cdot (n+1)}{2 \cdot \pi \cdot n \cdot F} \cdot \left(\ln\left(\frac{4 \cdot L}{\pi \cdot N \cdot R}\right) - \ln\left(\tan \frac{\pi}{2(n+1)}\right)\right) \tag{14}$$

where N is the number of sheds.

Substituting the values of r_a, r_p, D_{eq}, I_c, ℓ_c in eqn. 10, results in the following formula for the critical voltage U_c:

$$U_c = \frac{A}{n+1} \cdot (L + \pi \cdot n \cdot D_m \cdot F \cdot K) \cdot (\pi \cdot A \cdot D_m \cdot \sigma_s)^{-\left(\frac{n}{n+1}\right)} \tag{15}$$

This equation provides the value of U_c against only the known geometrical characteristics L, D_m of the insulator, the constants A, n and the pollution C, since σ_s is a function of C, as well as, F and K are functions of L and D_m:

$$U_c = f(A, n, L, D_m, C) \tag{16}$$

The meaning of eqn. 15 is that, if the exact values of the arc constants are known, the model of the polluted insulator can be used not only to conclude qualitatively about the flashover mechanism, but also quantitatively about it: the critical voltage of any insulator under any pollution severity can be evaluated in a very simple way, using eqn. 15. Hence, the dielectric behaviour of insulators under pollution conditions can be exactly predicted and, eventually, the expensive and time-consuming experimental tests can be omitted, or, at least, minimised.

3 Investigated insulators

Some 19 different types of insulators were investigated for the purposes of this paper. The first 12 insulators are of cap-and-pin type (standard suspension insulators and of fog type), the next two are of pin type and the last five insulators are of stab type. The characteristics of these insulators are presented in Table 1.

4 Test setup and procedure

The experiments were carried out according to the solid layer-cool fog method to simulate the industrial pollution. The test specimens were suspended from the ceiling of the pollution chamber [8] and rotated in horizontal position at a speed of about 140rev/min. The used contaminant was: NaCl as required, 75g/l kaolin clay and 675g/l silica flour with particle size 2–20μm. The surface contamination was achieved by means of compressed air (p = 1.7 bar). The ratio of pollution between the bottom and the top surface of the insulator was in the range of 2/1–3/1.

The equivalent salt deposit density C on the insulator surface was used as an index for pollution severity. It was determined by washing off the surface of the insulator with ion free water. The value of C is given by

$$C = \frac{s \cdot V}{S} \tag{17}$$

where V is the wash-off solution volume (counted in cm^3), s is the salinity of the solution (in grams of NaCl per litre of solution) and S is the total surface of the insulator (in cm^2).

The fogging procedure [9] was carried out in a fog chamber, by means of a spraying system arrangement in accordance to IEC norms [10]. The air pressure was about 3 bar and the water flow was about 0.5l/min (per spray).

The testing circuit consists of the high-voltage source, the test specimen and the measuring equipment. A 750V/65kV/130kV, 260kVA high-voltage transformer of tank type was used, with two special bushings with an extended leakage distance permitting the introduction of them into the fog chamber. The ratio resistance/reactance (R/X) of the testing plant was greater than 0.02 and the short-circuit current during the tests varied in the range of 5–15A.

Table 1: Characteristics of the investigated insulators

Insulator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
D_m (mm)	268	268	254	254	254	254	292	279	321	254	280	254	200	229	180	200	150	150	180
H (mm)	159	159	165	146	146	146	159	156	178	146	170	145	165	166	290	320	248	294	290
L (mm)	330	406	432	279	432	318	470	368	546	305	370	305	400	432	605	960	370	400	480
F	0.79	0.86	0.90	0.68	0.92	0.72	0.92	0.76	0.96	0.70	0.80	0.74	1.29	1.38	1.43	2.04	1.06	1.14	0.71

The test specimens were suspended from the ceiling isolated from their suspension wire rope by means of a disc insulator's chain. They were energised from the high-voltage source on their lower part via a 3m section of a 180mm^2 ACSR bundle conductor, to simulate the dielectric field encountered on a transmission line, and were grounded via a 75Ω measuring resistance.

The voltage was applied to the insulator when the conductivity reached maximum and was increased continuously until flashover. The layer conductivity was indirectly checked: the insulator resistance was repeatedly (every 5 minutes) measured during the wetting using a 2.5kV Megger. At the beginning of the wetting the obtained resistance values are very high, rapidly decreasing so that in 3–40 minutes the measured resistance is very low, and remains thereafter practically constant. It is obvious that this lowest resistance value depends on the salt deposit density, as predicted from eqn. 4. The duration of the wetting, in order to reach the maximum layer conductivity, is not constant. It depends on the temperature difference between pollution layer and fog, the contaminant composition and the humidity in the test chamber.

The surface conductivity of the polluted insulator is determined by measuring the highest peak value of the leakage current [11]. The voltage drop across a measuring resistance, caused by the leakage current was measured and recorded by means of an oscilloscope as well as of an arrangement that registers on paper the leakage current peak value.

5 Test results and analysis

5.1 Critical voltage of polluted insulators

Both the values of voltage and current were measured during the voltage increase, as well as at the instant of one cycle just before flashover. The values of the above quantities at the moment are called further on critical. The experimental results concerning the critical voltage of a cap-and-pin suspension insulator and a disc insulator of fog type (columns 10 and 5 of Table 1, respectively), are shown in Fig. 2.

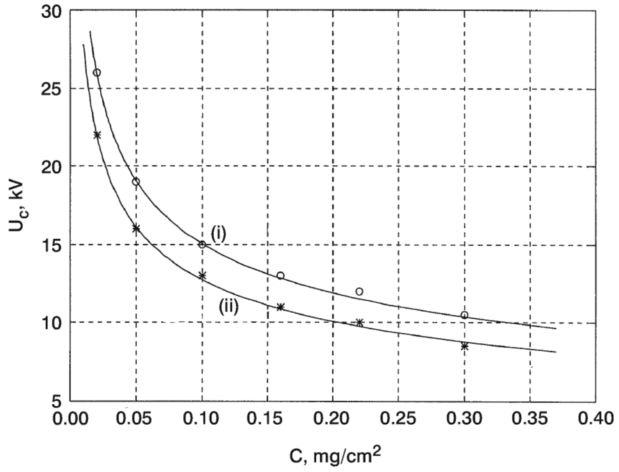

Fig.2 *Critical voltage for insulators No.5 and No.10 against ESSD*
Measurements:
(i) ○ fog-type
(ii) ✱ cap-and-pin
——— model

The tests were carried out on several types of single suspension insulators and were extended to an area of contamination values, which seems to cover the pollution estimated to dominate at several heavily polluted sites in Greece.

It has been proved that the RMS value of critical voltage U_c (in kV) depends on the equivalent salt deposit density C (in mg/cm^2) according to

$$U_c = K_c \cdot C^{-m} \tag{18}$$

where K_c is a linear function of the insulator leakage distance L (in cm), according to

$$K_c = 0.12 \cdot L + 2.43 \tag{19}$$

The exponent m seems to depend on the insulator form. Its value for usual porcelain cap-and-pin suspension insulators is in the range of 0.325 ± 0.009 with C given in mg/cm^2

5.2 Determination of the arc constants

Using the analytical expressions, which are based on the polluted insulator model, the most important factor is the determination of the arc constants A and n. The use of the calculated values [12] for steady arc in air between copper electrodes (A = 63, n = 0.76) gives inconsistent results compared with the experiments. The elaboration of the data available in the literature shows that the real values of constants A and n, in the case of thin pollution layers, are in the range of 50–400 and 0.3–1, respectively [4, 12, 13]. The identification of these constants seems to be a very difficult task, due to the fact that the determination of the heating effects in the pollution layer is very complicated [12].

The experimental data (U_c against C) and the geometric characteristics (D_m, L, F) of the tested insulators were put in eqn. 15, thus resulting a system of 84 of equations with unknowns the arc constants A and n:

$$U_{ci} = f_i(A, n, L, D_m, C) \Rightarrow g_i(A, n) = 0 \qquad i = 1, 2, 3, \ldots, 84 \tag{20}$$

This system of equations, with unknowns the arc constants A and n was solved using the least square method. The requirement is the minimising of the expression:

$$\sum_{i=1}^{84} [U_{c_i} - f_i(A, n, L, D_m, C)]^2 \tag{21}$$

The solution of this system is:

$$A = 131.5 \pm 2.5 \qquad n = 0.374 \pm 0.006 \tag{22}$$

The experimental results show that the values:

$$A = 131.5 \qquad n = 0.374 \tag{23}$$

are independent of the insulator type and the experimental pollution procedure. These values give very consistent results compared to the experiments. The calculated U_c-values from eqn. 15, using A and n as determined above, show a relative divergence from the measured U_c-values between 1.7% and 1.0% (Fig. 2). Furthermore, the predicted U_c-values for several other disc insulators were compared to measured values. Results from these insulators had not been used in the evaluation of A and n. This comparison was also very satisfactory; e.g. the predicted U_c-values for disc insulators of fog type diverge from the measured values between –1.9% and 2.8%.

6 Application of the mathematical model

The developed mathematical model was applied to the 19 insulators of Table 1, using the determined values of the arc constants in eqn. 23. The curves of the calculated critical voltage Uc and critical current I_c for 3 typical insulators are presented in Fig. 3.

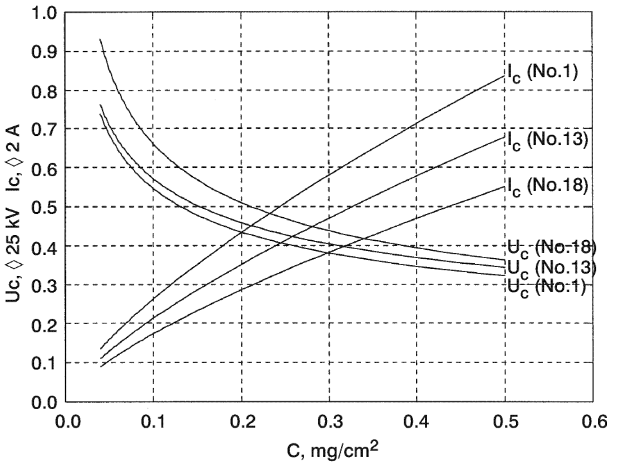

Fig.3 *Critical voltage U_c and critical current I_c for insulatoprs No.1, No.13 and No.18 against ESSD C*

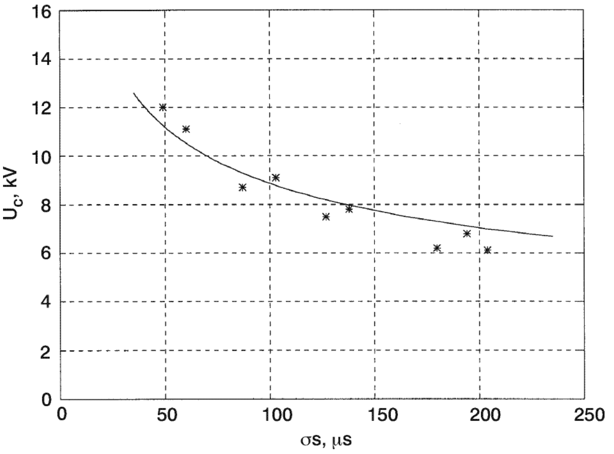

Fig.4 *U_c against σs for cap-and-pin insulator No.4*
——— model
* experiment [14]

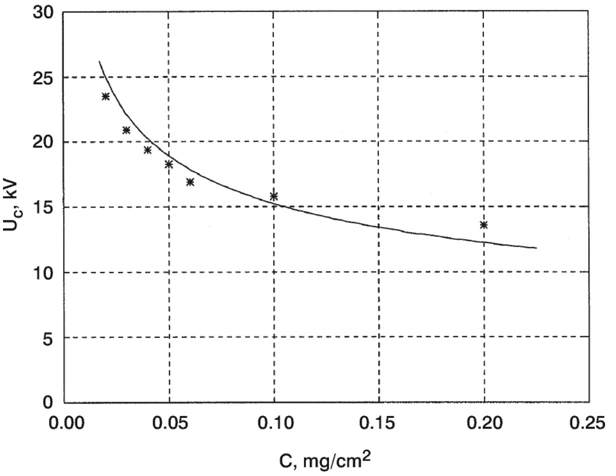

Fig.5 *U_c against ESSD C for pin-type insulator No.14*
——— model
* experiment [15]

The validity of the model was verified by comparing the computer results with measurements found in the literature besides the already presented experimental results. Fig. 4 shows a comparison of the model and experimental data [14] for the cap-and-pin insulator No.4. It can be seen that there is a good correlation between the model and the measurements at every surface conductivity. Fig. 5 shows similar results obtained for the pin-type insulator No.14. The correlation between the model and the measurements [15] is also good at any contamination severity. The comparison of model and experiments [16] for the stab-type insulator No.19 in Fig. 6 is quite satisfactory, especially at light contamination. Measurements of U_c against surface conductivity σ_s [14] for the stab-type insulator No.15 are compared with the model in Fig. 7. On the other hand, experimental results [16] obtained for the same insulator, are also presented in this Figure after conversion of the ESDD values in surface conductivity ones. The correlation is still good given that the computed curve passes through the experimental ones.

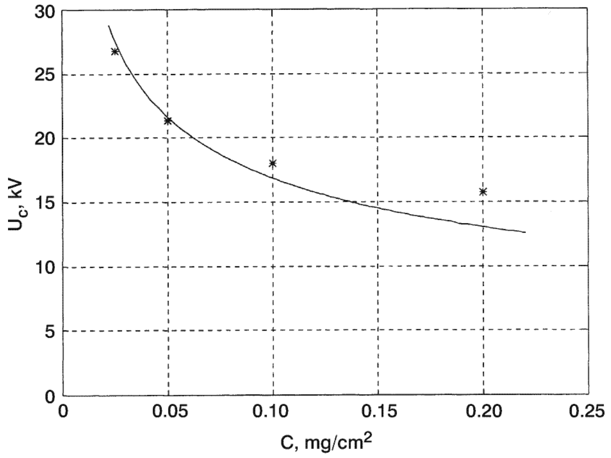

Fig.6 *U_c against ESSD C for stab-type insulator No.19*
——— model
* experiment

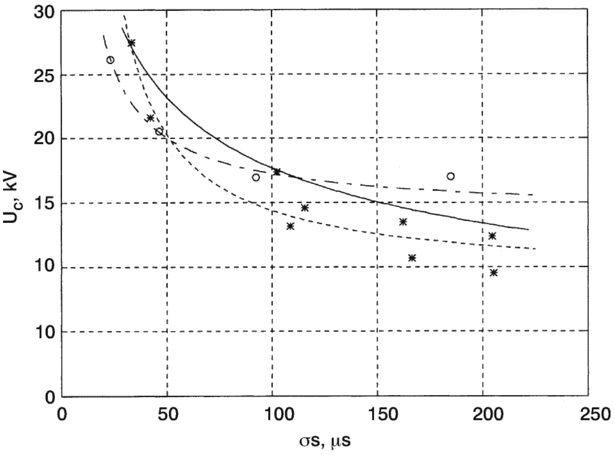

Fig.7 *U_c against σs for stab-type insulator No.15*
——— model
Experiments:
– –*– – [14]
– –○– – [16]

The computations show that the variation of the critical parameters U_c and I_c upon the ESDD C follow the analytical expression of the power function

$$U_c = a \cdot C^{-b} \tag{24a}$$

$$I_c = e \cdot C^{f} \tag{24b}$$

where a, b, e and f are always positive. Further investigation permits the evaluation of these coefficients and exponents and the determination of simplified analytical expressions giving their dependence upon the dimensions of the insulators:

Exponent b of $U_c = a{\cdot}C^{-b}$: The exponent b seems to be independent of the insulator dimensions (L and D_m), changing its value only with the type (F) of the insulator: its value lies between 0.32 and 0.33 for cap-and-pin insulators, 0.35 and 0.37 for stab-type insulators and 0.31 and 0.32 for pin-type insulators.

Coefficient a of $U_c = a{\cdot}C^{-b}$: The coefficient a is a function of the geometrical characteristics L, D_m and F of the insulator (Fig. 8) and therefore of the type of the insulator. The use of curve-fitting methods does not lead to a simple mathematical relation between a and D_m or a and F. Unlike, the following relation between a and L is determined:

$$A = 0.130 \cdot L + 1.947 \qquad (25)$$

Eqn. 25 means that the critical voltage increases linearly with the increase of the leakage distance, given that the exponent b is independent of the insulator dimensions, as it is found above.

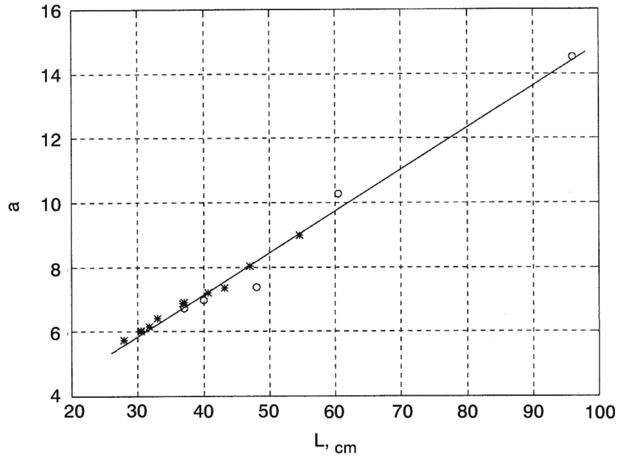

Fig.8 *Coefficient a of $U_c = a{\cdot}C^{-b}$ against leakage distance L*
✱ cap-and-pin
○ stab-type

Exponent f of $I_c = e{\cdot}C^f$: The exponent f of I_c seems to be constant and independent of the dimensions (L and D_m) and even the type (F) of the insulator. Its value was found equal to 0.719.

Coefficient e of $I_c = e{\cdot}C^f$: The coefficient e is a function of the geometrical characteristics (L and D_m) of the insulator and therefore of the type (F) of the insulator. The relation between e and L or e and F is not a simple mathematical formula. However, the relation between the coefficient e and the diameter D_m of the insulator is linear (Fig. 9), independently of the insulator type, according to the formula

$$e = 0.079 \cdot D_m + 0.643 \qquad (26)$$

This means that the critical current increases linearly with the increase of the diameter of the insulator, given that the exponent f is constant and independent of all the dimensions and even the type of the insulator as it is found above.

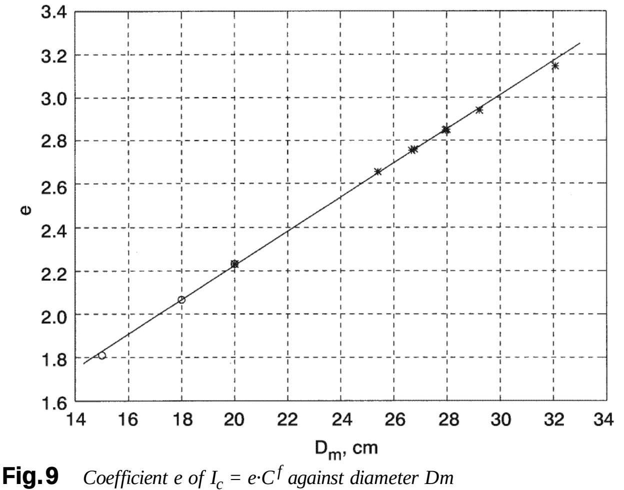

Fig.9 *Coefficient e of $I_c = e{\cdot}C^f$ against diameter Dm*
✱ cap-and-pin
○ stab-type

7 Conclusions

The elaboration of the experimental data leads to the identification of the arc constants, which are used in the polluted insulator model. The use of the derived values of the arc constants allows not only the qualitative but also the quantitative description of the dielectric behaviour of polluted insulators, providing the users of insulators with a polluted insulator model of general application. The application of the mathematical model to different types of insulators shows a satisfactory agreement between the computed results and the experimental ones.

The variation of the critical voltage follows the form of the power function in both cases, mathematical and experimental. The respective analytical forms are almost identical. The experimentally determined relation between the critical voltage and ESDD differs slightly from the calculated one.

The validity of the developed model, independently of the type of the insulator, allows the determination of the critical voltage, using only the geometrical characteristics of the insulator and the distribution of the pollution layer. The distribution of contaminants and consequently, the evaluation of local layer conductivity can be obtained by means of special measurements.

The quantitative description seems to be very significant, given that the exact knowledge of the arc constants allows the accurate prediction of the behaviour of insulators in polluted environment. It is expected that complicated experiments for the estimation of this behaviour can be drastically reduced or even eliminated. The information that can be obtained by means of the proposed method is very useful in the dimensioning of the insulation of the electric power overhead lines.

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