Electrical Parameters Associated With Discharges in Resistive Soils

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***Abstract*—The electrical parameters associated with discharges in resistive soils have been studied under inhomogeneous fields in order to achieve a better understanding of the nonlinear behavior of grounding systems subject to high surge currents. The soil resistivity and the other parameters associated with discharges are defined using experimental and calculating methods. The dielectric strength is found to be a function of water content of the soil. The same goes for the discharge-guiding field. The inception current has been also measured and the experimental results are in good agreement with the calculated values.**

***Index Terms*—Dielectric strength, discharge-guiding field, electrical discharges, grounding system, inception current, permittivity, resistivity, soil ionization.**

I. Introduction

THE importance of the investigation of the soil ionization and discharge process in earthed electrodes is mainly due to the fact that these nonlinear phenomena reduce the resistance of a grounding system when it is subjected to a high current discharge.

Despite the practical consequence of this effect, few experimental data for electrical parameters of discharges in resistive soils have been presented in the specialized literature. Moreover, the disagreements between the parameter significance published by different authors make the comparison between their values a quite difficult task.

That is why, before proposing an evaluation procedure, we have decided to give a definition for the most important parameters associated with electrical discharges in variable resistivity soil, such as dielectric strength, inception current and discharge-guiding field. A set of experimental data of the parameters conditioning the soil discharge is presented in order to clarify the role of each one in the transient resistance of the grounding system.

All these critical parameters allow for more understanding on the inception and development of electrical discharges in resistive soils. Precise knowledge of these parameters aids to improve the design of grounding systems by reducing the transient resistance at high surge currents, as produced by strokes of lightning on protective devices in power electric systems and buildings or equipment sensitive to electromagnetic interference.

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The entire experimental tests were performed in laboratory by using small samples of resistive soils and concentrated electrodes.

II. Determination of the Soil Resistivity

The soil resistivity plays a decisive role on the resistance of the grounding system. In order to study the ionization phenomena in the soil, the tests were carried out with concentrated electrodes. Electrodes are so short that their inductive behavior can be neglected [12], and then the electric field distribution around the ground electrode is mainly conditioned by the resistivity of the soil and the current density.

In this study, a large range of resistivity, between 50 and 500 000 $\Omega\mathrm{m}$, was considered.

Two experimental methods are proposed to determine the resistivity of several soils whose characteristics are the following:

- sand composed of 82.8% of quartz, 2.9% of potassium feldspar, 7.2% of limestone, 3.1% of calcium carbonate, 0.9% of mica, 2.4% of biotite, 0.7% of magnetite;
- black clay;
- mixture made by sand (50%) and clay (50%);
- concrete composed by 4.8 dm^3 of sand, 1.6 dm^3 of cement and 1 dm^3 of water.

The water content of the soils used in the experiences varies from about 0.06 to 15% by weight.

A. Homogeneous Electric Field Method

Experiments were carried out in a plane-to-plane gap. The surface S of the electrodes was 72.4 cm^2 and, in order to maintain a significant uniformity of the electric field, the distance d between electrodes cannot exceed 1 cm.

In all the experiments, the used Marx generator (600 kV, 4 kJ) delivers current impulses with 8 μs front time (typically, the time for the lightning currents of first strokes). A fast resistive divider allows the measurement of the voltage variation against time. Current was measured by using a 0.18 Ω coaxial shunt with 0.35 μs time constant, in series with the earth plane.

Fig. 1 shows the temporal evolution of the voltage U, the current I and the resistance $\mathrm{R_t}$ of the system containing sand of unknown resistivity.

In this example, a careful examination of the voltage and current records reveals that no impulsive discharge develops into the gap. Consequently, the resistance of the grounding system $\mathrm{R_t}$ is defined as the ratio between the applied potential and the resistive current (linear condition). But the measured current I

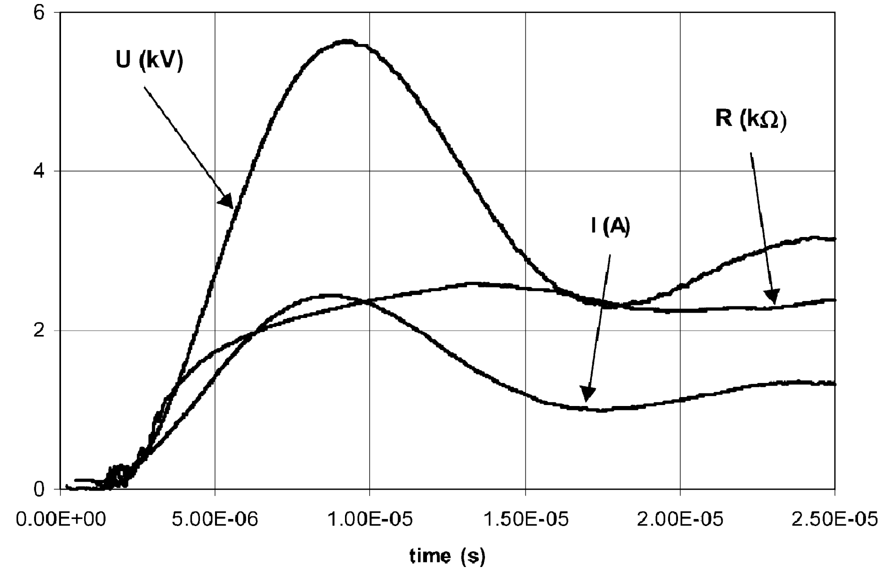

Fig. 1. Temporal evolution of the voltage, the current and the resistance of the system (plane-to-plane configuration − d=1 cm − positive polarity).

is given by the contribution of resistive current Ir and capacitive current Ic

$$\mathrm{I} = \mathrm{Ir} + \mathrm{Ic} = \mathrm{Ir} + \mathrm{C}\frac{dU}{dt}. \tag{1}$$

So, in order to neglect the capacitive current, the value of $\mathrm{R_t}$ is determined for $dU/dt = 0$.

The knowledge of this resistance allows calculation of the soil resistivity by using the well-known formula

$$R_\mathrm{t} = \rho \times \frac{d}{S} \tag{2}$$

and we find

$$\rho = 1600\ \Omega \cdot \mathrm{m}.$$

Resistivity was calculated for several voltage levels, up to 8 kV (beyond this value, a discharge develops into the gap and leads to a breakdown). It appears that the resistivity of the sand is constant in this range of voltage. The same happened for the clay and the mixture 50% sand/50% clay. Besides, the behavior of the concrete is absolutely different, as shown in Fig. 2.

The resistivity of the concrete decreases as the applied electric field increases, which conveys its nonlinearity.

Though the measured soil resistivity (sand, clay, and mixture) remains unchanged up to 8 kV, this method does not allow to assess this property for higher voltage.

In order to clarify this significant topic, we propose an experimental method for measurement of the resistivity of soils at higher voltage.

B. Inhomogeneous Electric Field Method

Experiments were carried out in rod-plane (Fig. 3) configurations:

- configuration n°1: 1.25 cm-diameter rod ended with a sphere of 1.45 cm radius;

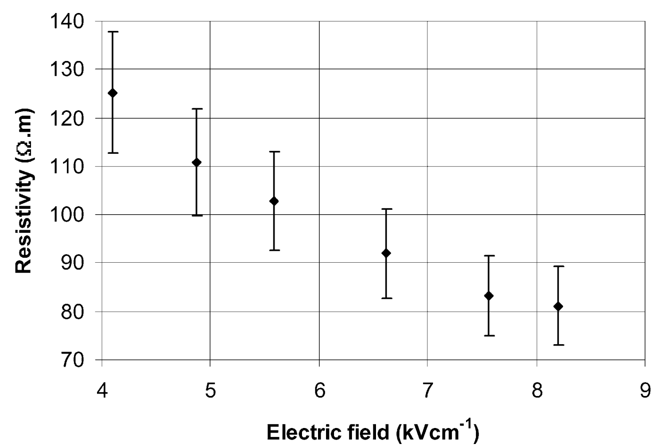

Fig. 2. Measured resistivity of concrete as a function of electric field.

- configuration n°2: 1.25 cm-diameter rod ended with a 60° cone-shape tip of 0.2 cm radius;
- configuration n°3: 0.8 cm-diameter rod ended with a sphere of 0.85 cm radius.

Some tests were also carried out in two additional configurations:

- configuration n°4: 0.8 cm-diameter rod ended with a square plate of 0.2 cm-thickness and 3.8 cm of side;
- configuration n°5: 1.25 cm-diameter rod ended with a disc plate of 0.2 cm-thickness and 3 cm of diameter.

All these electrodes were put vertically on a P.V.C. cylinder tube, of 10.4 cm of diameter and 20 cm of length, containing sand, clay, mixture, or concrete. An earth plane electrode closes the inferior extremity of this tube. The distance between the two electrodes was fixed at 9 cm and the hv electrode length driven into the sand was 8.6 cm.

Calculating the Soil Resistivity: The resistance $\mathrm{R_t}$ of a vertical electrode of length L and radius r driven in the soil is calculated as the resistance of an electrode of length 2L immersed in an infinite medium of resistivity ρ. Assuming that $\mathrm{R} \ll \mathrm{L}$,

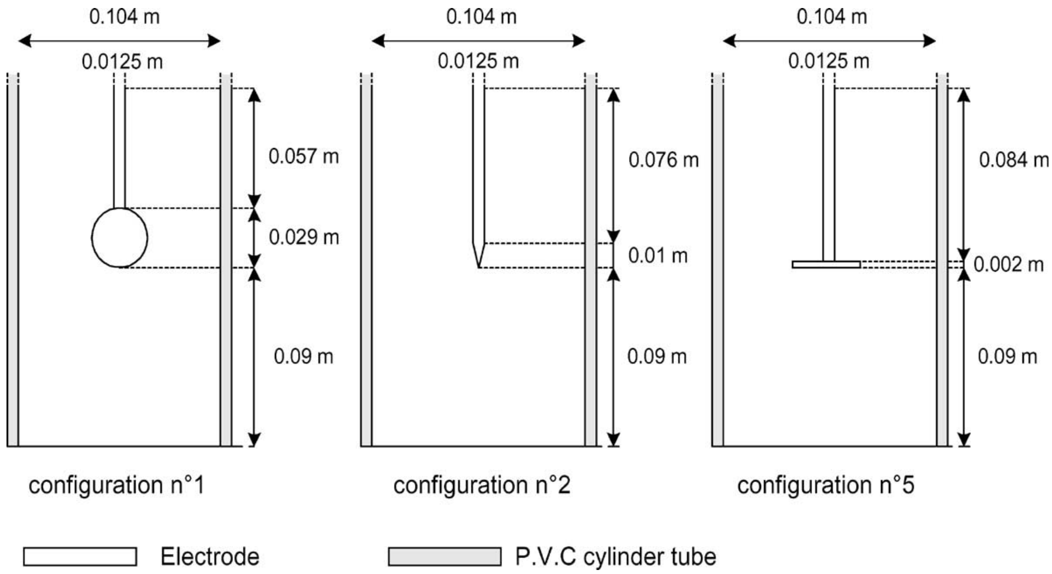

Fig. 3. Sketch of the rod-plane configurations.

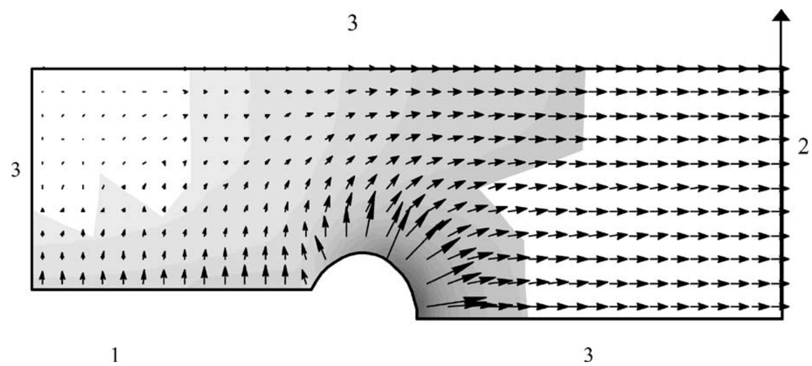

Fig. 4. Spatial distribution of the current density in the configuration $\mathrm{n}^{\circ}1$. (This figure shows half the electrode configuration because of symmetry) 1– h-v electrode (U), 2 – earth plane electrode (U_0), 3 – $\mathrm{J_N} = 0\ \mathrm{Am}^{-2}$. Maximum current density: 1.8 Am^{-2}.

the hypothesis of a leakage current uniformly distributed along the electrode leads to the well-known formula [7], [12]

$$R_{\mathrm{t}} = \frac{\rho}{2\pi L} \times \left[\ln\left(\frac{4L}{r}\right) - 1\right]. \tag{3}$$

In our experimental configurations, the presence of a plane and a P.V.C cylinder tube modifies the current density distribution so that this formula is no longer valid. Therefore, we developed a method to calculate the soil resistivity by using software based on the finite element method (Quick-Field™).

Fig. 4 shows the simulation result for the configuration $\mathrm{n}^{\circ}1$ and an arbitrary value of the resistivity. This simulation allows the calculation of the spatial distribution of the vectors of current density J for a certain level of voltage $(\mathrm{U} - \mathrm{U}_0)$ between electrodes.

The value of the current I is then obtained by integrating the current density at the electrode surface, for example, on the plane (Fig. 5)

$$I = \int_{plane} jdS = 2\pi \int_0^{0.052} \omega \cdot j(\omega) d\omega \tag{4}$$

where ω is the distance between the center and any point of the plane.

Under linear conditions, the resistance $\mathrm{R_t}$ of the system is defined by the well-known formula

$$R_{\mathrm{t}} = \frac{U - U_0}{I}. \tag{5}$$

Experimental Determination of the Soil Resistance $\mathrm{R_t}$*:* Under configuration $\mathrm{n}^{\circ}1$ and positive polarity, we determine experimentally the resistance of the system containing the sand previously used. The applied voltage varies from 10 kV up to 40 kV. In such a condition, no corona develops at the immediate vicinity of the h-v electrode and the measured resistance remains unchanged, $\mathrm{R_t} = 21\ \mathrm{k}\Omega$, whatever the applied voltage level.

The soil resistivity is calculated adjusting its value until the computed resistance value is equal to the experimental one. Finally, the sand resistivity calculated from several configurations is equal to 1600 $\Omega \cdot \mathrm{m}$. This is in accordance with the value determined, at lower voltage, using the method A what means that the sand resistivity is constant whatever the applied voltage level.

This method is all the more interesting as it provides the soil resistivity value, and verifies the linearity, for high strengths.

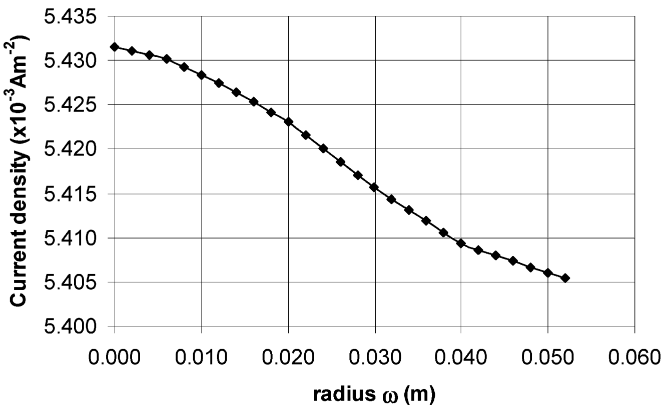

Fig. 5. Spatial distribution of the current density at the plane surface for 1 V applied between electrodes.

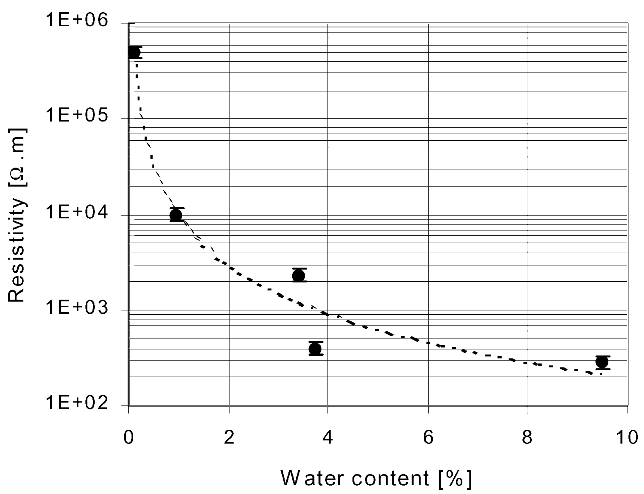

Fig. 6. Measured sand resistivity versus water content.

C. Validity of the Proposed Methods

For each soil, tests were also performed with added or reduced moisture to modify the resistivity value, as shown in Fig. 6. The resistivity of the sand was determined from method A and the moisture was measured by using the water weight content procedure. Then, for each resistivity, under positive and negative voltage polarities, the values of the resistance of several systems were measured following method A ($R_{experimental}$) and these values were compared to those determined by method B ($R_{calculated}$).

The results are presented in Table I.

The agreement calculation/experiment is very satisfactory and it validates the proposed method.

TABLE I
RESISTANCE COMPARISON: CALCULATION/EXPERIMENT

		$R_{experimental}$ (kΩ)		$R_{calculated}$ (kΩ)
configuration n°	ρ (Ωm)	*positive polarity*	*negative polarity*	
1	3600	48.5	48.9	49.2
2	3600	58.2	53.7	53.7
3	3600	55	57.4	56.1
1	1600	21.2	19.7	20.3
1	9200	135.2	x	131.2
1	15400	x	193.2	196.8

TABLE II
VALUES OF Ec DETERMINED BY SEVERAL AUTHORS

Reference	$\rho(\Omega.m)$	Ec ($kVcm^{-1}$)
Korsuntcev [4] *	470	12
	180	10
	100	8
Petropoulous [5] **	290	8.3
Bellashi [6] **	100	3
	75	2.2
	300	4.25
Liew and Darveniza [7] **	50	2
	60	0.5
	150	2
	300	0.5
IEEE Working Group [8]	***	10
CIGRE Lightning Performance [9]	***	4

(*) Korsuncev recommended theses values on the basis of tests done but he does not give any further references or descriptions regarding these tests.
(**) The value of Ec was chosen so that the theoretically predicted results best fitted the experimental results.
(***) Whatever value of resistivity

III. DETERMINATION OF THE DIELECTRIC STRENGTH

In this paper the dielectric strength of soils, noted Ec, is considered as the value of the electric field intensity, which causes breakdown under homogeneous field configuration.

In actual ground electrodes with inhomogeneous field distribution, Ec is the threshold over which the ionization phenomena start in the soil.

In the soils, the initiation of the discharge begins when the electric field becomes large enough to ionize the air present in the voids between the soil grains. Because of the field enhancement due to the irregular shape of the voids and the effect of the relatively large dielectric constant of the soil, the average field across the whole soil gap at the time of the breakdown inside the voids can be much smaller than the breakdown field in an equivalent air gap [1], [2]. It is clear that soils are compound materials, whose components have diverse conductivity and dielectric pemittivity, and then the electric field presents local enhancements around the electrodes.

Several researchers have determined the dielectric strength Ec for different soil resistivities.

Some of them have determined it experimentally, while others have treated it as a variable which is adjusted until the impulse impedance, described theoretically in terms of a uniform ionization zone surrounding the electrode, best fits the experimental results. Some values for Ec are listed in Table II.

Oettle [3], [11] suggested a power-law regression between soil resistivity ρ and dielectric strength Ec, giving

$$E_c = 241 \times \rho^{0.215} \tag{6}$$

where Ec is in $\mathrm{kVm^{-1}}$ and ρ in $\Omega \cdot \mathrm{m}$. This equation provides Ec values of 4 $\mathrm{kVcm^{-1}}$ for 10 $\Omega \cdot \mathrm{m}$ and 17.5 $\mathrm{kVcm^{-1}}$ for $10^4\ \Omega \cdot \mathrm{m}$.

In fact, a lot of disagreement subsists between authors. In an attempt to clarify the uncertainties regarding Ec, we propose a different experimental method to determine its value.

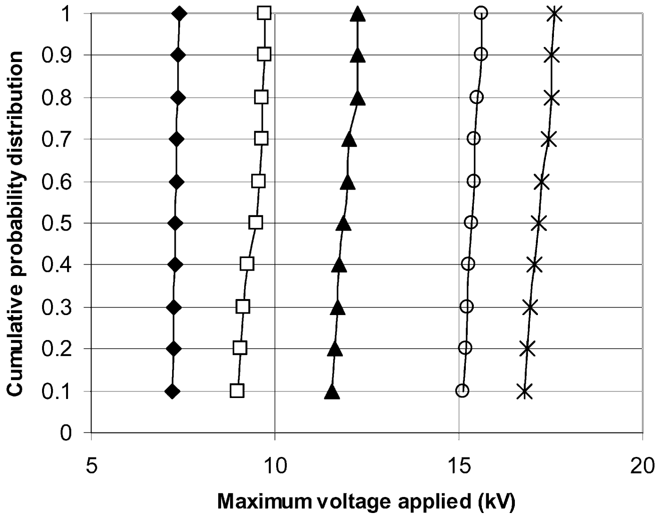

Fig. 7. Cumulative probability distribution $P(U_M)$ of the maximum applied voltage U_M, for different soil resistivities. ● 110 $\Omega \cdot m$, □ 1979 $\Omega \cdot m$, ▲ 5280 $\Omega \cdot m$, ○ 15 144 $\Omega \cdot m$, $*$ 100 000 $\Omega \cdot m$.

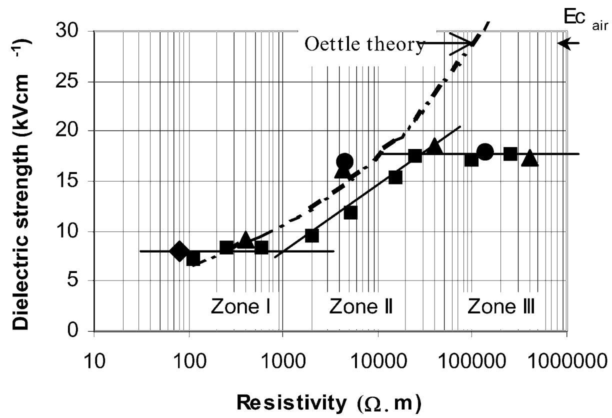

Fig. 8. Dielectric strength as a function of soil resistivity. ■ sand, ▲ mixture 50% sand/50% clay, ● clay, ♦ concrete, – – – Oettle theory.

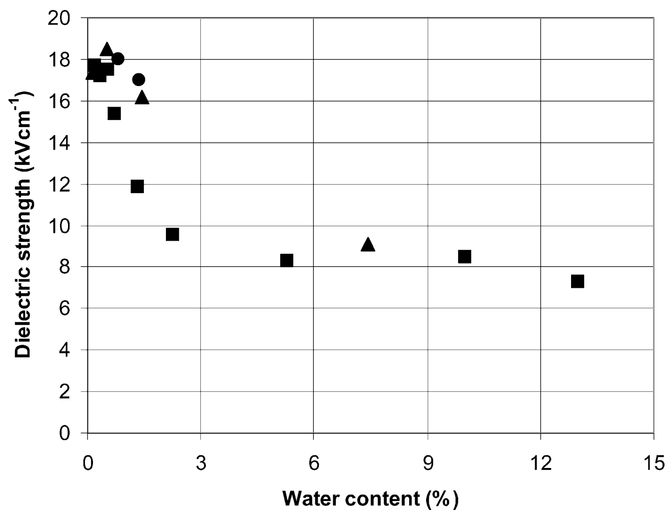

Fig. 9. Dielectric strength according to water content. ■ sand, ▲ mixture 50% sand/50% clay, ● clay.

A. Experimental Conditions

The dielectric strength of soils is a difficult parameter to be measured. It is not only greatly determined by the soil density, protrusions and voids, but it is also influenced by the applied wave shape and the statistical delay time. This delay time introduces errors in the experimental determination of Ec in inhomogeneous configurations. The advantage of our method is due to the construction of an homogeneous configuration specially designed to avoid boundary effects.

Thus, using a plane-to-plane gap configuration, breakdown occurs as soon as the geometrical field reaches the Ec value because the statistical delay time is minimized. The distance d between the two electrodes made of stainless steel is fixed at 1 cm. The field efficiency factor η, calculated as the ratio between the average electric field and the maximum electric field at the surface of the electrode, is equal to 0.96.

B. Experimental Determination of the Dielectric Strength

Fig. 7 illustrates the cumulative probability distribution P of the maximum applied voltage U_M for different soil resistivities.

Note that all the curves present a very low dispersion (for example, the standard deviation σ is equal to 0.1% for $\rho = 110\ \Omega \cdot m$), what means that the plane-to-plane configuration used in the experiment is homogeneous in agreement with the calculated value of the field efficiency factor.

The applied voltage Uc divided by the spacing d between the electrodes gives the value of the dielectric strength Ec

$$E_c = \frac{U_c}{d} \tag{7}$$

and Uc is defined for cumulative probability $P = 50\%$, $U_M = Uc$.

Experiments have been carried out under positive and negative polarities with the above-mentioned Marx generator. The effect of the soil resistivity on the dielectric strength was studied. The results of tests can be seen in Fig. 8, where the dielectric strength is presented as a function of soil resistivity.

From Figs. 6 and 8 we can deduce Fig. 9, the evolution of the dielectric strength according to the percentage of humidity.

It is important to note that Ec does not depend on polarity. Moreover, whatever the nature of the soil and its resistivity (from 100 up to 250 000 $\Omega \cdot m$), the value of the dielectric strength is always lower than approximately 30 $kVcm^{-1}$ as measured in air.

Besides, this value is not constant in the range of resistivity studied and the curve $Ec = f(\ln \rho)$ presents three quite distinct zones:

Zone I: For $100\ \Omega \cdot m < \rho < 1000\ \Omega \cdot m$, Ec is equal to 8 $kVcm^{-1}$: the diminution of the percentage of H_2O contained in soil, from 15% up to 4.6%, does not affect this value. It would seem that the soil is saturated with H_2O and initiatory electrons are present in large quantity.

Zone II: For $1000\ \Omega \cdot m < \rho < 25\,000\ \Omega \cdot m$, Ec varies linearly according to the logarithm of the resistivity. As a matter of fact, when the percentage of humidity becomes lower than 4% ($\rho > 1000\ \Omega \cdot m$), the initiatory electrons number decreases. Therefore, the value of the breakdown voltage increases just as the

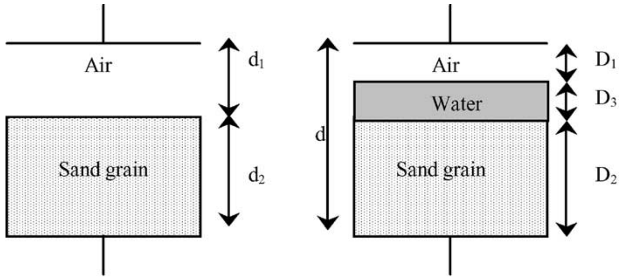

Fig. 10. Sketch showing sand grains for calculating the electric field. σ_1, σ_2 and σ_3 are, respectively, the conductivity for air, sand, and water.

value of Ec: 8 $\mathrm{kVcm^{-1}}$ for 1000 $\Omega \cdot \mathrm{m}$ and 17 $\mathrm{kVcm^{-1}}$ for 25 000 $\Omega \cdot \mathrm{m}$.

Zone III: For 25 000 $\Omega \cdot \mathrm{m} < \rho <$ 250 000 $\Omega \cdot \mathrm{m}$, Ec is constant, equal to 17 $\mathrm{kVcm^{-1}}$. For this zone the experimental results are completely different from the expected values of the Oettle's regression. A possible explanation is given in the following paragraph.

C. Analysis

Using the plane-to-plane type configuration both current and voltage impulses of the system, with and without sand, were measured under linear behavior. From the values of current, voltage and resistivity it was possible to estimate the capacitances of the system and then to deduce the dielectric permittivity of the sand. For example, when the measured sand resistivity was in the order of 400 $\Omega \cdot \mathrm{m}$, the calculated relative permittivity was equal to 23. When the sand resistivity increases up to 25 000 $\Omega \cdot \mathrm{m}$, relative permittivity decreases until 2. Measurements show a decreasing function between dielectric permittivity and resistivity of sand. Assuming the intrinsic time constant of the sand quite small compared with the front time of the impulse current, then the electric field distribution is determined by the resistivity rather than by the dielectric permittivity of the soil. In order to explain the variation of the dielectric strength for different resistivity, a simple model is proposed. It is based on the modification of the conductivity of the sand due to the presence of water.

Consider now the distance d between two fictitious electrodes and V the applied voltage. Fig. 10 shows the simple model used for calculating the electric field in the voids between the sand grains.

Combining the equations previously defined in Fig. 10, we can deduce the electric field in the voids between the sand grains:

– if $\rho > 25\,000\ \Omega \cdot \mathrm{m}$ (high resistivity sand)

$$e_1 = \frac{V}{d_1 + \frac{\sigma_1}{\sigma_2} \times d_2}; \tag{8}$$

– if $\rho < 1000\ \Omega \cdot \mathrm{m}$ (low resistivity sand)

$$E_1 = \frac{V}{D_1 + \frac{\sigma_1}{\sigma_2} \times D_2 + \frac{\sigma_1}{\sigma_3} \times D_3}. \tag{9}$$

Assuming the conductivity of the sand grains very low, equal to the conductivity of air ($\sigma_1 = \sigma_2$), (8) and (9) can be written as

$$e_1 = \frac{V}{d} \tag{10}$$

$$E_1 = \frac{V}{d - D_3 \times \left(1 - \frac{\sigma_1}{\sigma_3}\right)}. \tag{11}$$

As the conductivity of water is well above the conductivity of air ($\sigma_3 \gg \sigma_1$)

$$d - D_3 \times \left(1 - \frac{\sigma_1}{\sigma_3}\right) < d \tag{12}$$

hence, it may be deduced that

$$E_1 > e_1.$$

So, the presence of water on the surface of the sand grains would reinforce the local electric field in the voids between the grains, which would lead to decrease the breakdown voltage and therefore the dielectric strength Ec.

On the upper side of the curve, the saturation effect is produced by the low conductivity of the sand grain, in the order of the air conductivity, and, as shown by the field expression e_1, the dielectric strength is constant. The decrease in this dielectric strength, compared with the air value is due, perhaps, to the presence of protrusions and the in-homogeneities of the soil. The same interpretation may be applied for the clay and mixture sand/clay.

IV. Determination of the Inception Current

When the electric field at the surface of vertical earth electrode exceeds the dielectric strength Ec previously defined, discharge can develop into the soil. This discharge leads to a modification of the soil properties and the value of the transient impedance Z_t becomes lower than the resistance value R_t defined in linear condition. A circuital parameter related with the dielectric strength is the injected current that allows the initiation and development of soil discharges around the electrode, noted inception current Ic. It is then defined as the value of the injected current when the ratio Z_t/R_t becomes inferior to the unit value.

The objective of this section is to determine the relationship between inception current and dielectric strength, underlining how in earthing systems the use of the Ic value for calculating Ec leads to lower values when the inhomogeneous electric field distribution is neglected.

A. Experimental Determination of the Inception Current

Experiments were carried out under positive and negative polarities. Results for the configuration n°1 are presented in

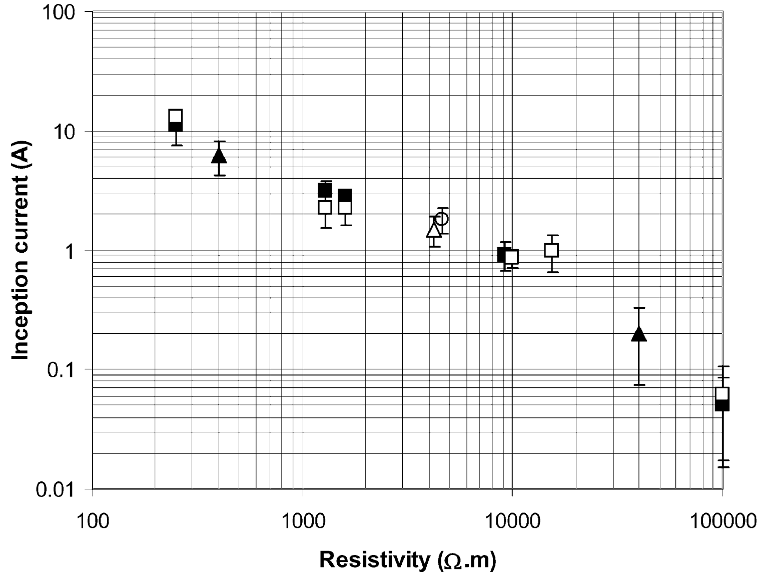

Fig. 11. Inception current according to soil resistivity (configuration n°1). ■ sand (positive polarity), □ sand (negative polarity) ▲ mixture 50% sand/50% clay (positive polarity), ▲ mixture 50% sand/50% clay (negative polarity), ◯ clay (negative polarity).

Fig. 11. The other configurations, tested with sand, present results in perfect agreement with this figure.

B. Theoretical Considerations

With a vertical ground rod, the critical current is usually deduced considering a uniform spark zone [3], [4] given by the formula derived from the Ohm's law at a point

$$I_c = \frac{S}{\rho} \times E_c. \tag{13}$$

When the potential is supposed to be equal to zero at the infinite, the current lines are perpendicular to the grounding electrode. Then, S represents its whole surface. In our experimentations, this formula is not valid because only the extremity of the vertical ground electrode will be active, and in general cases this equation should be used with precaution for calculating the dielectric strength, as later shown.

As a matter of fact, because of the presence of the plane electrode, the current lines are modified and concentrated at the tip of the vertical ground electrode. Then (13) becomes

$$I_c = \frac{S}{\rho} \times \overline{E} \tag{14}$$

where $\overline{E}$ is the mean electric field along the surface of the system, which produces inception current.

Let's study configuration $\mathrm{n}^\circ 1$ more precisely, when the soil resistivity is equal to $1600\,\Omega \cdot \mathrm{m}$. In such a condition, the inception current, I_c, is roughly equal to 2 A (Fig. 11). Then with the hypothesis of a uniform spark zone, from (14), we can deduce the value of the mean electric field $\overline{E}$ all along the grounding electrode

$$\overline{E} = 6.7\,\mathrm{kVcm}^{-1}.$$

Now, the mean electric strength is computed from the distribution of the electric field along the surface of the h-v electrode, at the ionization voltage, by using the finite element software (see Fig. 12). From this curve, by surface integration all along the electrode, we can calculate the average electric field $\overline{E_\mathrm{t}}$

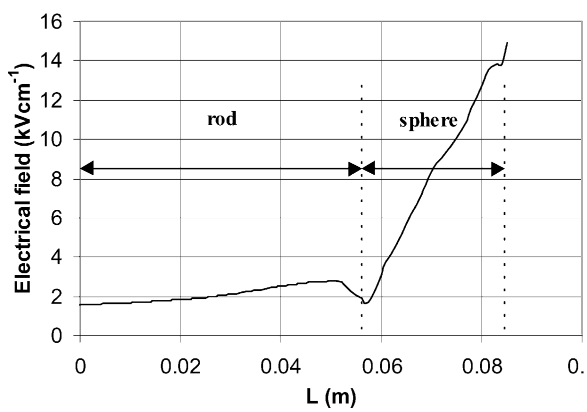

Fig. 12. Distribution of the electric field along the surface of the h-v electrode $(\mathrm{configuration\ n}^\circ 1 - \rho = 1600\ \Omega \cdot \mathrm{m} - \mathrm{U} = 48\ \mathrm{kV})$.

$$\overline{E_\mathrm{t}} = \frac{1}{\overline{S}} \int E(x)dx \text{ and } \overline{S} = \int \pi r^2(x)dx. \tag{15}$$

This computed value $\overline{E_\mathrm{t}}$ is 5,6 kVcm^{-1}. The critical current deduced from (14) and $\overline{E_\mathrm{t}}$ is 1.7 A, which is also in good agreement with the experimental result.

The average electric field value $\overline{E_\mathrm{t}}$ so calculated is some what smaller than the mean value $\overline{E}$ and quite lower than the measured Ec under uniform field condition, as shown in Fig. 8. Note that the calculated maximum electric field on the sphere tip is close to 15 kVcm^{-1}. The obtained difference explains how the electric field strength values presented in the literature (see Table II), several of them calculated from driven rods, could be lower than the dielectric strength in the soil Ec, when the ionization begins in high electric field zones, as the electrode tip. It is expected that this effect would be more marked as long as the nonuniform field distribution zone on the electrode surface increases.

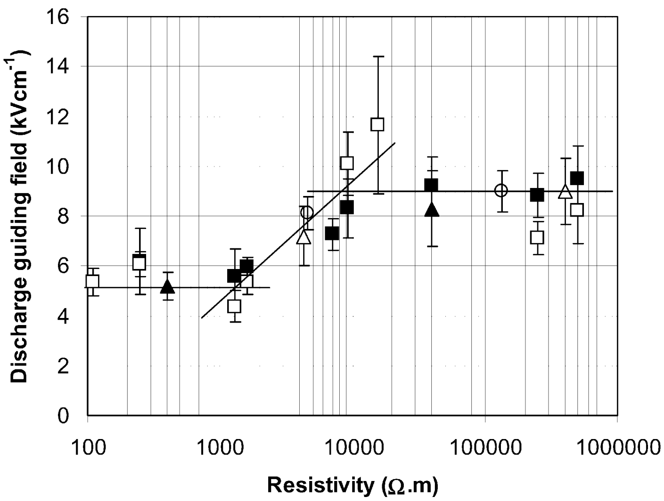

Fig. 13. Discharge-guiding field Ep according to the resistivity of the soil (configuration n°1). ■ sand (positive polarity), □ sand (negative polarity) ▲ mixture 50% sand/50% clay (positive polarity), △ mixture 50% sand/50% clay (negative polarity), ○ clay (negative polarity).

TABLE III
DISCHARGE-GUIDING FIELD Ep ($kVcm^{-1}$) FOR THE CONFIGURATIONS OF THE SYSTEM AND $\rho = 250\ \Omega \cdot m$

Configuration	Positive polarity	Negative polarity
n°1	6.2	6.1
n°2	4.5	4.3
n°3	3.6	3.4

V. DETERMINATION OF THE DISCHARGE-GUIDING FIELD

In this paper, the discharge-guiding field is defined as the minimal average field necessary for the discharge to cross the gap under inhomogeneous electric field configuration. The discharge-guiding field is useful for defining the ionized zone around the electrode in order to develop models to predict the variation of resistance with time for impulse currents [7], [10].

Using a plane-to-plane gap, breakdown occurs as soon as the geometrical field reaches the Ec value. Then, the breakdown is direct and we are not able to differentiate positive discharge from negative one and therefore to determine the discharge-guiding field in both polarities. So, it is necessary to work with an inhomogeneous field configuration. The three experimental configurations previously defined were used.

The method consists in creating a discharge, which has energy hardly sufficient to cross the gap. Then, the applied voltage divided by the spacing between the electrodes gives an approximate value of the discharge-guiding field.

But if the energy injected into the gap is too high, it means that the discharge could propagate farther. In such a case, the discharge field's value can be very optimistic if some precautions are not taken.

Fig. 13 represents the discharge-guiding field according to the resistivity of several soils, for both polarities and using configuration n°1. The uncertainties were calculated for 2σ.

This curve shows that the value of the discharge-guiding field is roughly the same under positive and negative polarities, but depends on the soil resistivity under consideration. Besides, it is important to note that the discharge-guiding field presents the same evolution as the dielectric strength. The explanation could be the afore mentioned. As a matter of fact, the presence of water should decrease the voltage inception, and therefore the discharge-guiding field also decreases.

The discharge-guiding field also depends on the studied system geometry. This result could be explained considering the different electric field distribution in each configuration. Some experimental data are given in Table III.

VI. CONCLUSIONS

In order to adopt some critical parameters as inception current, dielectric strength and discharge-guiding field of electrical discharges in resistive soils, a useful experimental data set was presented.

Experimental and computational procedures for determining these parameters were described in order to assure repeatability and comparison with other soils and grounding systems.

Linearity of sand resistance and nonlinearity of concrete resistance were put in evidence for strong electric fields.

An experimental method to determine the value of the dielectric strength Ec in different soils was proposed. Ec is found to be a function of resistivity of the soil (i.e., a function of water content of the soil), varying from about 8 $kVcm^{-1}$ to 17 $kVcm^{-1}$, for resistivity between 50 and 500 000 Ωm. The feature of Ec as a function of soil resistivity presents three distinct zones with like saturation effect for low and high resistivity.

An interpretation of the role of water has been proposed explaining the effect on dielectric strength, under positive and negative impulse polarity. The presence of water into the sand would reinforce the electric field in the voids between the sand grains so that breakdown voltage would occur at lower voltage level. This interpretation is in agreement with the saturation feature measured for the dielectric strength and the discharge-guiding field, as a function of the soil resistivity.

The knowledge of these critical parameters will constitute a necessary basis in order to design grounding systems for high surge currents where the transient reduction of resistance becomes significant.

REFERENCES

[1] T. M. Flanagan, C. E. Mallon, R. Denson, and Smith, "Electrical breakdown properties of soil," *IEEE Trans. Nucl. Sci.*, vol. NS-29, no. 6, pp. 1887–1890, 1981.

[2] R. E. Leadon, T. M. Flanagan, C. E. Mallon, and R. Denson, "Effect of ambient gas on arc initiation characteristics in soil," *IEEE Trans. Nucl. Sci.*, vol. NS-30, no. 6, pp. 4572–4576, 1983.

[3] E. E. Oettlé, "A new general estimation curve for predicting the impulse impedance of concentrated earth electrodes," *IEEE Trans. Power Delivery*, vol. 3, pp. 2020–2029, Oct. 1988.

[4] A. V. Korsuncev, "Application of the theory of similitude to the calculation of concentrated earth electrodes," *Elektrichestvo*, no. 5, pp. 31–35, May 1958.

[5] G. M. Petropoulos, "The high voltage characteristics of earth resistances," *Proc. Inst. Elect. Eng.*, pt. II, vol. 95, pp. 59–70, 1948.

[6] P. L. Bellashi, "Impulse and 60-cycle characteristics of driven grounds," *AIEE Trans.*, vol. 60, pp. 123–128, 1941.

[7] A. C. Liew and M. Darveniza, "Dynamic model of impulse characteristics of concentrated earth," *Proc. Inst. Elect. Eng.*, vol. 121, no. 2, pp. 123–135, 1974.

[8] "Estimation Lightning Performance of Transmission Lines II – Updates Analytical Models," IEEE Working Group, IEEE Paper 92 SM 453-1 PWRD, 1992.

[9] *Guides to Procedures for Estimating the Lightning Performance of Transmission Lines*, CIGRE Working Group on Lightning, Paris, France, 1991.

[10] A. M. Mousa, "The soil ionization gradient associated with discharge of high currents into concentrated electrodes," *IEEE Trans. Power Delivery*, vol. 9, pp. 1669–1677, July 1994.

[11] W. Chisholm and W. Janischewskyj, "Lightning surge response of ground electrodes," *IEEE Trans. Power Delivery*, vol. 4, pp. 1329–1337, Apr. 1989.

[12] S. Bourg, B. Sacepe, and T. Debu, "Deep earth electrodes in highly resistive ground: Frequency behavior," in *Proc. IEEE Int. Symp. EMC*, Aug. 1995.

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