# Soil ionisation under lightning impulse voltages

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**Abstract:** Experiments have been carried out to study soil ionisation and the variation of the critical ionisation gradient against the soil resistivity. Compared with relevant experimental results of other researchers a satisfactory convergence has been proved. An accurate estimation of the critical ionisation gradient has been achieved, of the order of 200 kV/m, following the finding that the critical voltage gradient for wet soil decreases to approximately 35% of the corresponding value for dry soil.

## 1 Introduction

It has been known for years that the value of soil resistivity drops when a discharge of high impulse current is injected [1, 2]. This helps in reducing the value of the ground resistance of the system embedded in soil [3–5], and of course helps in reducing the transient ground-potential rise on the surface of the ground. Soil is not a homogeneous medium. This inhomogenity is caused by the variation of the moisture of the soil, the variation in grain size, and the existence of organic and or inorganic material and rubble [2].

A large number of measurements of the ground resistance have been carried out using high impulse current for many decades; these measurements result in values considerably lower than those measured by the methods based on the use of weak alternating current. This fact was first stated by Towne in 1929 [6]. His measurements were carried out on a loose gravel soil with unknown moisture; the critical soil ionisation gradient was in the range 160–520 kV/m. The critical soil ionisation gradient was calculated in the range 120–420 kV/m in 1941 and 1942 by the tests of Bellaschi *et al*. [3, 4]. In 1948 Petropoulos [1], in 1953 Armstrong [7], in 1974 Liew and Darveniza [8], and in 1978 Dick *et al.* [9] carried out a large number of resistance measurements under high current discharge conditions. The tests have been used by Mousa [2] for the calculation of the critical voltage gradient of the soil.

Loboda *et al.* [10–12] presented the results of experimental investigations concerning the electrical properties of different soils injected with current pulses. The critical soil ionisation gradient was calculated to be in the range 560–900 kV/m. Electrical breakdown characteristics of resistive soil have been studied in an inhomogeneous field by Espel *et al.* [13]. The critical soil ionisation gradient was found to be in the range 800–1700 kV/m.

A series of experimental tests was performed by Liew and Darveniza [8], their object being limited to the provision of reliable data for the development and the verification of the model proposed by them. Three types of soil (clay, sand and gravel) and two types of grounding system (driven rod and hemispherical electrode) were chosen; the critical soil ionisation gradient was found to be approximately 300 kV/m [8].

A new general estimation curve for predicting the impulse impedance of concentrated earth electrodes has been published by Oettle [14] and Chisholm *et al.* [15]. In the impulse tests of Oettle, which covered several types of soil, the critical soil ionisation gradient was found to be 600 and 1850 kV/m for wet and dry soil, respectively [14]. Under thunderstorm conditions, rain would take place and the moisture content of the soil will generally be high and the critical soil ionisation gradient was found to be in the range 600–800 kV/m [2]. The inhomogenity of the soil in the laboratory tests is smaller than outdoors because the samples are made with sifted soil, which has the water in it reasonably well mixed. Therefore the critical soil ionisation gradient was deduced to have fallen to approximately 50% of the previously mentioned values and to be in the range 300–400 kV/m [2].

Mousa [2] has estimated that the critical soil ionisation gradient is equal to 300 kV/m by using a large number of reliable impulse resistance measurements carried out by several researchers. The value of 400 kV/m is used by CIGRE [16] without any other explanation. The current IEEE method for calculating the lightning tripout rates of power lines [17] does not take soil ionisation into consideration. An IEEE working group [18] does not recommend a value and only quotes the 1000 kV/m value suggested by Oettle [14].

## 2 Test arrangements

When the voltage gradient in the soil becomes greater than the critical soil ionisation gradient, it causes a change in the behaviour of the soil; i.e. the value of the soil resistivity and the value of the grounding system resistance decrease. For studying this behaviour the test arrangement presented in Fig. 1 has been used. It includes a two-stage high impulse voltage generator with a charging capacity of up to 100 kV and with energy of up to 245 Ws per stage constructed by Messwandler-Bau GmbH, Bamberg. The control apparatus and measuring instruments (fast transient digitiser, Yokogawa DL1540 oscilloscope, peak voltmeter, etc.) are placed in a Faraday cage with a 50 dB signal attenuation up to 1 GHz. A high-frequency rejection filter and an isolating transformer shield the power supply of the instruments from noise and disturbances. The mains supply is regulated to a constant value of $230 \pm 0.1$ V AC, 50 Hz by means of a voltage stabiliser. The elements of the generator and of the



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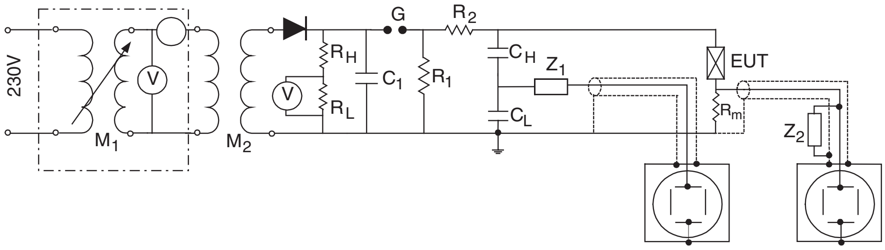



**Fig. 1** *Test and measuring arrangement*

measuring system were $R_1 = R_2 = 500\,\mathrm{k\Omega}$, $R_H = 140\,\mathrm{M\Omega}$, $R_L = 3.86\,\mathrm{k\Omega}$, $C_I = 6000\,\mathrm{pF}$, $R_I = 9.5\,\mathrm{k\Omega}$, $R_2 = 416\,\Omega$, $C_H = 1200\,\mathrm{pF}$, $C_L = 485\,\mathrm{nF}$ and $Z_1 = Z_2 = 75\,\Omega$.

A typical test sample (EUT in Fig. 1) used in this investigation consisted of soil filling the intermediate volume between two coaxial cylinders, positioned vertically. The bases (top and bottom) of the external cylinder were round insulating plates. The inner cylinder had the form of a thin conductor fixed between the centres of the outer cylinder bases. The resistance $R$ of the test arrangement was measured using an ohmmeter. The resistivity of the soil was calculated by means of the following equation [12]:

$$\rho = \frac{2\pi \ell R}{\ln \frac{r_{out}}{r_{in}}} \tag{1}$$

where $\ell$ is the effective length of the sample (equal to the height of the filled cylinder), $r_{out}$ is the inner radius of the outer cylinder and $r_{in}$ is the radius of the inner conductor.

Measurements were carried out in the High-Voltage Laboratory of the National Technical University of Athens. Before the voltage application the resistance $R$ was measured to provide the soil resistivity $\rho$ according to (1). Thereafter, by keeping constant the spacing of the sphere gap $G$, the charging voltage of the capacitor $C_1$ was gradually increased up to the breakdown of this sphere gap $G$, Fig. 1. The current and voltage curves were shown on the oscilloscope and recorded in digital form. In the case whenever ionisation phenomenon did not occur for a particular gap spacing the charging voltage as well as the gap spacing were gradually increased, providing an impulse voltage and impulse current of greater amplitude. This procedure was carried out repeatedly until the oscillograms indicated the presence of soil ionisation. At that point the required slight adjustment of the sphere gap spacing were undertaken to detect an accurate value of impulse voltage (and consequently of the impulse current) for which soil ionisation appeared.

After the experimental determination of the voltage and current values for which ionisation in dry soil appeared, the process was continued with the addition of a certain amount of water to the soil. Water was dispersed into the whole quantity of soil, measurement of the new resistance $R'$ and the calculation of the respective (new) resistivity $\rho'$ made, and a new procedure of voltage application, as described for the dry sample, carried out to define the value of impulse voltage (and consequently impulse current) for which ionisation in the wet soil occured.

## 3 Experimental results

It is well known that the soil ionisation gradient $E$ is given by

$$E = \rho j \tag{2}$$

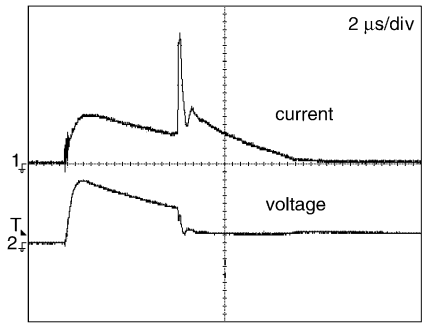
where the current density $j$ is

$$j = \frac{i}{S} \Leftrightarrow j = \frac{i}{2\pi r_{out}\ell} \tag{3}$$

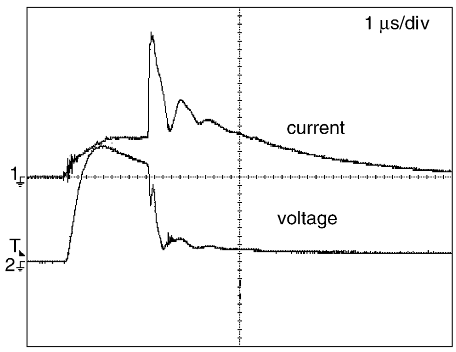
By introducing the critical current density $j_c$ obtained through (3), which exists due to the critical current $i_c$ (ionisation current), the soil ionisation gradient $E_c$ (i.e. the critical ionisation gradient) can be calculated as

$$E_c = \frac{\rho i_c}{2\pi r_{out}\ell} \tag{4}$$

Based on the proposed method for calculating the critical ionisation gradient, a number of tests and measurements were carried out to evaluate that phenomenon. Figure 2 presents oscillograms indicating the appearance of ionisation in soil. The upper waveform of each oscillogram (channel 1) refers to the current waveform, while the waveform beneath (channel 2) refers to the voltage waveform. To evaluate the voltage applied to the sample the ratio ($K = 405$) of the capacitive voltage divider ($C_H$, $C_L$) must be taken into account, whereas the impulse current can be estimated by using the upper curve of the oscillogram and the value of the measuring resistance $R_m$ (0.9917, 0.5028, 0.25, 0.04971Ω,), see Fig. 1. Ionisation is




*a*




*b*

**Fig. 2** *Impulse current and voltage from soil ionisation*
*a* Dry soil
*b* Wet soil

obvious by the rapid increase of current and corresponding decrease of voltage; thus, during the ionisation a significant decrease of soil resistivity occurs.

## 4 Test results-discussion

The resistivity of the dry soil used ranged from 1300 Ωm (soil type A) to 1000 Ωm (soil type B). The addition of water into the dry soil results, obviously, in the reduction of the soil resistivity; in this way the soil resistivity decreased even to 150 Ωm.

The variation of critical ionisation gradient against soil resistivity for two different kinds of soil (A and B) is presented in Fig. 3. The critical soil ionisation gradient was found to be in the range 350–1300 kV/cm. These values are similar with the values of Espel *et al.* [13] for equivalent soil resistivity. No direct correlation exists between critical ionisation gradient and soil resistivity because the resistivity is also dependent on the amount of salt in the soil [2].

The resistivity of each different type of soil was changed with the addition of tap water. The results of the experimental tests show that the decrease of soil resistivity with the addition of water reduces the value of the critical ionisation gradient.

Figure 4 investigates the dependence of the ratio between the critical soil ionisation gradients (wet to dry soil) for several kinds of soil on the ratio of soil resistivities (wet to dry soil). A comparison has also been performed with the corresponding experimental results of Flanagan *et al.* for other kinds of soil (SVBO and DWP25) [2, 19]. It is shown that the decrease in the ratio of soil resistivities is greater than the decrease in the ratio of the corresponding critical ionisation gradients. The experiments that had been carried out in the laboratory present a smaller ratio of critical ionisation gradients for the same ratio of soil resistivities in comparison with the experiments of Flanagan *et al.* [2, 19]. This is probably due to the different characteristics of the soil tested by the researchers (soils used by Flanagan *et al.* had generally a significantly higher resistivity than the soils used during the experiments presented here).

The critical ionisation gradient of the wet soil has been calculated by Flanagan [19] as approximately 60% of the corresponding value of the dry soil. In our experiments a stronger decrease in critical ionisation gradient has been found; the critical ionisation gradient for wet soil is around 35% of the corresponding value for dry soil.

Many disagreements subsist between values determined by various researchers [1–15]. The majority of values of critical ionisation gradient for different kinds of soil are in the interval between 600 and 1000 kV/m [14]. This range of values has been also used by other researchers [2] with the estimation that in wet soil the critical ionisation gradient appears to be half of the corresponding value in dry soil, resulting in an estimation of a critical ionisation gradient of approximately 300 kV/m. The finding presented in this paper (a decrease to 35%) is useful as a significantly more accurate estimation of the critical ionisation gradient, which can decrease to values of 200 kV/m. An optimistic estimation of critical ionisation gradient could be dangerous if used in the design of every grounding system. But knowledge of the exact value of each soil is very useful since it allows material and cost saving in the erection of grounding systems. For this reason it is necessary to investigate more soils.

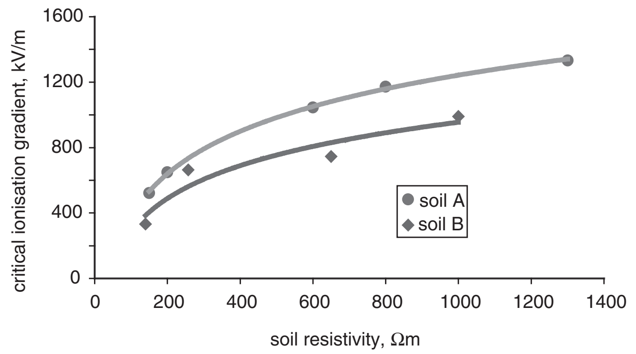



**Fig. 3** *Variation of critical ionisation gradient against the soil resistivity*

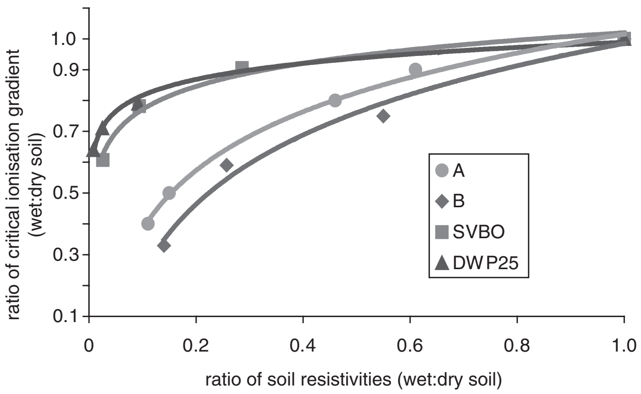



**Fig. 4** *Variation of ratio of critical ionisation gradient (wet:dry soil) against ratio of soil resistivities (wet:dry soil)*

## 5 Conclusions

The variation in the ratio of critical ionisation gradients against the ratio of resistivities (wet/dry soil) has been studied in the experiments presented, which have been carried out to study the critical soil ionisation different kinds of soil and different resistivies. It has been found that the decrease rate in the ratio of critical ionisation gradients is substantial, as expected, but less than the rate of decrease in the ratio of soil resistivities.

A satisfactory comparison has been, made with the relevant experimental results of other researchers for different kinds of soil. It was ascertained that the critical ionisation gradient for wet soil decreases to 35% of the corresponding value for dry soil. This finding is a significantly more accurate estimation of the critical ionisation gradient which can decrease to values of 200 kV/m. This knowledge is useful since it allows material and cost saving in the erection of grounding systems.

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