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Review

# Methodologies for determination of soil ionization gradient

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ABSTRACT

In this paper the results of the research being carried out on the impulse characteristics of soils and more specifically the ionization voltage gradient are presented. The determination of the soil ionization voltage and the respective gradient using a universally accepted method is yet to be established. Aiming at meeting this need, the present paper critically presents these methods and records the ionization gradient values for soil types, which have derived from different experimental approaches. The comprehensive study of these methods is intended to serve as a guide for researchers studying the nonlinear phenomena developed in the soil.

## 1. Introduction

Soil is a non-compact multiphase material consisting of solid grains including gaps containing liquid (usually water) and/or gas (usually air). Soil conductivity is influenced primarily by water and salts dissolved in it, while the grain size affects the intensity of the electric field, which is developed between soil grains when voltage is applied. Moreover, soil conductivity is the major parameter which determines the value of the ground resistance in steady state and the transient behavior of any grounding system. Since purpose of the grounding system is to provide a low impedance path to impulse and fault currents and to protect human life and electrical and electronic equipment, the behavior of the grounding system under steady state conditions as well as transients is under investigation. Although there are no dark points regarding the steady state behavior, many aspects of transient behavior are obscure and in need of further study. This can be attributed to the electrical behavior of the soil.

Towne [1] was the first who noticed decrease of the impulse impedance of concentrated grounding systems. This was attributed to the onset of ionization phenomena developed around the grounding system, which beneficially reduce the impulse impedance. When the electric field, which develops between the soil grains, exceeds a critical value, electric discharges appear in the vicinity of the electrode and short-circuit the region around the electrode. In literature two mechanisms have been proposed in order to describe the phenomena developed in the soil under surge conditions. The first one is the thermal mechanism introduced by Erler and Snowden [2] and the second one is the ionization of the air trapped between grains (Leadon et al. [3]). As stated by Nor and Ramli [4], the two mechanisms co-exist and their discrimination depends on the amount of absorbed energy. Furthermore, it is difficult to discriminate one from the other. However, the scientific community accepts that the prevailing mechanism is the ionization of the air, therefore, the critical value is named ionization gradient ($E_o$) and the corresponding voltage, ionization voltage ($V_o$).

Due to the influence of the development of such discharges in the soil, which influence the transient behavior of grounding systems, many researchers have contributed in the experimental investigation of ionization, proposing models and defining the parameters of the models. This paper aims to enrich and extend the reviews, which have already been published [5,6], giving an updated review of the work on issues of soil ionization. The comprehensive guide, provided here, will be proven to be useful for those studying the nonlinear phenomena developed in the soil and addressing questions regarding the experimental approaches for the determination of the ionization voltage and the calculation methods of voltage gradient ($E_o$), which have not been hitherto gathered and presented.

Utter purpose of this review is to shed light into the advantages and drawbacks of the methods, highlight the difficulties regarding

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the calculation of the critical voltage gradient and underline the necessity for further research on the subject and the establishment of a specific method for determining the ionization voltage and estimating $E_o$.

The rest of the paper is organized as follows: firstly, the methods for determining the voltage level above which ionization occurs are presented. Following, the methodologies for calculating the critical electric ionization are analyzed and their adequacy for the calculation of the critical value is examined. Moreover, representative values of ionization gradient are recorded. The last paragraph concludes the paper.

## 2. Determination of the ionization voltage

The first step in order to estimate the ionization gradient ($E_o$) is the measurement of the corresponding voltage ($V_o$) and current. The following methods have been recorded in the literature:

- V–I characteristic: As already mentioned, Towne [1] experimented on impulse characteristics of concentrated electrodes and produced V–I characteristics which form loops. Based on that observation Kalat et al. [7], Lee et al. [8], Nor [9], Lima and Visacro [10], and Asimakopoulou et al. [11] defined the ionization voltage as the level above which V–I curves start to form loops in the form of inclined “8”.
- Behavior of impulse impedance *Z*(t): Petropoulos [12] used impulse voltage and current measurements and plotted the variation of impulse impedance with the applied voltage. Given the 50 cycle resistance of the soil samples, the ionization or starting voltage is considered as the voltage level, which, when exceeded, the impulse resistance is lower than the steady state resistance.

  A similar approach, which is based on the impulse impedance of the soil sample, has been followed by Lima and Visacro [10]. The researchers plotted the *Z*(t) characteristic for various voltage levels. While voltage increases and ionization proceeds, the shape of *Z*(t) differs from the low voltage level characteristic. The voltage level at which the waveform starts to differentiate is the ionization voltage.
- Time lag between peaks of impulse current and voltage: Loboda and Scuka [13] performed experiments on different soil types placed in a coaxial configuration by applying impulse currents of increasing peak value. They observed that the peak of the voltage waveform and the peak of the impulse current waveform do not occur simultaneously. Moreover, they noticed that as higher impulse currents were applied, the current front time increased while the voltage front time remained constant. This behavior of the samples was attributed to the ionization of the soil. According to Loboda and Scuka the increase in time difference between current and voltage peaks is as an indication of the onset of ionization and can be used for estimating the critical current density and, consequently, the critical ionization gradient.
- Second peak in current waveform: In [8] [14,15], the researchers conducted laboratory experiments on sandy soil samples with various water contents and suggest that the voltage level which corresponds to initiation of ionization can be identified by the second peak in the current waveform. This conclusion however does not apply on soil media with high conductivity, as reported in [14] and [15]. Therefore, the applicability of this methodology is limited.
- Breakdown voltage: In case the gap between high voltage electrode and ground electrode is very short and the electric field is uniform, the breakdown can be easily identified by the voltage and current waveform as a sudden increase in current accompanied by a fall in voltage. In the case of a uniform field, the ionization gradient is considered to be the same with the breakdown gradient [14,16–19]. When conducting experiments by using configurations that produce uniform electric field, as long as the ionization level is reached, instantaneous breakdown occurs [14,16,17]. As a result, the determination of the ionization voltage coincides with the measurement of the breakdown voltage according to standard methods [20].

From these studies it is clear that numerous approaches have been made, however a unique method has not yet been adopted by the scientific community.

The methods which are based on recording the voltage and current waveforms have the disadvantage that -in the case of high resistivity soils- limited charging capacity of the impulse generator results in negligible current, which prohibits further application of the methods. Moreover, these methods are sensitive with respect to the voltage step, which is applied during the determination of the ionization voltage. Regarding the method of the second current peak, as stated by the introducers of the method, it has limited applicability on highly wetted sand due to the presence of water between the soil grains which does allow the development of ionization.

The last method, according to which the ionization voltage is related to 50% breakdown voltage of soil samples placed in uniform field configurations, has the advantage that is performed according to a standard procedure [20]. However, these conditions do not simulate measurements of real grounding system installations, where the field is highly non-uniform.

Apart from the methodology for the determination of the critical voltage, little information is available on parameters such as soil compaction of the soil sample. He et al. [18] have proved that critical voltage of highly compressed soil samples is higher than that for soil sample with lower density, while little information is available on the preparation of the soil samples.

Therefore, it is recommended that these methods be compared by applying them on the same soil sample. Their reliability should be examined by estimating the uncertainty of measured ionization voltage, while the applicability of each method as well as the demand in equipment and time should be taken into consideration before adopting one of the methods for general use.

## 3. Ionization voltage gradient calculation

The critical ionization gradient ($E_o$) is defined as the field intensity which leads to the formation of the streamer/spark zone around the electrode. Depending on the type of impulse experiments (field of laboratory measurements) the researchers have used different approaches for estimating $E_o$. These approaches are described in the following paragraphs.

### *3.1. Ohm’s law*

Bellaschi [21], Bellaschi et al. [22] and Armstrong [23] plotted the ratio of impulse impedance to steady state resistance against the logarithm of the current. From the point of unity-resistance-ratio the critical current is obtained. Given the configuration of the electrodes and the resistivity of the soil sample, $E_o$ is calculated by Ohm’s law assuming uniform ionization zone.

Mousa [6] and Loboda and Scuka [13] determined the critical ionization gradient as follows: for the critical voltage level firstly, the minimum impulse impedance is estimated by using voltage and current waveforms. The equivalent radius of the ionization zone is calculated. Then the current density at the surface of the ionized zone is calculated and $E_o$ is obtained by applying Ohm’s law. Liu et al. [24] use the resistance at peak current (since the derivative of current equals zero, the inductance of the grounding system is omitted). In a variation of this method, Loboda and Pochanke [25] use the instant value of voltage that occurs at peak current for the calculation of the ionization radius. As representative value for the impulse impedance, Oettle [26] proposes the ratio of the electrode voltage at 6 μs to the current at 6 μs. Lima and Visacro [10] use the impedance at 9 μs and the impedance at the lowest applied voltage level at the critical voltage level.

The selection of the minimum impedance for the calculation of the extend of the ionization area is justified by the fact that at the moment of minimum impulse impedance the ionization reaches its maximum extent. Therefore, it is considered to be less arbitrary in comparison to the selection of the impulse impedance at the 6 or 9 μs.

Drawback of the above mentioned approaches is the fact that they are based on the assumption that the ionization radius expands uniformly around the high voltage electrode and that the resistivity of the ionization area is negligible. Although the assumption of zero resistivity of the ionization area simplifies the calculations, the model proposed by Liew and Darveniza [27] is more realistic. Loboda and Scuka [13] compared the difference in ionization gradient introduced by neglecting the residual resistivity. In order to take into account the resistivity of the ionized zone, they determined the critical current density on the electrode surface indicated by the time delay between voltage and current peak, which is observed when non-linear phenomena are developed in the soil [13]. The results show that, when considering the residual resistivity the ionization gradient is higher.

In order to estimate the residual resistivity of the ionized zone, Liu et al. [24] considered the average value of the electric field on the surface of the high voltage electrode just before the onset of ionization and the resistance at peak current. The resistance comprises that of the ionized area and that of the non-ionized area. Given the electrodes' geometry, the radius of ionization area and its corresponding resistivity are calculated with minimal effort. Liu et al. [24] concluded that the resistivity of the ionization area is 3–8% of the steady state value. However, these estimations were made by using given values of $E_o$.

Asimakopoulou et al. [11] used a genetic algorithm approach in order to determine the ionization radius as well as the residual resistivity. Thus, previous knowledge of the ionization voltage gradient is not necessary.

### 3.2. Breakdown voltage

In parallel plate configuration the estimation of the ionization gradient is very simple: it is calculated as the 50% breakdown voltage divided by spacing between the electrodes.

In Table 1 the experimental configurations, the soil type and the soil resistivity ($\rho$), being used by various researchers for the determination of the ionization voltage gradient ($E_o$), are presented. These values result from high impulse experiments conducted in field (denoted by the letter F) or in laboratories (denoted by the letter L). As it can be easily seen, the majority of the experiments has been carried out in laboratories under controllable conditions using small soil samples, which are easier to be handled. In addition, the soil samples being used in laboratory experiments are usually sifted in order for foreign materials to be removed while the water is uniformly distributed after careful mixing. In real grounding systems, the surrounding soil is inhomogeneous and contains organic materials and other foreign materials. Therefore, it is imperative that more field experiments be conducted in different

**Table 1**
Summary of soil ionization experiments.

| Researcher | Experiments | Configuration | Soil type | $\rho$ (Ωm) | $E_0$ (kV/m) |
|---|---|---|---|---|---|
| Towne [1] | F | Rods | Gravel | 130–686 | 29–104 |
| Bellaschi [21] | F | Rods | Shale, clay | 90–150 | 2250–4100 |
| Bellaschi et al. [22] | F | Rods | Gravel, sand | 70–290 | 127–424 |
| Liew and Darveniza [27] | F | Rods | Sand, clay, gravel | 50–540 | 110–300 |
| Dick et al. [6,32] | F | Rods | – | 12–25 | 13–221 |
| Geri [33] | F | Rods, Horizontal wire | Agricultural soil | – | 30–800 |
| Asaoka et al. [28] | F | Rods | Sand | 487 | 1040 |
| | | | Mud | 228 | 1330 |
| | | | Gravel | 2059 | 1430 |
| | | | Mud | 365 | 1240 |
| Norinder [12] | L | Cylindrical | Vegetal clay, red clay | – | 327–360 |
| Berger [12] | L | Hemispheres | – | 1000 | 497–537 |
| Petropoulos [12] | L | Hemispheres | Calcinary | 290 | 830 |
| Armstrong [23] | L | Rods | Sand, clay | 52–495 | 330–480 |
| Korsuntcev [26] | L | Cylindrical | | 100–470 | 800–1200 |
| Loboda and Pochanke [25] | L | Cylindrical | Sand, clay, humus | 30–750 | 150–500 |
| Loboda and Scuka [13] | L | Cylindrical | Sand, clay, organic soil | 40–2150 | 560–900 |
| Liu et al. [24] | L | Hemispherical | Sand mixed with salt | 174–827 | 328–516 |
| Espel et al. [17] | L | Parallel discs | | <1000 | 800 |
| | | | | 1000–25,000 | 800–1700 |
| | | | | >25000 | 1700 |
| Lima and Visacro [10] | L | Parallel discs<br>Cylindrical | 4 different soil types with different moisture content | 80–10000 | 370–1440<br>312–882 |
| Lee et al. [8] | L | Hemispherical | Sand | 134.3–336.5 | 1020–1650 |
| Nor et al. [14] | L | Hemispherical | Sand | 2.7–5.5 | 520–660 |
| Asimakopoulou et al. [19] | L | Parallel discs | Clay | – | 767–984 |
| Asimakopoulou et al. [11] | L | Cylindrical | | 400–880 | 660–938 |
| Flanagan et al. [34] | L | Parallel discs | Soil | – | 2700–3000 |
| Dabkowski [16] | L | Parallel discs | Sand | – | 720–810 |
| Oettle [37] | L | Parallel discs | Sand, red clay, black clay, mixture | | 600–1850 |
| He et al. [18] | L | Spherical cupreous electrodes | Sand, clay, sand-clay, humus | – | 300–1700 |
| Nor et al. [14] | L | Parallel discs | Sand | 2.7–5.5 | 790–900 |
| Manna and Chowdhury [35] | L | Parallel discs | 3 soil types | 67–10000 | 560–1432 |

grounding systems in order to study the phenomenon in real conditions. To this end, Asaoka et al. [28] conducted ionization experiments on real tower footings, while Nixon [29] performed ionization experiments in field by placing a single rod in a three-layer soil. Worth mentioning is the attempt of He et al. [30] who correlated field and laboratory experiments. At this point, it should be mentioned that a limiting factor for the realization of field measurements is the charging capacity of the impulse generator, which should be such that it can cause ionization in real grounding system installations.

Furthermore, $E_o$ varies over a wide range of values depending on soil resistivity, earth electrode's dimensions, electrode's configuration and impulse polarity. It should be commented that Lima and Visacro [10], performed laboratory, impulse experiments for the same type of soil samples and moisture content placed in a parallel plate configuration and in a cylindrical configuration. By comparing the obtained results, the influence of the experimental configuration on estimating $E_o$ can be examined. The values obtained with the parallel plate configuration were similar to those proposed by Oettle [26], while the coaxial geometry results were closer to the results found by Gonos and Stathopulos [31] and Mousa [16].

In the studies regarding the transient behavior of grounding systems and, in order to take the ionization phenomenon into account, researchers adopt a representative value for the ionization gradient. As a result, various values have been used for $E_o$. Oettle [26] suggested 1000 kV/m, Mousa [6] proposed that the value 300 kV/m should be used for studies, while CIGRE [36] has adopted the value 400 kV/m. Gonos and Stathopulos [31] studied the variation of $E_o$ against the soil resistivity and $E_o$ was found to decrease down to 200 kV/cm.

However, since the electrical characteristics of soil vary among different soil types, the adoption of one value for ionization gradient is not suggested. Some researchers attempted to relate $E_o$ with soil characteristics. Oettle [37] attempted to correlate the critical ionization voltage gradient with the soil properties resulting in the following power-law regression between soil ionization gradient and resistivity:

$$E_o = 241 \cdot \rho^{0.215} \tag{1}$$

where $E_o$ is the soil critical ionization voltage gradient (in kV/m) and $\rho$ is the soil resistivity (in Ωm).

Manna and Chowdhuri [35], based on soil breakdown experimental results under uniform field, proposed the following formula:

$$E_o = 8.6083 \cdot k_g^{-0.0103} \cdot \sigma_g^{-0.15264} \tag{2}$$

where $E_o$ is the soil critical breakdown field (in kV/cm), $k_g$ is the soil dielectric constant and $\sigma_g$ is the soil conductivity (in mS/m).

At this point it is worth mentioning that soil permittivity and resistivity are frequency depended parameters, a fact which is completely disregarded in these formulas. It is possible that $E_o$ is frequency-depended, which means that the same soil sample for impulses with different rise and fall times will present different $E_o$. This fact is supported by the findings of Lima and Visacro [10] who conducted experiments with impulse currents with front time 1 and 3 μs. Since impulse currents present a wide frequency spectrum, it is suggested that the influence of frequency should be further investigated. Moreover, according to the proposed equations soils with different characteristics (such as grain size, porosity, compactness, moisture content, salt content etc.) but with the same resistivity will result in having the same critical fields. As it was reported by Mousa [6] [16], there is no direct relationship between the ionization gradient and the soil resistivity, since the ionization voltage gradient depends on the voids between the grains, while the soil resistivity may be influenced by the amount of salt in the soil. This fact can be also verified by the experiments of Lima and Visacro, where the ionization gradient for soil with resistivity of 2000 Ωm is 370 kV/m. For different soil type with resistivity 1090 Ωm the ionization gradient is 950 kV/m. Furthermore, the correlations have been developed on the basis of experiments in some soil types, therefore, the validity of the proposed regression models is limited on the experimental results from which they derived. Consequently, there is no generalization ability and the use of these formulas for different types of soil and different conditions can lead to incorrect estimations of the electrical behavior of the soil, and thus, the behavior of the grounding system. In contrast, the variation of the ionization and breakdown gradient according to the type of soil should be taken into consideration when estimating the behavior of grounding systems. These formulas should be used only for preliminary estimations and should be verified by testing samples of soil under study. In the future, the influence of soil parameters (such as porosity, dielectric constant, resistivity, chemical composition, etc.) on the critical parameters should be investigated before formulas are proposed by means of Artificial Intelligence.

## 4. Conclusion

An extensive review of the research being carried out on the ionization voltage of the soil has been made. Moreover, a digest of the proposed methods for the estimation of the ionization voltage gradient is presented and representative values are tabulated. Through this review the following observations can be made, which can be considered as a starting point for further research:

Firstly, the determination of the ionization voltage is made using different approaches. All methods are based on the voltage and current characteristic waveforms, however, due to limitations (in some cases a second current peak is not present, in other cases -when the soil resistivity is very high- the current trace cannot be recorded), different approaches are adopted.

As far as the proposed empirical equations concerns, these equations derive from limited experimental data and, thus, lack generalization ability.

Regarding the values of $E_o$, it is clear that, only one representative value for these parameters is not justified and further study of the factors that affect them is necessary. Undoubtedly, it is very encouraging that some research toward this direction is already performed. However, since the ionization of soil is not yet fully understood, whatever endeavor to correlate the ionization voltage gradient to grain size, current rise time, porosity of the soil etc. should be attempted with caution.

Most importantly, it should be kept in mind that the onset of ionization phenomena should be determined by a universally accepted method and the estimation of the ionization voltage gradient should be made with minimum possible approximations and assumptions. Among the available methodologies, the one based on the determination of breakdown voltage of soil samples placed in uniform field configurations can be considered advantageous to the others since it provides a standard procedure and involves simple calculation for determining the ionization gradient.

To sum up, the analysis of the above mentioned methods reveals the advantages and the drawbacks of each one, highlights the difficulties regarding the calculation of $E_o$ and underlines the necessity for further research on the subject and the establishment of a specific method for determining $V_o$ and estimating $E_o$.

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