Estimation of critical electric field of soil ionisation based on tangential electric field method

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Abstract: The critical electric field of soil ionisation is very important for the performance of grounding system and spatial distribution of electromagnetic field in the soil when lightning directly strikes the lightning protection system. To estimate the critical electric field in the soil, a tangential electric field method is proposed based on the electromagnetic field analysis presented in this study. With this method, the instant moment when the soil ionisation occurs is obtained by examining the tangential component of horizontal electric field. According to the maximum electric field in soil without soil ionisation for every moment, the soil critical electric field could be estimated. In addition, the critical electric fields for four different types of soil reported in the literature are estimated with the tangential electric field method, yielding satisfactory agreement.

1 Introduction

The grounding system is a crucial component of a lightning protection system. The grounding system dissipates the stroke current into soil, and thus the damages to human beings and structures are reduced. It is well known that the impulse behaviour of the grounding system differs from the behaviour at mains frequency. When the electric field in the soil around the grounding system exceeds the critical electric field in soil, the soil becomes ionised and the resistivity of the affected soil section decreases, resulting in reduction of impulse impedance [1]. Therefore the soil critical electric field is very important to investigate the impulse behaviour of grounding systems and the spatial distribution of electromagnetic field in the soil.

Various reference values and ranges of soil critical electric field $E_c$ have been proposed. Oettle [2] suggested an $E_c$ value of 1 MV/m. Mousa [3] found that Oettle’s results varied in a range of 600–1850 kV/m, with the lower values of 600–800 kV/m for soils with higher moisture content. After further investigation, Mousa [3] suggested that the lower range of Oettle’s results could be about the half, namely, 300–400 kV/m, and he also suggested that 300 kV/m should be used as $E_c$ for typical soil by referring to Liew’s research [4].

It is well known that the soil critical electric field $E_c$ depends on soil types. Even for the same soil, $E_c$ varies with moisture and temperature. Gonos and Stathopulos [5] studied the relationship between $E_c$ and soil resistance. In Mohamad’s Nor [6] study, the $E_c$ value is first obtained when two current peaks were observed. After that, using the available voltage and current traces from the previous study, for the first time $E_c$ is taken when the $i$–$v$ curve starts to form a loop. Manna and Chowdhuri [7] proposed a general expression for soil critical electric field as a function of significant soil parameters, based on extensive laboratory tests for different types of soils. Asimakopoulos et al. [1] analysed the components of uncertainty which influence the value of breakdown voltage and estimated the uncertainty of parameters derived from the oscillograms. This paper will present a new method to derive the soil critical electric field $E_c$ based on electromagnetic field analysis. Although the critical electric field for soil ionisation varies with moisture and temperature of soil, the soil state of natural environment is definitive at specific times. Then, the soil critical electric field $E_c$ could be obtained at specific time by the method presented in this paper.

At present, there are some analytical methods to calculate the lightning electromagnetic field: numerical integration [8–11], finite-difference time-domain (FDTD) [12], finite element method [13, 14], moment method [15], transmission line method [16], hybrid electromagnetic model [17] and extended Rusck model [18]. The FDTD method provides a broadband simulation. As a consequence, a broad frequency response can be analysed via a single simulation, and this method is amenable to high-fidelity modelling of very complex geometries. It has been widely applied in the studies of impulsive sub-ionospheric propagation [19]. Moreover, this method is also used to analyse the grounding grids [20], transmission line [21] and the electromagnetic field of the area close to lightning [22].

Liew’s dynamic model is characterised by low-current value of resistivity ($\rho_0$), ionisation time constant ($\tau_i$), de-ionisation time constant ($\tau_d$), soil critical electric field ($E_c$) and the value of resistivity ($\rho$) where $E = E_c$ in the course of electric field decay [4]. Recent research shows that Liew’s dynamic model can be integrated with FDTD and achieve excellent agreement between simulation and experiment [23]. Therefore the electromagnetic field in the process of soil ionisation can be analysed by combining FDTD and Liew’s dynamic model. Undoubtedly, the soil critical electric field can be estimated from electric fields which contain information of soil ionisation. The simulation in this paper demonstrates a method is easy to apply to any homogeneous soil with high accuracy. Moreover, the abrupt changes are always obtained by the electric field in the tangential direction of the circle whose centre at the rod under test. Moreover, then we define this method as tangential field method. Moreover, only the electric fields around the moment when soils begin to ionise are analysed. Consequently, the error introduced by Liew’s dynamic model does not have a significant influence on the estimation.
Meanwhile, according to existing studies [4, 6, 24] on the critical electric field of soil ionisation, this critical electric field is intrinsic to the soil in specific ambient conditions (such as moisture and temperature [25]). Although the critical electric field for soil ionisation varies with moisture and temperature of soil, the soil state of natural environment is definitive at specific times. Furthermore, different physical and chemical characteristics will result in different electrical parameters of soil and parameters of Liew’s model. Owing to that we have tested validity of our method against the other three different kinds of soil mentioned in Liew’s paper. Moreover, because the distribution of electromagnetic fields formed by the vertical earth electrode is relatively simple and is easy to analyse, this paper will only examine the computation of vertical earth electrodes to derive the critical electric field of soil ionisation. $E_c$ obtained by our method can be applied to analyse earth electrodes of any shapes for the contemporary soil state.

2 Relationship between the soil ionisation and the grounding instantaneous resistance

Theoretically, the electric field at any position in soil always contains the information of soil ionisation. It is known that the maximum electric field strength in soil always appears in the region closest to the earth electrode. The soils around the electrode begin to ionise as soon as the electric fields in this region reach the critical electric field $E_c$. At this time, the ionisation of soil around the earth electrode results in different conductivity between soil in this region and ambient intact soil, and hence the conductivity as one of the electromagnetic parameters is inhomogeneous. Consequently, the electromagnetic wave in the ionised region is composed by outward travelling waves and standing waves [26], whereas the non-uniformity will not cause significant loss. Therefore the equivalent network of non-uniformity can be considered to be composed by lossless components, such as capacitor, inductor and ideal transformer. Thus, the effect of reactance caused by the difference in conductivity between the ionisation soil and non-ionisation soil will occur. As the conductivity of ionisation soil increases, the reactance also increases until the outer intact soil begins to ionise. Since the impact of reactance is very small in comparison with that of resistance when the system running in low frequency, the influence of reactance is usually ignored and it is termed as grounding resistance, which although actually is ground impedance. According to the composition of grounding resistance, if the soil around the grounding electrode is ionised, namely, the resistivity decreases, the grounding resistance of earth electrode will decrease. However, when one uses 8/20 $\mu$s pulse current as a source (the FDTD region is sketched in Fig. 2, where the PML is perfectly matched layer), as shown in Fig. 1, the instantaneous resistance does not decrease and instead it increases in a certain time period (calculation parameters are given in detail in Section 3). This is because the peak-valley position before the first peak corresponds to the instant moment when the soil clinging on the earth electrode becomes ionised. Owing to the sustaining ionisation of soil in this region, the conductivity distribution is not uniform in the soil, and thus the impedance distribution gradually increases as the degree of ionisation increases. During the rise time of the first peak, increases in reactance affect the grounding resistance more than decreases in resistance, which causes the instantaneous resistance to increase. As the current flowing through the earth electrode into soil further increases, the outlier soil becomes ionised. As the difference between resistivity of initial ionised soil and outer soil decreases, the initial impedance of soil also becomes smaller. Meanwhile, the new distribution of impedance is generated outside to form the second peak. However, because the distribution of newly formed impedance is more and more displaced from the earth electrode, the influence on the grounding resistance also becomes smaller, and thus the undulation of second peak value also decreases. The first peak value appears immediately when the electric field reaches $E_c$, and therefore contains the temporal variation of $E_c$. The consequent change of voltage can be used to determine the moment of critical electric field, which is an important parameter to estimate the critical electric field of soil. However, for the instantaneous resistance, the undulation is always too small to observe. In the following section, the tangential electric field method will be proposed based on the analysis above.

3 Simulation model

The electric field in soil can be obtained based on the simulation model mentioned by Ala et al. [23], and then the variation in tangential electric field is acquired. On this basis, we proposed the tangential electric field method to evaluate the critical electric field. Moreover, the critical electric fields of the other three different kinds of soil in Liew’s paper will be evaluated through the method in Section 5.

The computational model adopted in this paper is the electric circuit model described in [23]. The FDTD region is sketched in Fig. 2, where the PML stands for the perfectly matched layer. The rod is directly fed by an ideal 8/20 $\mu$s pulse current generator. Four auxiliary rods are used in order to build the current return path. The rods are embedded in the homogeneous soil, and the relative permittivity of two types of soils are $\varepsilon_r = 1$ and $\varepsilon_r = 8$; the relative permeability and conductivity of the soils are $\mu_r = 1$ and $\sigma = 0.02$ S/m. The radius of thin-wire reported by Liew and Darveniza [4] is $r_0 = 6.35$ mm. According to this model, the intrinsic radius is set to $r_0 = 0.2298\Delta x$, where $\Delta x$ is the step of the related spatial grid. Since we use $\Delta x = 0.061$ m in the computation, the radius of thin wire is set to $r_0 = 0.014$ m [23]. Owing to the computation complexity, the radius of thin wire in this paper is about twice that at 6.35 mm reported by Liew and Darveniza [4] and Ala et al. [23]. Fortunately, the estimate of critical electric field of soil ionisation does not require the data of the entire process, and the
data from the beginning to the moment of soil ionisation are sufficient. Owing to the application of 8/20 μs pulse current, the ionisation always occurs on the rising stage of the pulse, and, in general, it is not longer than 8 μs. According to the peak of pulse current and soil used in this paper, the actual situation is that the ionisation will start in soil within 2 μs. Therefore the computation time mentioned above will not significantly affect the estimate of critical electric field.

When the local electric field $E$ in FDTD grid exceeds the critical value $E_c$, the ionisation begins in the local cell and the soil becomes ionised in the following manner [23]

$$\rho = \rho_0 \cdot e^{-t/\tau_c}$$

(1)

where $\rho_0$ is the steady-state resistivity, $t$ is the time defined so that $t = 0$ at the instant of $E = E_c$ and $\tau_c$ is the ionisation time constant. The decreasing resistivity with time represents soil ionisation process.

During the de-ionisation process, the variable resistivity law is expressed as follows [23]

$$\rho = \rho_t + (\rho_0 - \rho_t) \cdot (1 - e^{-t/\tau_i}) \cdot (1 - E/E_c)^2$$

(2)

where $\rho_t$ is the minimal values reached by soil resistivity during the ionisation process, $\tau_i$ is the de-ionisation time constant and $E$ is the actual amplitude of the electric field. The increasing resistivity with time from $\rho_t$ to $\rho_0$ represents de-ionisation process of soil.

However, as mentioned in the result of analysis above, the parameter $\tau_i$ is not required. Furthermore, only the electric fields around the moment when soils begin to ionise are analysed, and thus the error introduced by Liew’s dynamic model does not substantially affect the estimation. The estimation in this paper will be discussed based on the simulation data. Since we can obtain the instant moment of soil ionisation based on the following tangential electric field method as long as the soil begins to ionise, actually there is no need to know any parameters of Liew’s model when applied this method.

Fig. 3  Sketch map of the locations of sampling points A and B (according to [23])

4 Tangential electric field method

4.1 Simulation research based on double exponential function

The adopted FDTD region and sampling locations A, B are shown in Fig. 3.

The soil critical electric field $E_c$ is set to be 110 kV/m [4, 23], and the varying resistivity laws reported in Liew and Darveniza [4] and Ala et al. [23] are expressed as (1); furthermore, the time constants are chosen the same values as those reported in Liew and Darveniza [4] ($\tau_c = 2 \mu s$). The electric fields in the $x$, $y$ and $z$ directions at point A within 0.6 μs with and without soil ionisations are shown in Figs. 4a and b, respectively. In the situation without soil ionisation, the conductivity of soil always remains at the initial setting whether or not the electric field strength exceeds the critical electric field of soil during the entire computation.

From this we can calculate the strength of electric field without soil ionisation in the computational domain. The difference between them is obvious. Therefore for homogeneous soil without ionisation, the maximum electric field intensity at every time step could be obtained. $E_x$ and $E_z$ monotonically change, except for a small abrupt change on the $E_y$ curve as shown in grey region of Fig. 4a, which indicates the electric field in the $z$-direction also contains the information of soil ionisation. The abrupt changes of the electric fields in the $x$ and $z$ directions as shown in Fig. 4a correspond to the first peak-valley of grounding instantaneous resistance as shown in Fig. 1, but the range of change in the $y$-direction is more obvious. $E_x$ which is shown in Fig. 4a by dash line are the electric fields in the $x$-direction when $E_y$ = 8. Moreover, it can be seen that the abrupt change is delayed when relative dielectric constant is $>1$.

The electric fields in the $x$, $y$ and $z$ directions at point B within 0.6 μs with soil ionisation are shown in Fig. 5. The tangential electric field ($x$-direction at point A and $y$-direction at point B) changes considerably because of ionisation. There is also a small abrupt change on the $E_y$ curve. The dash line also indicates the electric field in the $y$-direction when relative dielectric constant is 8, and the abrupt change is also delayed. As shown in Figs. 4a and 5, the abrupt changes of $x$-component at point A and $y$-component at point B are observed at 0.29483 and 0.29460 μs, respectively, which can be considered to occur simultaneously. Moreover, the abrupt change of $E_y$, which is indicated by dash line in Fig. 5 has happened at 0.30547 μs. This phenomenon is caused by soil ionisation, and hence the result is reasonable.

In electromagnetic theory, the retarded potentials are the electromagnetic potentials for the electromagnetic field generated by time-varying electric current or charge distributions in the past. The fields propagate at the speed of light, so the delay of fields connecting cause and consequence at earlier and later times is an important factor: the signal takes a finite time to propagate from a
point in the charge or current distribution (the point of cause) to another point in space (where the effect is measured). Therefore it is necessary to correct the time of soil ionisation obtained by the aforementioned tangential electric field method. In this simulation, the separation between the rod and sampling location is 1.83 m. It is well known that the ionisation always first occurs in the region closest to the rod. Then, the separation of 1.83 m is defined as the distance between the region where the ionisation first occurs and sampling location. According to the electromagnetic theory, the energy propagation velocity is a function of frequency for electromagnetic waves that propagate in lossy medium. Therefore the group velocity of electromagnetic waves should be taken into account in order to strictly calculate the energy propagation velocity. Moreover, the non-linear characteristic of soil conductivity resulted by soil ionisation leads to the abrupt changes of tangential velocity. Moreover, the non-linear characteristic of soil conductivity and the ionisation begins to occur. The maximum electric field strength is determined as the moments when the ionisation begins to occur. The maximum electric field strength is calculated by FDTD, as shown in Fig. 6. Then, the soil critical electric field can be found with (4) and (5). The maximum electric field strength at the two moments

\[
E_{\text{max}} |_{t_{a}=1} = 1.1079 \times 10^5 \text{V/m}
\]

\[
E_{\text{max}} |_{t_{b}=8} = 1.0956 \times 10^5 \text{V/m}
\]

respectively. Moreover, because the distance between sampling points and source is <2 m, the associated error is very small according to the calculation results presented later in this paper. Consequently, there are

\[
t_{a} |_{t_{a}=1} = \frac{1.83}{v_1} = 1.83 \times \sqrt{\varepsilon_0 \mu_0} \simeq 52\Delta t
\]

\[
t_{b} |_{t_{b}=8} = \frac{1.83}{v_1} = 1.83 \times \sqrt{\varepsilon_0 \mu_0} \simeq 147\Delta t
\]

where \(\Delta t\) is the time step of simulation. In terms of \(t_a\), there are

\[
\text{Time}_{a} |_{t_{a}=1} = (2514 - 52) \cdot \Delta t = 2462\Delta t
\]

\[
\text{Time}_{a} |_{t_{a}=8} = (2608 - 147) \cdot \Delta t = 2461\Delta t
\]

\[
\text{Time}_{a} |_{t_{a}=8} = (2512 - 52) \cdot \Delta t = 2460\Delta t
\]

\[
\text{Time}_{a} |_{t_{a}=8} = (2607 - 147) \cdot \Delta t = 2460\Delta t
\]

The times defined by (4) and (5) are regarded as the moments when the ionisation begins to occur. The maximum electric field strength in soil at the time is defined as the critical electric field (denoted as \(E_{cr}\)) of soil. It is known that the electric field here should be the vector sum of components in \(x, y\) and \(z\) directions.

For homogeneous soil without ionisation, the maximum electric field strength in soil within 0.6 \(\mu s\) is calculated by FDTD, as shown in Fig. 6. Then, the soil critical electric field can be found with (4) and (5). The maximum electric field strength at the two moments is

\[
E_{\text{cr}} \times |_{t_{a}=1} = 1.1096 \times 10^5 \text{V/m}
\]

\[
E_{\text{cr}} \times |_{t_{b}=8} = 1.0956 \times 10^5 \text{V/m}
\]

It is known that the actual value of critical electric field is \(E_{cr} = 1.1 \times 10^5 \text{V/m}\) [4, 23]. The relative errors between them are only 0.64, 0.72\% when \(E_1 = 1\) and 0.36, 0.4\% when \(E_8 = 8\), respectively, demonstrating good agreement. The beginning moment of ionisation is defined as \(t_{cr}\).

After that, as shown in Fig. 7, the electric fields in the \(x, y\) and \(z\) directions at points \(B'\) and \(B''\) are obtained, and the temporal variation within 0.6 \(\mu s\) when \(E_1 = 1\) is shown in Figs. 6a and b. As shown in Fig. 8b, the electric field strength in all directions is too strong to find out the abrupt changes for ionisation. However, when the fields arrive at point \(B'\), the fields in the \(y\)-direction have dropped below 100 \(V/m\), which makes the change of the curve
easy to observe, as shown in Fig. 8a. Moreover, the electric fields in the z-direction have also dropped below 1000 V/m, and the small variation appears. It is well known that the aforementioned phenomenon could be more obvious for the attenuation when the fields arrive at point B, as shown in Fig. 5. From the discussion above, the variations of electric field caused by soil ionisation is more obvious at farther distance from the rod. Hence, it is helpful to obtain the beginning time of soil ionisation if the data are collected at places far from the rod, as long as the abrupt changes of curves can be observed clearly.

4.2 Simulation research based on Heidler function

In this section, Heidler function instead of double exponential function is used as source and the waveform of Heidler function is shown in Fig. 9. The parameters of soil are \( \varepsilon_r = 8 \), \( \mu_r = 1 \) and \( \sigma = 0.02 \) S/m. The waveform of tangential electric field (y-direction) at point B is shown in Fig. 10.

According to (3) and (4), the moment of soil ionisation is

\[
\text{Time}_B \big|_{\varepsilon_r=8} = (573 - 147) \cdot \Delta t = 426 \Delta t
\]

Moreover, the maximum electric field strength in soil at the moment is

\[
E_{y, \text{max}} \big|_{\varepsilon_r=8} = 1.0961 \times 10^5 \text{ V/m}
\]

Thus it can be seen that the satisfactory results could be achieved by tangential electric field method whether the source is double exponential function or Heidler function. Actually, as mentioned before, this critical electric field is intrinsic to the soil in specific ambient conditions (such as moisture and temperature [25]), which is independent of pulse current source.

The research above indicates that the beginning moment of soil ionisation can be estimated directly by tangential electric field method. This method acquires very high precision, as long as the electromagnetic parameters of soil can be obtained accurately. Furthermore, the information of soil ionisation can also be obtained by the radial component and longitudinal component of horizontal electric field, but the information cannot be distinguished clearly for the high magnitude of the two components unless after propagating over a certain distance. However, the propagation might cause extra error because of the measurement of electromagnetic parameters and the dispersion of soil [27]. Consequently, from the perspective of calculation cost, precision and operation feasibility, tangential electric field method is the better option.

5 Simulation and discussion

Numerical simulations are carried out for another three different soil types reported in Liew’s paper to show the validity and effectiveness of tangential electric field method. The parameters of soils are shown in Table 1. Other parameters used in the simulation are the same as Section 3 (\( \sigma = 0.02 \) S/m, \( \varepsilon_r = 1 \) and \( \mu_r = 1 \)). The derivation process
and calculation method of the critical electric field of soil $\alpha$ have been considered in this section. Since the calculating procedures are essentially the same for different soils, the numerical results of two other examples are provided directly.

### 5.1 Simulation examples

The adopted FDTD region and the sampling locations A, B are the same as in Fig. 3.

The electric fields in $x$, $y$ and $z$ directions at point A within 1.8 $\mu$s with soil ionisation are shown in Fig. 11. $E_x$ and $E_z$ monotonically change except for a small abrupt change on $E_x$ curve, as shown in grey region of Fig. 11, which indicates that the electric field in the $z$-direction also contains the information of soil ionisation.

Similarly, the variation of electric field strength of sampling locations lags behind source for the retarded potentials. The moments of soil ionisation obtained by the tangential component of electric fields at points A and B are given by

$$\text{Time}_A = (7215 - 52) \cdot \Delta t = 7163 \cdot \Delta t$$
$$\text{Time}_B = (7213 - 52) \cdot \Delta t = 7161 \cdot \Delta t$$

For homogeneous non-ionised soil, the maximum electric field strength in soil within 1.8 $\mu$s can be calculated. Along with the equations above, the critical electric field strength at the two moments is

$$E_{z, \text{max}, A} = 3.0022 \times 10^5 \text{ V/m}$$
$$E_{z, \text{max}, B} = 3.0015 \times 10^5 \text{ V/m}$$

It is known that the actual value of critical electric field strength is $E_c = 3 \times 10^5 \text{ V/m}$, and the relative errors are only 0.0733 and 0.05%, respectively.

### 5.2 Discussion

In the following, the reasons for the phenomenon of the abrupt changes of electric fields will be discussed. Presuming that the critical electric field strength is

$$E_t = \alpha \cdot E_c$$

where $\alpha$ is the reflection coefficient of the bottom of the metal above ground is [28]

$$\rho_s = \frac{Z_g - Z_s}{Z_g + Z_s}$$

It is not difficult to derive that there should be $Z_s < Z_g$ in the range of frequency spectra of the pulse current. Therefore when the first peak shown in Fig. 1 appears, namely, when $Z_s$ increases, the absolute value of $\rho_s$ increases. Then, there is more energy reflected from the bottom of the metal. Considering that the current of electrode increases by very little in an infinitesimal time when the soils closest to electrode just begin to ionise, the current could be assumed to be constant during the time. Owing to the increase of ground impedance, the energy that penetrated into soil is reduced during the time when the soils closest to electrode just begin to ionise. Parameters and corresponding estimated errors of four kinds of soils are listed in Table 2. As we can see, the estimated errors decrease with the increase of the critical electrical field strength.

### 6 Conclusions

In summary, since the method proposed in this paper is based on the high frequencies resulted by the non-linear characteristic of soil
conductivity because of soil ionisation, the electric field which leads to the high-frequency component emergence can be treated as the critical electric field \( E_c \). According to the discussion above, this method is independent of pulse current source, but dependent of the steepness of pulse.

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8 References