Onset electric field of soil ionisation around grounding electrode under lightning

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Abstract: Onset electric field of soil ionisation is one of the basic parameters to analyse the lightning impulse performance of a grounding electrode, which has been fully investigated based on experiments on hemispherical electrode or rod-to-rood gap. Until now, there has been lack of onset electric field of rod-to-plane gap, which is the real situation for grounding electrode. In this study, the soil ionisation around the grounding electrode is studied by experiment. Method to judge the start of ionisation is discussed. Both the effect of the soil resistivity and that of the radius of the grounding electrode on the onset electric field of soil ionisation are investigated. It shows that the onset electric field decreases as the radius of the electrode increases, while increases as the soil resistivity increases. A formula to predict the onset field with respect to soil resistivity and the radius of the grounding electrode is proposed.

1 Introduction

The lightning impulse performance of a grounding electrode plays an important role in lightning protection. The performance of grounding systems under lightning is non-linear due to soil ionisation [1-5]. That is, when a high magnitude impulse current is injected into the grounding electrode, it will be dissipated into soil, and then the electric field surrounding the grounding electrode may exceed the onset value and soil ionisation occurs [6, 7]. Then, it looks like that the grounding impedance decreases as the lightning current increases, and this is the value of interest in analysing the surge response of the grounding electrode. Unlike that at power frequency, the current will be dissipated into soil mainly near the injection point due to the inductance of ground conductor [8], which may make the soil ionisation strong.

Many papers have studied the soil ionisation. However, the composition of the soil is highly non-uniform. As a result, the shape of the ionised zone is not uniform. Rather, the current flows in discrete channels [7, 9, 10]. To facilitate the calculation of the grounding resistance, the ‘ionisation gradient’ $E_i$ is defined as the value which when applied in the uniform resistivity model would produce the measured value which corresponds to non-uniform ionisation. The $E_i$ is widely used to describe the characteristic of soil ionisation. However, the value of $E_i$ reported in the literatures varies from tens to thousands kV/m [11-18]. Mousa [16] estimated that the onset soil ionisation gradient was 300 kV/m. The value of 400 kV/m is used by CIGRE [17]. In fact, the parameters of soil such as the resistivity, moisture content and so on, are all the important factors impacting on $E_i$. Oettle [18] proposed the relation between the onset electric field of soil ionisation and the resistivity as

$$E_i = 241\rho^{0.215}$$  \hspace{1cm} (1)

where $E_i$ is in kV/m, and $\rho$ is the soil resistivity in $\Omega$ m. Besides the parameters of soil, the shape of the grounding electrode may also affect $E_i$ according to the theory of discharge. However, most results in the above literatures did not emphasise this effect. Some of them were carried out on hemispherical electrode [10] or in rod-to-rood gap [19], which cannot reflect the influence of the shape of the grounding electrode. Since the grounding electrode is usually regarded as thin rod, the dependence of the onset field of soil ionisation on the radius of rod should be considered in simulation. However, as far as the author's knowledge, there has been no formula to predict the onset field on the surface of the grounding electrode with respect to the electrode's radius.

In this paper, a coaxial cylindrical structure is used to setup the electric field distribution around the grounding rod, with which both the effect of the resistivity of soil and the radius of the grounding electrode on the onset electric field of soil ionisation is investigated. X-ray imaging technology is used to make sure that the soil ionisation takes place. A formula to predict the onset electric field of soil ionisation with respect to the soil resistivity and the radius of the grounding rod is proposed.

2 Experimental model

In order to simulate the electric field distribution around the grounding rod, a coaxial cylindrical structure is setup as shown in Fig. 1. A copper cylinder with both ends open is put on an insulation board. The cylinder is filled with soil. The diameter of the cylinder is 0.8 m and the depth of the soil is 0.5 m. The grounding rod under test is at the axis of the cylinder, whose two ends are all exposed to air (there is a hole in the insulation board to let the electrode pass though). All the test facilities are insulated from the ground. The oscilloscopes are powered by batteries. An impulse current is applied between the grounding rod and the copper cylinder. As the rod is much shorter compared with the wavelength of the main frequency of the impulse, the leakage current is almost evenly distributed along the rod, and the current in the soil is in radial direction. This means that the electric field in the soil is also in radial direction. When the current is large enough, the strong electric field will result in soil ionisation near the electrode, which will decrease the equivalent soil resistivity and change the waveforms of the impulse current and voltage between the electrode and the cylinder. Thus, theoretically, by observing the variation of the waveforms of the measured impulse voltage and current, the onset voltage of the soil ionisation may be obtained. Then, the corresponding onset electric field can be derived by

$$E_i = \frac{V_i}{\sqrt{\ln\frac{R}{r}}}$$ \hspace{1cm} (2)

where $V_i$ is the onset voltage of the soil ionisation, $r$ is the radius of the electrode and $R$ is the radius of the cylinder.
In order to make sure that the soil ionisation takes place, X-ray imaging technology is used. In [19], the soil around rod was considered, but the X-ray film changed the current path because the film and the rod were arranged in parallel, and then electric field distribution was different from the reality. In this paper, taking into account the dispersion of the discharge position, four layers of X-ray films crossed by the electrode are buried in the soil as shown in Fig. 1. As both the films and the path of the current are perpendicular to the electrode, the influence of the films on the current path as well as the electric field around the electrode is very small. Meanwhile, in order to make sure that the discharge is mainly in the soil, not along the surfaces of the films, the onset voltages of the soil ionisation with and without the films were compared. It was found that the ionisation on the top-layer X-ray film was just a little bit larger than those on the other films. This may be because the electrode under test is so short that potential difference along the electrode is very small.

After the experiment, when the soil was taken away, the state of the surface of the insulation board was checked. It showed that there was no apparent surface discharge on the insulation board, which means that the insulation board has no influence on the test results. At the same time, there was no visible discharge on the air-soil interface during the test. Thus, the discharge takes place only in the soil.

The cultivated soil in the Guanzhong Plain of Shaanxi Province, China was used. The resistivity of the soil was adjusted by controlling the moisture content of the soil which was measured in a four-electrode soil box at 50 Hz [20]. Table 1 shows the relationship between the soil resistivity and the moisture content. Meanwhile, the curves of the transient resistances at different low voltages coincide. Therefore, it seems that there is little ionisation in the soil.

Then, with the increase of the impulse voltage, the current peak time lags the voltage peak time apparently, which means that the current continues to increase as the voltage begins to decrease. This can be explained by the ionisation in the soil. When the voltage increases to a certain extent, soil ionisation appears near the electrode and the soil resistivity decreases, which results in the increase of the current. Then, the ionisation continues to develop and the current continues to increase even when the voltage begins to decrease. Finally, the soil ionisation decreases and disappears as the voltage decreases. In this case, the transient resistance varies with time apparently. For each impulse voltage, the transient resistance decreases first and then increases and finally approaches its initial value. The trend is opposite to the impulse current.

Finally, when the impulse current is very high, a second peak of the current appears, and there are apparent voltage drop and transient resistance drop at the moment. It seems that the soil resistivity becomes very low which results in the increase of the current and the decrease of the voltage. Maybe there is another kind of discharge different from the ionisation in the soil.

The above analysis can be verified by the X-ray photos in Fig. 4. Fig. 4a shows that when the impedance just begins to decrease, there has already been ionisation near the grounding electrode. Then, with the increase of the applied voltage, the ionisation area becomes larger and larger until it touches the cylinder. At this time, there are obvious discharge channels as shown in Fig. 4b, which results in the sudden decrease of the

| Moisture content, % | Resistivity, Ω·m |
|---------------------|-----------------|
| 10                  | 1300            |
| 15                  | 850             |
| 20                  | 420             |
| 25                  | 260             |

Table 1 Relationship between soil resistivity and moisture content
transient resistance and a sudden increase of the current as shown in Fig. 3.

It is also interesting that at the beginning, there is a sudden drop for the transient resistance. This may be due to the capacitance between the electrode and the cylinder since the current and voltage have following relationship in time domain:

\[
I(t) = \frac{U(t)}{R_s} + C_i \frac{dU(t)}{dt} \tag{3}
\]

where \( I \) and \( U \) are the transient current and voltage, respectively, \( R_s \) and \( C_i \) are the resistance and capacitance between the electrode and the cylinder, respectively. It should be noted that the frequency variations of \( R_s \) and \( C_i \) are neglected in (3) [21]. The capacitive current is dependent on the variation of the voltage with time. If the variation is great, the capacitive current is high. Therefore, when the voltage suddenly starts to increase, the capacitance between the electrode and the cylinder plays an important role, and the transient resistance drops greatly. For example, the capacitive current is much greater than the resistive current at the first 0.1 μs when the soil resistivity is hundreds Ω·m and the relative permittivity is up to tens. Then, when the increase of the voltage becomes slow, the transient resistance grows back towards its initial value quickly. If the voltage is high enough that the soil ionisation takes place, the transient resistance cannot grow back to its initial value and varies with the development of the soil ionisation. When the voltage varies slowly, the contribution of the second term in (3) is very small. Therefore, finally the transient resistance with low voltage (no soil ionisation occurs) returns to its initial value and keeps constant.

Another interesting discussion is the contribution of the voltage and current during the soil ionisation. High voltage results in high electric field strength, leading to electrical ionisation. High current results in high temperature, leading to thermal ionisation. From Fig. 3, it seems that if the peak time of voltage is very short, the onset of soil ionisation is determined by the voltage, and the development of ionisation is determined not only by the voltage, but also the current. This is because the ionisation occurs rapidly during the voltage rising stage. The time is too short to accumulate enough heat. However, the ionisation continues to develop and the current continues to increase even when the voltage begins to decrease. The minimum transient resistance appears later than the peak of the current. What is more, even if the voltage has dropped for a while, the discharge channel can still appear. Thus, it can be inferred that heat plays an important role for the development of the ionisation. When the heat accumulated in the soil is high enough, the ionisation will be strengthened. As the electric field is the main factor for the start of the soil ionisation if the peak time of voltage is very short, there should be a clear electric field for the onset of the soil ionisation, which is the main topic of this paper. It should be noted that the above conclusion is drawn based on the case that the peak time of voltage is very short. If this peak time is long, heat will be the main factor and the electric field for the onset of the soil ionisation will be an unfixed value.

To draw the transient resistance to determine whether soil ionisation has occurred or not is troublesome. Then, the impulse resistance which is defined as the ratio of voltage peak to current peak is used to depict the characteristic of the soil ionisation. The start of the soil ionisation can be determined according to the variation of the impulse resistance with respect to applied voltage. As the test results in Fig. 3 are few, additional experiments under other impulse voltages are done, and the corresponding impulse resistance is obtained as shown in Fig. 5.

It can be seen from Fig. 5 that the impulse impedance keeps constant when the peak voltage is smaller than 32 kV. Then, the impedance decreases as the voltage increases until there is a sudden impedance drop at 46 kV. In fact, the appearance of the second peak of the current and the sudden voltage drop and resistance drop in Fig. 3 corresponds to the sudden impedance drop in Fig. 5, which is due to the breakdown of the soil between the grounding electrode and the cylinder. Before that, there is ionisation in soil when the impedance begins to decrease. Thus, the onset electric field of soil ionisation should be that when the impedance just begins to decrease. Since the soil is not totally broken down at this stage, there is neither apparent increase of the current nor apparent decrease of the voltage. It is difficult to determine whether the soil ionisation happens just according to the current waveform or the voltage waveform. The best way to find the onset voltage of soil ionisation is to draw the impulse resistance curve varying with the peak voltage to find the inflection point. For example, the ionisation onset voltage in Fig. 5 is 32 kV not 46 kV.

### 4 Analysis of test results

Based on the above analysis, if the impulse resistance varying with peak voltage is obtained, the onset voltage and electric field of soil ionisation can be derived. By using electrodes with different radii and soils with different resistivities, the dependence of the onset value on the electrode radius and soil resistivity can be obtained.

In this paper, the test was carried out when the rise time of the voltage curve is about 0.7–0.9 μs (it is difficult to fix the rise time of the current because the presence or absence of ionisation and the intensity of ionisation have a significant impact). In order to reduce the effect of the dispersion, the test was repeated at least three times in each case even though the consistency and stability of the measurement results were very good.
In fact it is a weak partial discharge begins with creeping discharge which develops along the gas–solid interface formed on the particle surface and propagates along the gap between the particles [7]. Due to air participation, the ionisation is related to the shape of the electrode. As is well known, the generation of secondary electron avalanche is the key to the sustainable development of ionisation in air, which is dependent on the attainment of critical size of the primary avalanche for the negative. Although the criterion for positive is slightly different, in either process, sufficient electric field strength in the space is necessary so that the electron can be accelerated quickly to gather enough energy [22]. That means, in order to sustain the ionisation, not only the electric field on the surface of the electrode should be strong enough, but the electric field near the electrode should be strong enough also. Since the electric field near the thin electrode decreases fast, more electric field on the electrode surface is required to make the electric field near the electrode large. Then, the onset electric field of the thin electrode is great. With the increase of the electrode radius, the electric field in the soil tends to be a quasi-uniform field. Then, the onset electric field tends to be that in quasi-uniform field. Theoretically, there is no onset field of soil ionisation but soil breakdown in uniform field. That is the reason that in Fig. 7 the gap between the ionisation onset voltage and the breakdown voltage becomes small with the increase of the radius, which means that the ionisation onset voltage approaches the breakdown voltage when the radius of the electrode is large. From Fig. 8 it can be seen that the onset electric field approaches 300–400 kV/m, which is in agreement with the Mousa's and CIGRE's results [16, 17].

Fig. 9 shows the average impulse resistances of grounding electrode in different soil resistivities when the radius of the electrode is 25 mm. The soil ionisation onset voltage is shown in Fig. 10. It can be seen that the onset electric field of the soil ionisation is shown in Fig. 11, where the results predicted by (1) are presented also. It can be seen that the onset electric field increases with the soil resistivity also. The gap between the results in this paper and those by (1) is perhaps due to the difference of the electrode and soil under test.

In this paper, the change of soil resistivity is achieved by reducing the water content. Water adheres to the surface of the particles which makes the creeping discharge easy. Therefore, if water content increases, both the soil resistivity and the ionisation gradient will decrease. Another way to change the soil resistivity is to adjust salt content in the soil. The salt will dissolve in the water and will then adhere to the surface of the soil particles with the water, which makes flashover easy. Therefore, if salt content increases, both the soil resistivity and the ionisation gradient will decrease also. Thus, no matter which way to change the soil resistivity is used, if the soil resistivity increases, both the ionisation onset voltage and the ionisation gradient will increase. As the soil is hard to recover if salt is added, in this paper the soil resistivity was adjusted just by controlling the moisture content of the soil. The absolute results in this paper may be not suitable for other soils. However, the relative variation of the onset electric field with the electrode radius and soil resistivity could be applicable to other soils.

5 Prediction formula

There are many factors affecting the soil ionisation besides the soil resistivity, such as the type and composition of soil. That may be the reason that the value of $E_i$ reported in the literatures varies so great. Thus, the absolute results in this paper may be changed for other soil. However, the results can reflect the relative variation of the onset electric field with the electrode radius and soil resistivity. This relationship can be a good reference for the amendment of the test results in other soils. Based on the results in Figs. 8 and 11, a formula can be derived to predict the relationship.

First, suppose that the onset electric field of soil ionisation with respect to the electrode radius and soil resistivity could be

$$E_i(r, \rho) = f_i(r) \cdot f_s(\rho) \quad (4)$$
where $f_1(r)$ is a function of $r$ and $f_2(\rho)$ is a function of $\rho$.

Then, according to (1) and the trend of the measured curve in Fig. 11, $f_2(\rho)$ may be expressed by

$$f_2(\rho) = \rho A$$

(5)

From (4), we have

$$E_i(\rho_1)E_i(\rho_2) = \rho_1\rho_2 A$$

(6)

Then, $A$ can be obtained by

$$A = \ln\left(\frac{E_i(\rho_1)}{E_i(\rho_2)}\right) / \ln\left(\frac{\rho_1}{\rho_2}\right).$$

(7)

According to the measured $E_i$s and $\rho$s in Fig. 11, $A$ is in the interval from 0.153 to 0.184. Let us take 0.17 as an example. If the first measured point in Fig. 11 is known which is 522.15 kV/m at 260 $\Omega \cdot m$, the onset electric fields at the other three points in the figure are shown in Table 2. It can be seen that the predicted results by (6) are in good agreement with those by measurement.

According to the trend of the curve in Fig. 8, $f_1(r)$ should decrease with the radius, which is similar with that in air. Since both the grounding electrode and the conductor of transmission line can be regarded as thin wire, $f_1(r)$ with respect to $r$ may have the similar form with that of the corona onset electric field of overhead transmission line. Peek's formula is widely used to predict the corona onset electric field [22], according to which $f_1(r)$ may be expressed by

$$f_1(r) = B + C/r$$

(8)

where $B$ and $C$ are constants. When the soil resistivity is 260 $\Omega \cdot m$, according to the measured $E_i$s in Fig. 8, by using the method of least squares, it can be obtained that $B = 19.916$ and $C = 30.861$. Then the formula to predict the onset electric field of soil ionisation with respect to the soil resistivity and the radius of the grounding electrode is

$$E_i(r, \rho) = (19.916 + 30.861/r)^{0.17}$$

(9)

where $E_i$ is in kV/m, $\rho$ is the soil resistivity in $\Omega \cdot m$ and $r$ is the electrode radius in m. From (9), the predicted onset electric fields at the four points in Fig. 8 are shown in Table 3. It can be seen that the predicted results are in good agreement with those by measurement.
Table 2 Predicted onset electric fields with respect to soil resistivity

| Soil resistivity, Ω·m | Measured electric fields, kV/m | Predicted electric fields, kV/m |
|----------------------|--------------------------------|---------------------------------|
| 420                  | 561.78                         | 566.51                          |
| 850                  | 628.03                         | 633.31                          |
| 1300                 | 678.98                         | 675.07                          |

Table 3 Predicted onset electric fields with respect to electrode radius

| Electrode radius, mm | Measured electric fields, kV/m | Predicted electric fields, kV/m |
|----------------------|--------------------------------|---------------------------------|
| 3                    | 1477.71                        | 1501.36                         |
| 6                    | 1104.03                        | 1076.63                         |
| 10                   | 873.19                         | 845.51                          |
| 25                   | 522.15                         | 553.59                          |

6 Conclusions

In this paper, the onset electric field of soil ionisation with respect to the soil resistivity and the radius of the grounding electrode is studied by measuring the waveforms of current and voltage, and taking X-ray photos. It shows that it is difficult to determine whether the soil ionisation happens just according to the current waveform or the voltage waveform because there is neither apparent increase nor decrease of the waveforms. It is suggested to determine the onset voltage of soil ionisation by drawing the impulse resistance (the ratio of voltage peak to current peak) curve that varies with the peak voltage to find the point where the impulse resistance starts to decrease. A formula to predict the onset electric field of soil ionisation is proposed. It shows that the onset electric field is approximately inversely proportional to the root of the electrode radius, and is approximately proportional to the power of the soil resistivity which is <1. The absolute values in this paper may be not suitable for other soils. However, the relative variation of the onset electric field with the electrode radius and soil resistivity could be applicable to other soils.

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8 References

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