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Ionization Characteristics of Soil in Coaxial Cylinderical Electrode Systems under Impulse Voltage

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***Abstract*—In this paper, breakdown characteristics of soil in a coaxial cylindrical electrode system stressed by impulse currents were experimentally investigated. The breakdown voltage and current waveforms for 4 types of soils were measured, and the threshold electric field intensity, the ground impedance-time (*Z-t*) curves and the voltage-current (*V-I*) curves were analyzed and discussed. As a result, the breakdown voltage and current waveforms are strongly dependent on the type of soil and the voltage and current waveforms for gravel and sand differ from those for silt and loess. The threshold electric field intensity is increased in the order of gravel, sand, loess and silt. The *V-I* curves for all test samples show a 'cross-closed loop' of ∞-shape under ionization.**

Keywords-component; Soil ionization, V-I curve, breakdown voltage, lightning voltage, transient grounding impedance, Finite Element Method

I. INTRODUCTION

Land in Korea mostly consists of various types of soil such as mud, clay, sand, gravel, rock, etc., and the soil resistivity is closely related to the topography and geology. The ground resistance depends on the shape, size and structure of the ground electrode, the burial ground location, types and conditions of the soil. In particular, if the electrical discharge in soil is occurred around the ground electrode, the ground impedance is changed to transient [1-3]. Although until recently, many studies on the ionization characteristics of the soil due to the lightning surge voltages have been done, analytical theories about the breakdown and ionization characteristics according to the nature of the soil have not been clearly established. Therefore, it is required to accumulate basic data about soil's ionization phenomena and discharge characteristics [4-6].

This paper introduced the coaxial cylindrical grounding system in order to analyze the impact of soil ionization phenomena due to the lightning impulse voltage on the transient performance of grounding system and ground impedance, and described the results of experiments and simulations of ionization growth when lightning impulse voltage is applied to the ground electrode. The paper measured the breakdown voltage and current waveforms appearing when applying 1.2/50 μs standard lightning impulse voltage on the sand, loess and gravel, and based on these results, this paper further evaluated the critical field intensity causing the ionization growth, the voltage-current characteristics due to soil ionization, and the ground impedance-time characteristics, and analyzed the transitory nature of ground electrodes such as the equivalent radius of soil ionization due to lightning impulse voltage.

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II. EXPERIMENTS

A. Configuration of the experimental setup

The experimental setup was constructed with the Marx generator, the ground electrode system and the waveform observing devices of the voltage and current, as shown in Figure 1.

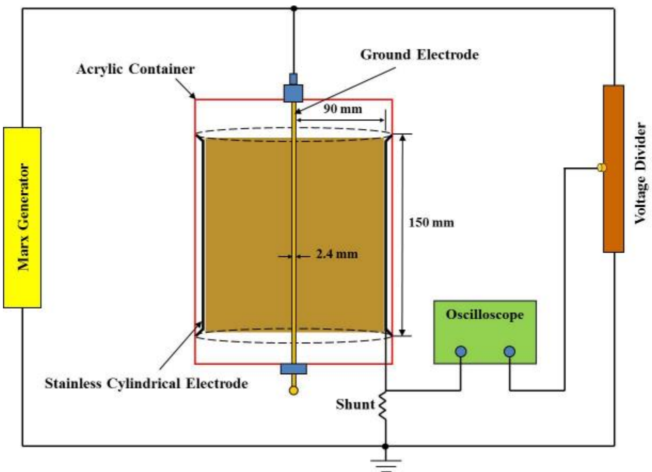


Figure 1. Schematic of experimental system

The experiment container consists of a cylinder of 180 mm diameter stainless steel, with a cylindrical end rounded to prevent electrical field concentration. The ground electrode made of a cylindrical copper wire with the diameter of 2.4 mm in the axial direction was placed on the center of the test container. One end of the ground electrode would be supplied with the test voltage, and the other end is equipped with a round-shaped electrode. The soil ionization phenomena around the ground electrode and the critical breakdown field intensity can only be properly observed when the electric field is not concentrated locally on the part of the ground.

The columnar electrode simulated with the ground rod is connected to the Marx generator, and the outer circumferential electrode is grounded by way of the 0.02 Ω coaxial-type shunt with the frequency band of DC-15 MHz. The test voltage is up to 400 kV, supplied by the Marx generator. The test voltage was measued by using the capacitive voltage divider. In addition, the waveforms of lightning impulse voltage and the discharge current were observed using 4 channel oscilloscope with 500 MHz(2.5 GS/s) and the digital impulse analyzer(MIAS 100-14/B, IMS23).

B. *Method of Experiment*

In this study, gravel, sand, silt and loess were used as 4 types of soil medium and the positive and negative impulse response and the ionization growth were evaluated when the lightning impulse voltage was applied to the ground electrode in cylindrical container filled with each sample. Under this condition, the experiments observing the ionization growth and transient ground impedance were carried out. Breakdown voltages were measured in dry soils, and the analysis of ionization phenomena was studied with respect to soil samples mixed with 4 % actual rainwater by weight that has the resistivity of 220 Ω·m.

III. RESULTS AND DISCUSSION

A. *Waveforms of breakdown voltages and currents*

Typical basic characteristics of soil ionization phenomena under the lightning impulse voltage were already reported[7], and this paper attempts to describe the transient ground impedances associated with the ionization growth in soil due to lightning impulse voltages. Figure 2 represents typical examples of voltage and current waveforms of dry gravel, sand, silt and loess under a breakdown by lightning impulse voltage. Soil discharges caused by lightning impulse voltage was different from each other. Soil discharges showed a typical pattern of impulse discharges where the voltage decreases rapidly and the current increases after breakdown.

During the electrical discharge, the breakdown voltages for gravel and sand decreased rapidly while the current rose up to several hundred amperes[A]. On the other hand, compared to gravel and sand, silt and loess's discharge voltages and currents dropped and rose relatively slowly.

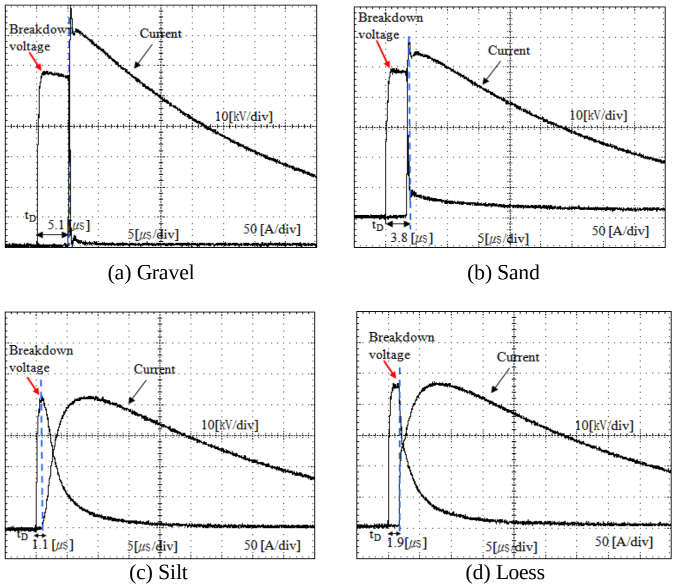


Figure 2. Typical waveforms of the breakdown voltage and current in soils

Gravel and sand have larger gap between soil particles compared to loess and silt, so the ratio of the voids between the particles increases [8]. Since particles as small as silt and loess have higher particle density, the change in discharge voltage and current becomes slowly.

B. *Critical breakdown field intensity*

The electric field intensity causing the electrical breakdown of soil was determined by applying a value, which is the breakdown voltage using the standard up and down method of IEC-60060-1 by 10 times, to the equation (1), and Figure 3 shows the results for the positive and negative polarities.

The applied electric field intensity causing the electrical breakdown in a coaxial cylindrical electrode system can be expressed as the following equation (1) [9].

$$E = \frac{V}{r_i \ ln\left[\frac{r_o}{r_i}\right]} \text{ [kV/cm]} \qquad (1)$$

Here,

V : breakdown voltage [kV]

r_o : radius of external electrodes [cm]

r_i : radius of inner electrode [cm]

The electric field intensity causing the electrical breakdown in the dry state decreases in the order of gravel, sand, loess and silt.

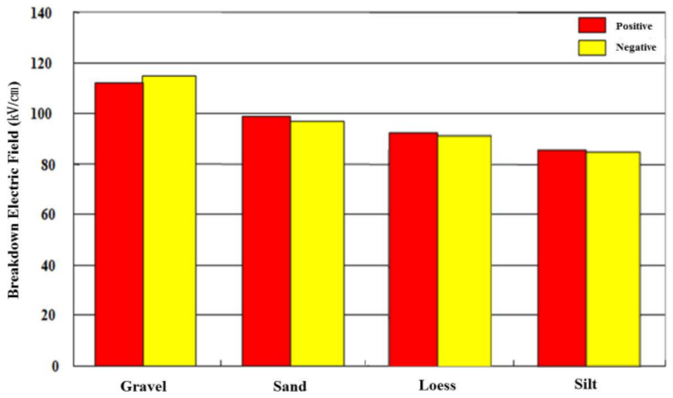
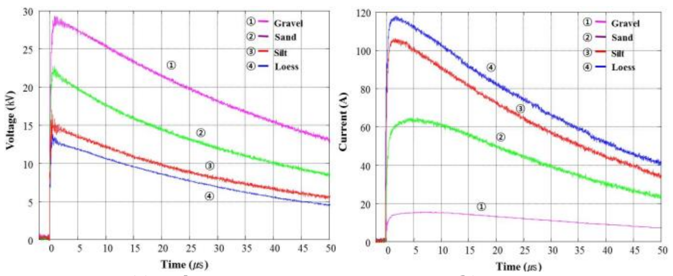


Figure 3. Electric field intensity that causes the electrical breakdown by type of soil

As in the previous analysis of the electrical breakdown voltage and current waveforms, the larger the size of the particles of the soil, the higher the ratio occupied by air voids, which is thought to be the cause of the rise in electrical breakdown voltage. In addition, the difference of electrical breakdown voltage for four soil samples according to the polarity was not evidently observed.

C. Transient ground impedance

Soils were uniformly mixed with the content of 4 % rainwater with 220 Ω·m resistivity and were supplied with a lightning voltage of 32 kV. Figure 4 shows the typical examples of the terminal voltage and current waveforms between the electrodes. Even with the same applied voltage, the terminal voltages and the currents showed different waveforms for each sample. Gravel showed the highest terminal voltage of 29.3 kV, and the loess was measured the lowest. In contrast, the current of the loess flowed the largest and the gravel the smallest. For loess, the peak of the terminal voltage showed approximately 13 kV because the electrical resistance of loess is small.



(a) Voltage (b) Current

Figure 4. Impulse voltage and current waveforms when the lightning impulse voltage of 32 kV was applied between the inner and outer electrodes

The terminal voltage and current waveforms for the sand sample is greater in current growth width and voltage drop rate, and the ionization was remarkable compared to other samples. The results indicate that out of four samples, the sand will relatively discharge more current to the ground when the ground electrodes were constructed in the ground. The voltage and current waveforms of Figure 4 where each soils were supplied with the impulse voltage of 32 kV, were calculated into *Z-t* curve and *V-I* curve using Matlab and were shown in Figures 5 and 6, respectively.

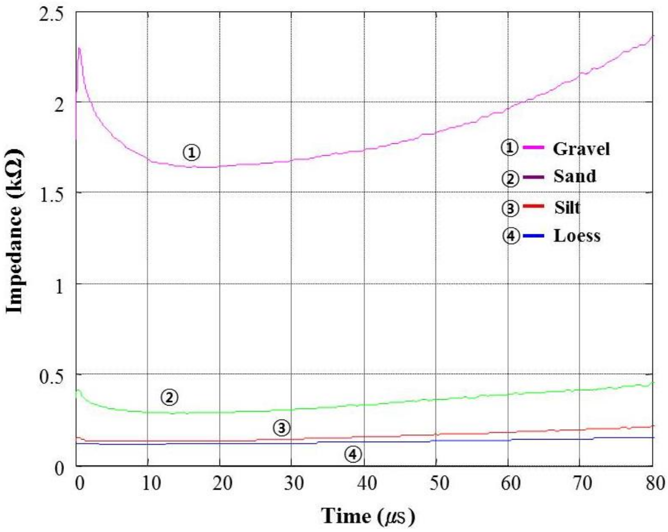


Figure 5. Exmaples of *Z-t* curves for each soil types

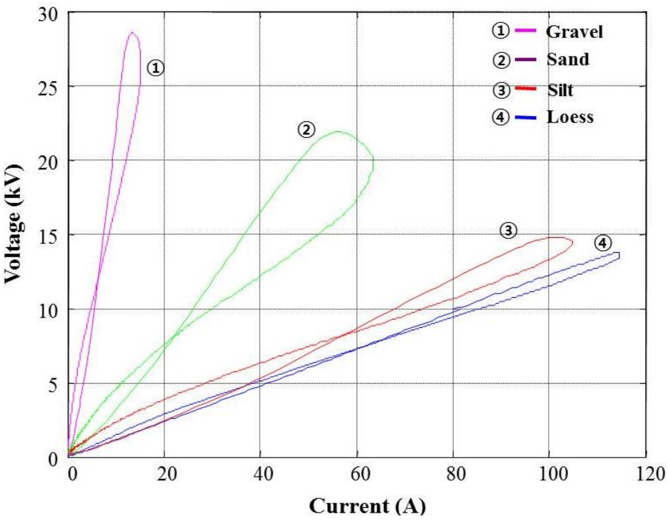


Figure 6. Examples of *V-I* curves for each soil types

When the ionization occurs in soil, because the soil flows along with not only the conducive current but with the ionized current, the ground impedance is dramatically reduced. When the ionization current reaches its maximum value, the ground impedance is reduced to a minimum, after which ground impedance returns to the initial value due to de-ionization phenomenon. The area of the cross-closed loop becomes larger as the ionization occurs more strongly [10].

The results in Figure 5 show that for the gravel, the reduction of the ground impedance due to ionization is much significant, and the reduction of ground impedance due to ionization growth in the sand was also observed to a significant degree. In contrast, a little change in the gound impedance in the silt and loess showed, with a substantially constant value.

V-I curve, when applied with the impulse voltage of 32 kV, represented a ribbon form of cross-closed loop in all soil samples. The gravel's ribbon area showed to have a small and slender cross-closed loop but strong variation, and in the case of loess, the ground impedance was small, therefore reducing the current growth rate of ionization due to large conduction current.

D. Equivalent ionization radius of soils

Ionization growth occurring on the surface of the ground electrode advances in the radial direction towards the outer electrode, so when the ionization occurs, the equivalent radius of the ground electrodes increases. Therefore, the equivalent radius of the ground electrode can be estimated from the reduction of ground resistance with the increasing current impulse. If the cylindrical container installed with ground electrode on the central axis is filled with the test soil, the ground resistance can be calculated with the following formula [5].

$$R = \frac{\rho}{2\pi l} \ln \frac{r_o}{r_i} \tag{2}$$

where,

l : length of the ground electrode

r_o : radius of the cylindrical container

r_i : radius of the ground electrode

ρ : soil resistivity

The ground resistance R without the effect of the inductance from the waveforms of the potential and current are calculated by the following formula (3). Assuming that the soil resistivity does not change due to ionization, the equivalent ionization radius can be calculated, respectively [5, 9, 10].

$$R = \frac{V_{Ipeak}}{I_{peak}} \tag{3}$$

$$r_i = \frac{r_o}{e^{\frac{2\pi l}{\rho}}} \tag{4}$$

Applying the above equation, Figure 7 represents the equivalent radius of ionization with time calculated by the Matlab when applying the impulse voltage of 32 kV to each soils. The peak value of the ionization radius of each soil was calculated in the order of sand 8.2 mm, gravel 5.7 mm, silt 4.7 mm, and the loess 2.8 mm. The time appearing the maximum ionization was different for each soil regardless of the size of the equivalent radius, and after passing the peak point, the ionization radius reduces again.

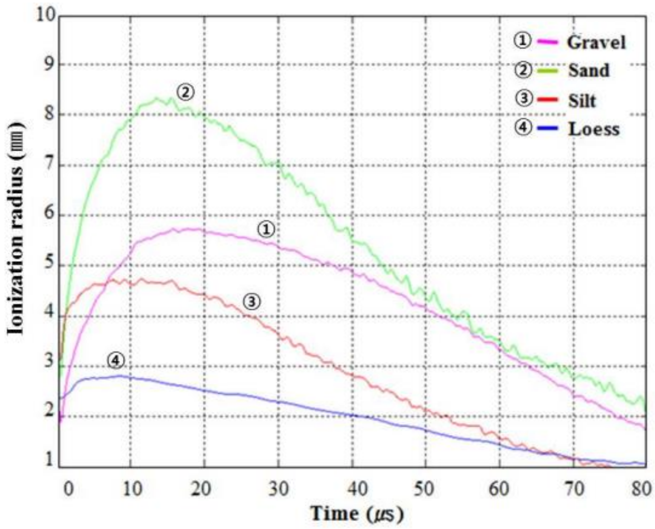


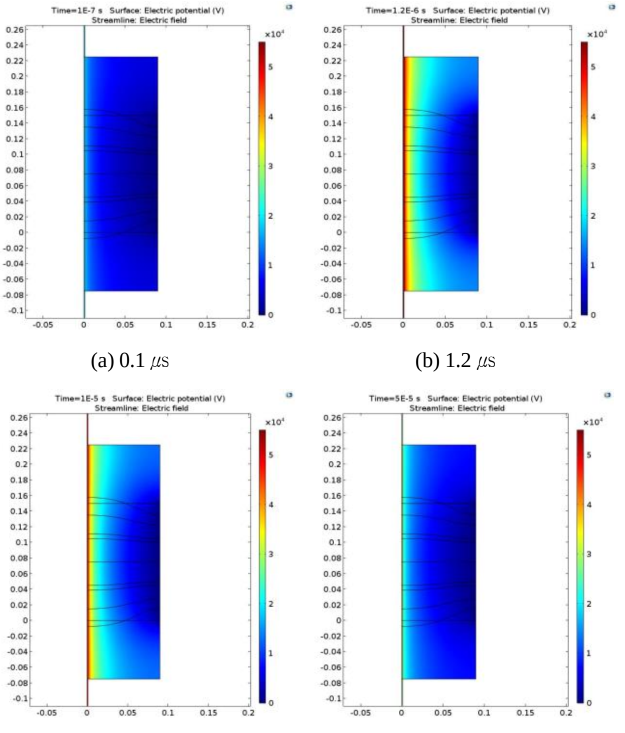
Figure 7. Equivalent ionization radius with time after the application of the lightning impulse voltage.

IV. REVIEW BASED ON NUMERICAL ANALYSIS

Figure 8 displays the distribution and the streamlines of the electric field that forms as time elapses after the lightning impulse voltage of 55 kV is applied between the inner and outer electrode filled with the dry sand. With the application of lightning impulse voltage, the electric field concentrates on the surface of the ground electrode placed on the central axis and you can view the streamlines towards the outer electrode from the center of the ground electrode. The electric field intensity near the surface of the ground electrodes is higher than in both directions along the upper and lower sides of the ground electrodes. That is, the soil ionization under the lightning impulse voltage is inferred to progress most actively in the central part of the ground electrode.

If lightning impulse voltage is applied to the soil, as shown in Figure 8, the electric field intensity over time, can be found with a tendency to gradually decrease after a rise. This process has noticeable similarities with the process when the 1.2/50 μs standard lightning impulse voltage is applied to the soil, the ionization current reaches the maximum value, and the ground impedance is reduced to a minimum, and due to the de-ionized ions, it returns to the initial value.

When a lightning impulse voltage is applied to the ground electrode, the electric field intensity at various positions around the ground electrode changes in time. That is, since the time-varying voltage is applied to the ground electrode, the electric field intensity at a certain point represents the time-varying characteristics.



(a) 0.1 μs (b) 1.2 μs

(c) 10 μs (d) 50 μs

Figure 8. Electric field distribution and the streamlines formed in the vicinity of the electrode surface

Figure 9 shows the electric field intensity according to the distance from the center of the ground electrode to the surface of the coaxial cylindrical container adopted in this work, supplied with 1.2/50 μs standard lightning impulse voltage.

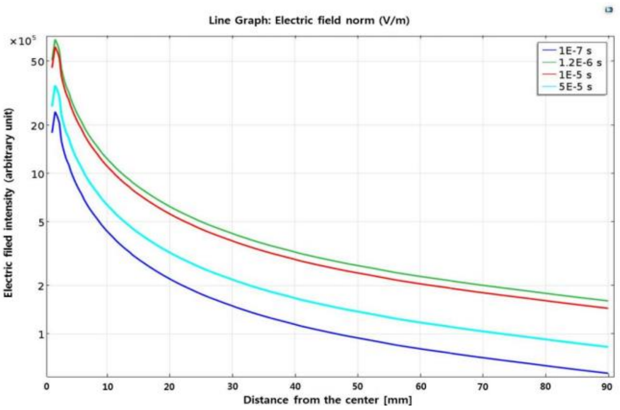


Figure 9. Electric field intensity according to the distance from the center of inner electrode stressed by the lightning impulse voltages

The electric field intensity gets different in every position over time, but when the impulse voltage is applied, and the electric field intensity reaches a peak point, and a drastic reduction can be seen.

V. Conclusion

As a result of studies to analyze electrical properties associated with the ionization growth of the soil in a coaxial cylindrical electrode system under lightning impulse voltage, the results were as follows.

a) Breakdown voltage and current waveforms of the dry soils are dependent on the type of soil, and the critical breakdown field intensity on both positive and negative polarities are found in order of gravel, sand, loess, and silt.
b) Transient ground impedance associated with the soil ionization decreased much significantly in the case of gravel. In the case of loess and silt, the ground impedance caused by the ionization was decreased weakly.
c) Under the application of the same amplitude of the lightning impulse voltage, the equivalent ionization radius of soils showed sand with the largest radius, and the loess with the smallest.
d) A method of analyzing the transient ground impedances of the ground electrode based on the soil ionization phenomena was presented and it could serve as useful means to improve the performance of the lightning protection system.

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