Analysis of Soil Ionization Behaviors under Impulse Currents

Bok-Hee Lee†, Geon-Hun Park*, Hoe-Gu Kim* and Kyu-Sun Lee*

Abstract – This paper presents the characteristics of soil ionization for different water contents, and the parameters associated with the dynamic properties of a simple model grounding system subject to lightning impulse currents. The laboratory experiments for this study were carried out based on factors affecting the soil resistivities. The soil resistivities are adjusted with water contents in the range from 2 to 8% by weight. A test cell with a spherical electrode buried in the middle of the hemispherical container was used. As a result, the electric field intensity E_c initiating ionization is decreased with the reduction of soil resistivities. Also, as the water content increased, the pre-ionization resistance R_1 and the post-ionization resistance R_2 became lower with increasing current amplitude. The time-lag to ionization t_1 and the time-lag to the second current peak t_2 at high applied voltages were significantly shorter than those of low applied voltages. It was found that the soil ionization behaviors are highly dependent on the water content and the applied voltage amplitude.

Keywords: Soil ionization, Critical electric field intensity for ionization, Soil resistivity, *V-I* curve, Impulse current

1. Introduction

To properly dissipate surge currents into the ground, it is necessary that grounding electrode systems have to be designed having low grounding impedance. The processes by which impulse currents diffuse into the ground are very complicated, and the high impulse currents generally cause soil ionization with nonlinear characteristics at the ground electrode. The performance of grounding systems under power frequency voltage or under low voltage is not necessarily valid under high-amplitude impulse voltages. So far, studies on non-linear ionization characteristics which occur in soils around ground rod flowing high currents have been carried out steadily [1] - [4].

The highly non-linear behaviors exhibited by grounding systems under high current discharge have been attributed to two main electrical processes: (a) thermal effects due to high currents, and (b) soil ionization due to the field enhancement in trapped air voids within the soil [5],[6]. The transient characteristics of grounding systems under high impulse currents are still not well understood [7], [8].

Understanding the soil ionization behaviors under transient currents is important in order to achieve the high performance grounding systems needed to protect the electrical and electronic equipment from over-voltages. The aim of this investigation is to achieve more detailed information on the soil ionization affecting the performance of grounding systems. The experimental studies on the soil ionization behaviors under lightning impulse currents were carried out. In this paper, the electrical parameters such as critical electric field intensity for ionization, pre-ionization and post-ionization resistances related to soil ionization behaviors were analyzed. The results obtained in this work will refer to the analysis of the dynamic performance of grounding systems under lightning impulse currents.

2. Experimental Arrangement

2.1 Experimental Set-up

Fig.1 shows the experimental set-up consisting of impulse voltage generator, electrode arrangement, voltage and current measuring system used in the observation of soil ionization. In this study, a hemispherical container 300 mm in diameter was adopted as a model grounding system. A spherical metal electrode 25.4 mm in diameter was half-buried in the middle of the container. This hemispherical ground electrode system is used to facilitate the analytical expressions for the electric field computations. The spacing between the ground electrode and the bottom of the container was 137 mm.

The 1.2/50 μs impulse voltage is generated by a four stage Marx generator with a voltage of 400 kV, which is

† Corresponding author: School of Electrical Engineering, Inha University, Incheon, Korea. (e-mail: bhlee@inha.ac.kr).
* School of Electrical Engineering, Inha University, Incheon, Korea. (e-mail: changeeyes@hanmail.net, jackals7@naver.com, leeks0482@hanmail.net).
Received 2 July, 2008; Accepted 17 November, 2008

applied to the test electrode. A capacitive divider with a ratio of 10,000:1 was used for the voltage measurement. The current was measured by using a coaxial shunt of 0.02 Ω in series with the grounded plate. The voltage and current signals were recorded by a 4 channel 500 MHz oscilloscope together with a function of data acquisition and Matlab software was utilized for the data analysis. The control devices and instruments were placed in a Faraday cage. Also, high-frequency line filters and an isolating transformer were installed on the power mains of the instruments to reduce noise and disturbances.

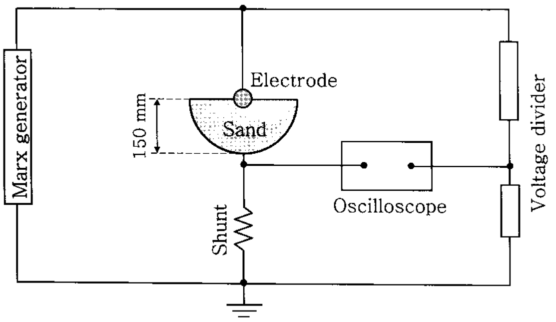


Fig. 1 Block diagram of the experimental set-up

2.2 Experimental Methods

Medium grain size sand was adopted as the test sample because the sand is easily wetted and dried without damage to its physical properties. Medium grain size sand of 0.425-2 mm based on ASTM (D422) and KS A 5101 was used in this experiment. Medium grain size sand is classified by using a standard sieve.

In order to analyze soil ionization characteristics as a function of water content, the water content of sand is controlled by using tap water with a resistivity of 70 Ω · m. Water contents of sand used as the test sample range from 2 to 8% by weight. The sand and water mixed equally to ensure uniform wetting of the sand. The sand is dried prior to subsequent experiments to ensure uniform conditions. After the sand is poured into the test container, it is compacted to a uniform pressure of 5 kPa by the weight in order to eliminate the effect of air voids among the sand grains that may result in air discharges.

Impulse tests were carried out for different voltage amplitudes from 15 to 30 kV. The physical and electrical parameters related to the effect of the soil ionization processes were analyzed and discussed based on the voltage and current waveforms, critical electric fields for ionization and breakdown, pre-ionization and post-ionization resistances and *V-I* curves.

3. Results and Discussion

3.1 Parameters characterizing soil ionization

Fig. 2 shows typical voltage and current responses indicating the appearance of soil ionization. Generally, nonlinear soil behaviour is said to occur when the second current peak is observed. Soil ionization leads to the increase of current and a corresponding decrease of voltage. Therefore, during the soil ionization, the soil resistivity is drastically decreased. Two current peaks could be attributed to thermal and ionization processes [5], [9]. High initial peaks on the current trace were considered to be caused by capacitive effects of the medium between the sand grains and at the interface between sand particles and the electrode [10]. The rise time of the current is slower than that of the applied voltage because of the ionization and inductance of the test circuit. The voltage and current traces are slowly decayed due to the large resistance. The voltage and current waveforms are similar to those reported by other researchers [5], [9], [11], [12].

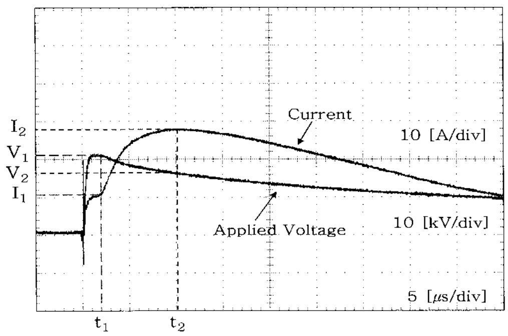


Fig. 2 Typical voltage and current traces for high voltage above an initiation level of ionization and the definition of time parameters for soil ionization

Soil ionization occurs by electric field enhancement in voids, and interfacial surfaces with the soil grain, which leads to localized arcing inducing the reduction of the impedance.

The voltage and current waveforms were observed for different water contents and current amplitudes in order to analyze the soil ionization processes under high impulse voltages. The soil ionization processes are classified into two categories: one part occurs before ionization and the other after ionization. It is assumed that the nonlinear behaviour of the voltage and current responses occurs due to soil ionization. When applying the impulse voltage above the critical value, the streamer corona is initiated at the surface of the test electrode placed in the middle of the hemispherical container, and it propagates from the test electrode toward the container. The second peak of the current trace is formed due to the occurrence of the streamer corona.

The time-lag to the initiation of soil ionization t_1 and the time-lag to the second current peak t_2 as time parameters of soil ionization are defined as indicated in Fig. 2.

3.2 Critical electric field intensities for ionization and breakdown

The principal factor affecting soil resistivity is the water content in soils. The soil resistivities ranging from a few Ω · m to several kΩ · m are changed, under controlled conditions, by using differing water content, grain size and type of soil [11],[13]. In this study, in order to determine the effects of soil resistivities on the critical electric field for ionization E_c, the sand resistivities were controlled by mixing the sand with different levels of water content. Generally, the critical electric field for ionization E_c is determined at the instant when the *V-I* characteristic starts to become nonlinear. The critical electric field intensity at the surface of the ground electrode consisting of the concentric hemispherical test cell is given by [11],[12]:

$$E(r) = \frac{V}{r^2(\frac{1}{r_1} - \frac{1}{r_2})} \tag{1}$$

where r_1 is the radius of the ground electrode, r_2 is the radius of the hemispherical container, r is the radius of the ionization and V is the applied voltage at the ground electrode.

The measurements of voltage and current waveforms were made repeatedly until the oscillograms indicate soil ionization or breakdown with fine adjustment of the applied voltage.

The critical electric field intensities for ionization and breakdown at the surface of the ground electrode were calculated by substituting the measured ionization and breakdown voltage into equation (1), respectively.

The critical electric field intensities for ionization and breakdown of the sand with varying water content under the positive impulse are shown in Fig. 3. The up-and-down method based on KS C IEC 60060 was employed to determine breakdown electric field intensity [14].

At least 10 shots were applied for each test sample to decide the breakdown voltage. It was found that the initiation voltage of 19.1 kV corresponds to the critical

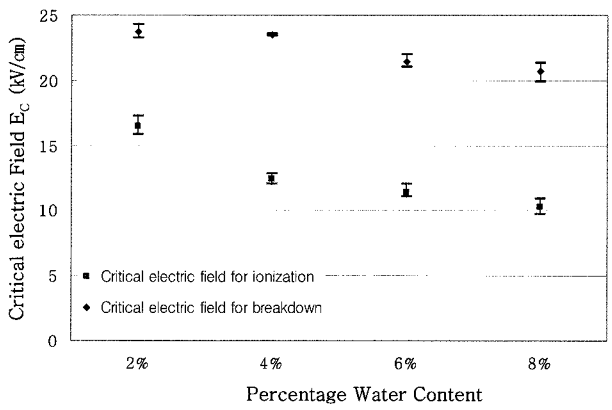


Fig. 3 Critical electric field intensities for ionization and breakdown in medium grain size sand as a function of water content

electric field intensity E_c of 16.5 kV/cm at a water content of 2% and the initiation voltage of 11.9 kV corresponds to the critical electric field intensity E_c of 10.2 kV/cm at a water content of 8%. The critical electric field intensity for ionization decreases as a function of the increasing water content, and is dependant on water content. This is because soil ionization occurs to a high degree in soil with higher water contents. Also, the critical electric field intensity for breakdown calculated to compare the critical electric field intensity for ionization decreases slightly with increasing water content.

3.3 Pre-ionization and post-ionization resistances

The transient impedances of grounding systems are directly related to the soil ionization processes under impulse voltages. It is now widely accepted that the second current peak shown in Fig. 2 is caused by soil ionization. The existence of the second current peak allows the definition of two resistances discriminating between pre-ionization resistance R_1 and post-ionization resistance R_2, where R_1 is related to the first current peak and R_2 corresponds to the second current peak. The resistances are calculated as the ratio of the voltage, when the current is the maximum, to the maximum current value. They are expressed as follows [5],[12]:

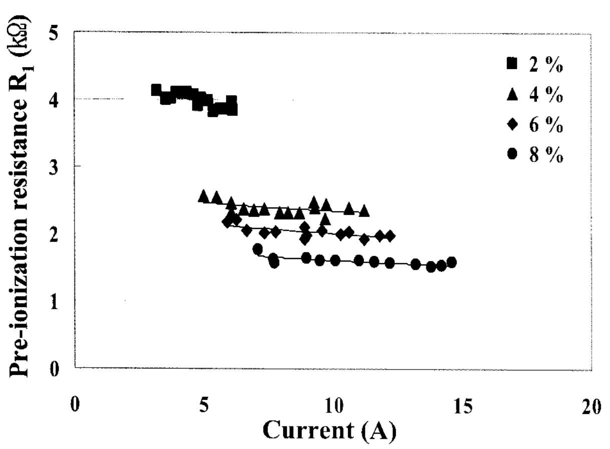
$$R_1 = \frac{V(I_{peak1})}{I_{peak1}} \tag{2}$$

and

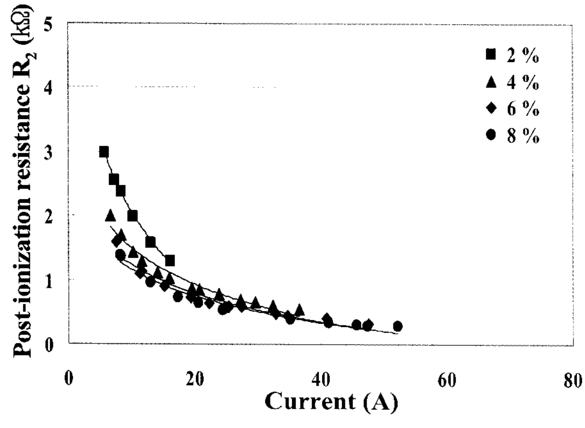
$$R_2 = \frac{V(I_{peak2})}{I_{peak2}} \tag{3}$$

where I_{peak1} is the first current peak, I_{peak2} is the second current peak and V is the applied voltage at the instant of the corresponding peak current. The inductive effect is excluded in these results since at the instant of peak current, d*i*/d*t* = 0.

The low conduction currents in the test sand medium with higher resistivity were observed. The pre-ionization resistance R_1 and the post-ionization resistance R_2 were measured as a function of peak currents obtained for different water content, up to the breakdown voltage of the test cell. Fig. 4(a) shows the pre-ionization resistance R_1 against the current amplitude. The pre-ionization resistance R_1 without soil ionization has only slight variation with increasing current amplitude. Also, R_1 is obtained to have lower amplitude with increasing water content.



(a) Pre-ionization resistance R_1 against current amplitude



(b) Post-ionization resistance R_2 against current amplitude

Fig. 4 Pre-ionization and post-ionization resistances as a function of current amplitude

The temperature of soil may be measured due to repeated application of the test current. The reason for the reduction of R_1 is due to thermal effects. If no evaporation occurs, an increase in the temperature of soil will result in a slight decrease of the soil resistance, due to the increased mobility of the ions. R_1 reduces to a minimum of 1.58 kΩ for sand mixed with a water content of 8%.

Soil ionization occurs near the surface of the ground electrode, above the critical electric field intensity, and decreases the ground resistance. The post-ionization resistance R_2 was illustrated as a function of peak currents obtained for different water content under positive impulse voltages, and it decreased with increases in the current amplitude for any given water content, as shown in Fig. 4(b). The post-ionization resistance R_2 is a nonlinear function of the injected impulse current.

The post-ionization resistance R_2 is significantly decreased according to, not only the increase of current amplitude, but also the increase of the water content. For higher water contents, above 6%, the post-ionization resistances were less dependent upon current amplitude. It was observed that the nonlinearity is much pronounced at peak current amplitude below 20 A where the resistance decreased steeply. The post-ionization resistance R_2 is reduced to a minimum value of 1.3 kΩ at a water content of 2% and the minimum of 290 Ω at a water content of 8%. Due to soil ionization, the effective radius of the live electrode is expanded to its maximum volume, and consequently it is reducing resistance. When impulse tests are repeated under the same conditions, good repeatability is obtained, and values of the post-ionization resistance R_2 are measured similarly. This resistance R_2 is always lower than the pre-ionization resistance R_1.

The ground resistance of the hemispherical grounding system can be given by:

$$R_1 = \frac{\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \quad (4)$$

where r_1 is the radius of the ground electrode, r_2 is the radius of the hemispherical container and ρ is the soil resistivity without soil ionization. The soil resistivity in this test condition was calculated by using the pre-ionization resistance R_1. The soil resistivity could be obtained with reasonable accuracy. The measured soil resistivity based on the pre-ionization resistance was tabulated in Table 1.

Table 1 Measured soil resistivity as function of water content

Water content [%]	2	4	6	8
Resistivity [Ω·m]	336.5	208.4	169.1	134.3

The post-ionization resistance is closely related to the extension of the soil ionization region and the variation of the ionization region's resistivity. The large second current peak is caused by the occurrence of the streamer corona at the surface of the ground electrode. The soil resistivity in the streamer corona region drops to nearly zero [15]. This results in the extension of the effective radius of the ground electrode. The dependence of the ionization region on the current amplitude was investigated. The current-dependent ionization region can be simply estimated on the assumption that the concentric hemispherical equipotential surface is formed with the equivalent radius of ionization, and this symmetry is maintained even during the soil ionization. Cooray *et al.* [16] have reported that the fractional volume of ionization remains constant as the discharge phenomena expand radially away from the conductor. This is not far from reality because in general the electrical discharges form branches and expand laterally as they proceed away from the high-voltage electrode. Fig. 5 shows a sketch of the cross-sectional view of ionization region near the surface of the ground electrode.

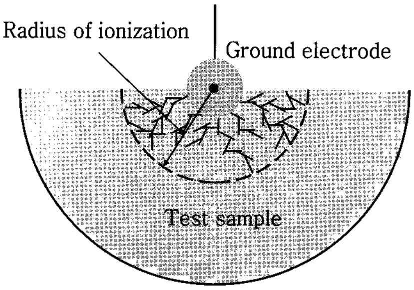


Fig. 5 Hemispherical model for ionization region

The post-ionization resistance R_2 can be explained by the extension of the ionization region. Assuming that the ionization region expands uniformly, the equivalent radius of the ionization region could be calculated based on the post-ionization resistance R_2. The equivalent radius of the ionization region is estimated as:

$$R_2 = \frac{\rho}{2\pi}\left(\frac{1}{r_i} - \frac{1}{r_2}\right) \tag{5}$$

where r_i is the equivalent radius of ionization region.

In this analysis, it has been assumed that the soil ionization takes place uniformly near the surface of the half-buried ground electrode. However, practically, the electric field may be enhanced at the contact point between the buried electrode surface and the sand grains, and it is probable that the ionization is initiated first at the field enhanced point and propagates toward the opposite electrode. The radius of the ionization region increases with current amplitude and is weakly dependent on the water content as shown in Fig. 6.

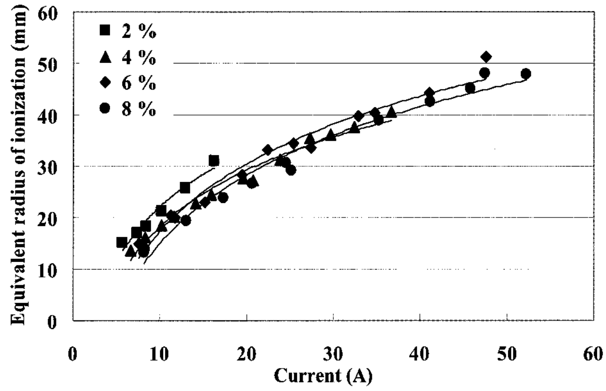
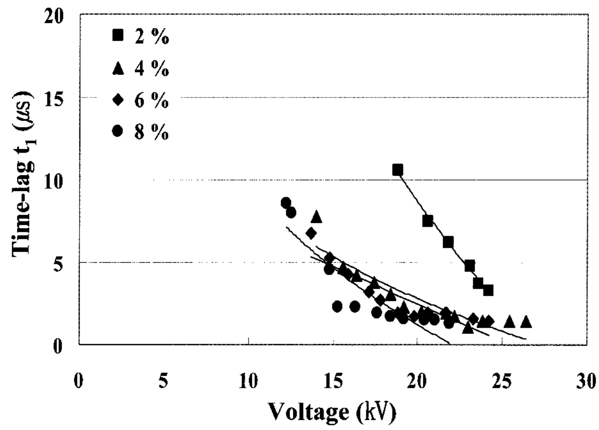


Fig. 6 Equivalent radius of ionization region against the current amplitude

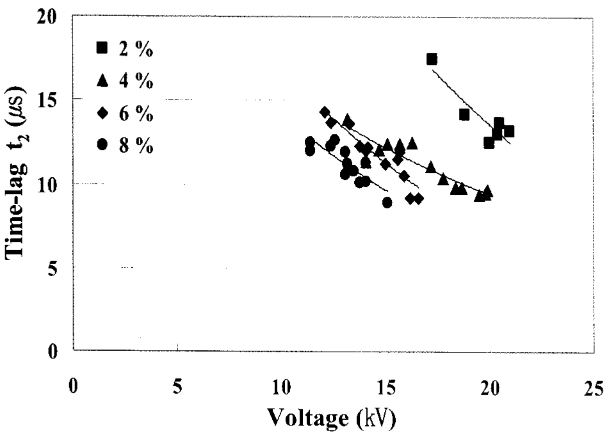
3.4 Time-lags to the initiation of ionization

The time-lag to the initiation of ionization t_1 and the time-lag to the second current peak t_2 were evaluated based on the voltage and current oscillograms as a parameter of water content.

The time-lag to initiation of ionization t_1 and the time-lag to the second current peak t_2 against voltage amplitudes with varying water contents were clearly illustrated in Fig. 7. Both time-lags are found to be shortened for with higher water contents, and are decreased as the voltage increases. i.e., it was known from this result that a fast ionization process occurs in sand with higher water content. Thus, it is considered relative to the ionization region reducing for low voltage and high soil resistivity. These results are in good agreement with previously reported trends [12].



(a) Time-lag to initiation of ionization



(b) Time-lag to the second current peak

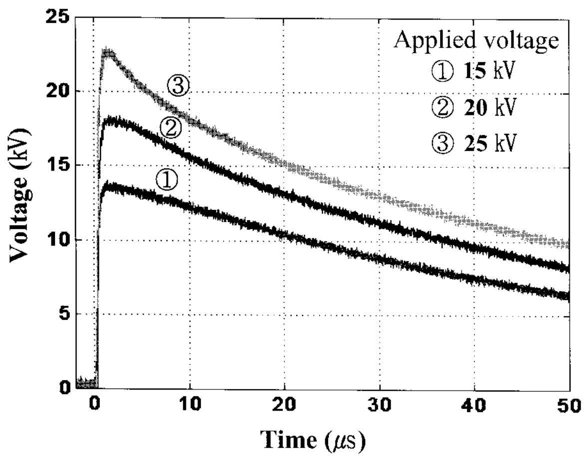
Fig. 7 Time-lags related to soil ionization process for various water contents

Consequently, it was known that the time-lags to ionization and propagation were influenced by the applied voltage amplitude and the water content.

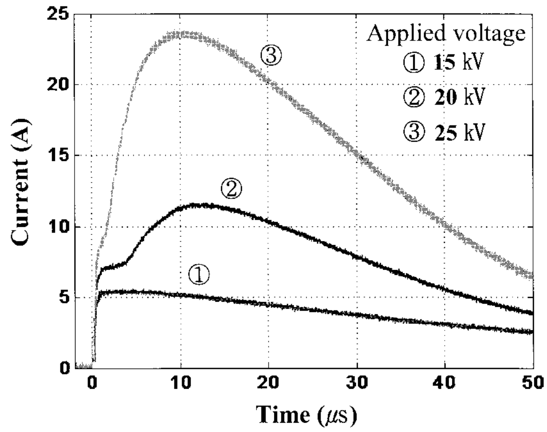
3.5 *V-I* curves

In addition, the analysis method of the *V-I* characteristic curve is utilized to analyze the nonlinear characteristics of the soil ionization related to the current amplitude. The starting point of the ionization can be determined from the *V-I* curves. i.e., *V-I* curves were used in this work as an indicator discriminating soil ionization.

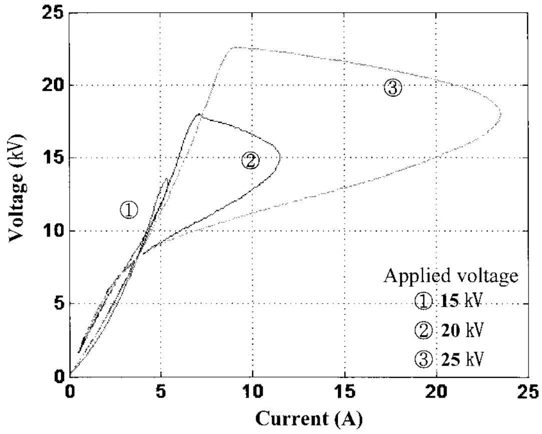
The voltage and current oscillograms and *V-I* curves indicated as a parameter of applied voltage in the sand with water content of 4% under impulse voltages are shown in Fig. 8. The voltage and current traces are dependent on the applied voltage amplitude.



(a) Voltage waveform



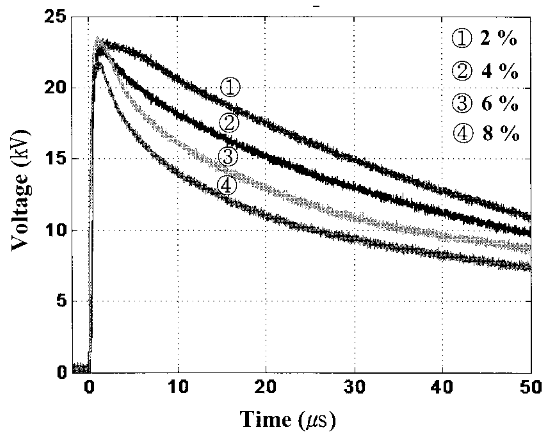
(b) Current waveform



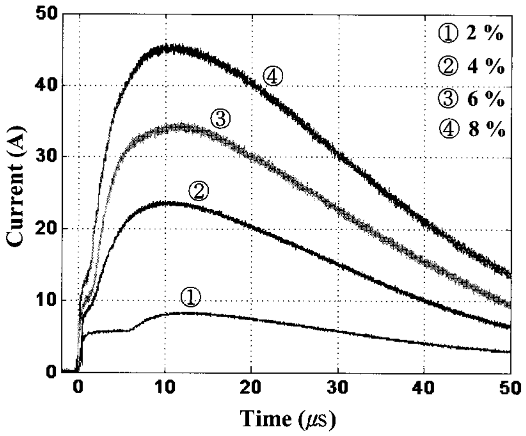
(c) *V-I* curves

Fig. 8 *V-I* curves indicated as a parameter of applied voltage amplitudes at the water content of 4%

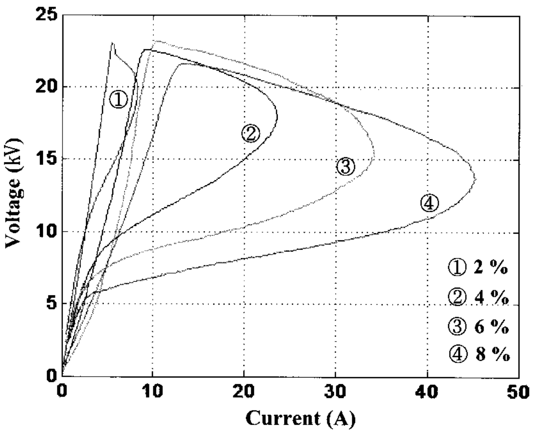
V-I curves are almost linear at the applied voltage of 15 kV. However *V-I* curves form a loop due to the difference in rise time and decay time between the voltage and current traces above the applied voltage of 20 kV. The large size of the loop indicates the discharge of large amounts of energy into the soil.



(a) Voltage waveform



(b) Current waveform



(c) *V-I* curves

Fig. 9 *V-I* curves indicated as a parameter of water contents at the applied voltage of 25 kV

Fig. 9 shows the voltage and current oscillograms, *V-I* curves indicated as a parameter of the water content at the positive applied voltage amplitude of 25 kV. *V-I* curves are strongly dependent on the water content, and the size of the loop increases with increases in the applied voltage and the water content. When the water content is increased, the potential rise is decreased but the current increases. It is obvious from the current traces that the soil ionization at the surface of ground electrode occurs, and the time-lag to initiation of ionization is shortened with increases in the water content. *V-I* curves are observed as loops with the feature rotating by a right-handed screw. Also, these are shifted into the right-hand side with increasing water content. The size of the enclosed *V-I* curves for higher water content is more extensive compared to that for lower water content. The parameters associated with soil ionization obtained in this work helps to achieve the design of high performance grounding systems subject to high impulse currents.

4. Conclusion

In this paper, investigations of soil ionization occurring in sand with varying water content under impulse currents were experimentally carried out. The results can be summarized as follows:

A linear relation between voltage and current traces at the low applied voltage has been observed. On the other hand, nonlinear characteristics between voltage and current traces appeared above the critical ionization voltages. As the soil resistivity reduces, the critical electric field intensity for ionization decreases. The pre-ionization resistance was found to be less dependent upon current amplitude. However, the post-ionization resistances decrease with increasing water content. The post-ionization resistance is always lower than the pre-ionization resistance regardless of water content. The higher the water content is, the shorter the time-lag to initiation of ionization and the time-lag to the second peak. The *V-I* curve is a novel method to determine the critical electric field intensity for ionization. Consequently, the soil ionization behaviors closely depend not only on the water content, but also the applied voltage amplitude. The obtained results may provide useful information on the design of grounding systems protecting electrical and electronic equipment from overvoltages.

Acknowledgements

This work was supported by the Ministry of Knowledge Economy under Grant R-2007-1-014.

References

[1] I. F. Genos, I.A. Stathopulos, "Soil ionization under lightning impulse voltages", IEE Proc.-Sci. Meas. Technol., Vol.151, pp. 343-346, 2004.

[2] J. Wang, A. C. Liew, M. Darveniza, "Extension of Dynamic Model of Impulse Behavior of Concentrated Grounds at High Currents", IEEE Trans. on Power Delivery, Vol.30, No.3, pp.2160-2165, 2005.

[3] P. Espel, R. R. Diaz, A. Bonamy, and J. N. Silva, "Electrical Parameters Associated With Discharges in Resistive Soils", IEEE Trans. Power Delivery, Vol.19, No.3, pp. 1174-1182, July. 2004.

[4] N. Mohamad Nor and A. Ramli, "Effects of Moisture content, impulse polarity and earth electrode's dimension on dry and wet sand under high voltage conditions", Euro. Trans. Electr. Power, John Wiley & Sons, Ltd, DOI; 10.1002, 2007.

[5] N. Mohamad Nor, S. Srisakot, H Griffiths, and A. Haddad, "Characterization of Soil Ionization Under Fast Impulses", Proc. ICLP 2000, pp. 417-422, 2000.

[6] P. Chowdhuri, "Impulse impedance tests on laboratory model ground electrodes", IEE Proc. Gener. Transm. Distrib. Vol.150, No.4, pp.427-433, 2003.

[7] Abdul M. Mousa, "The Soil Ionization Gradient Associated with Discharge of High Currents into Concentrated Electrodes", IEEE Trans. on Power Delivery, Vol.9, No.3, pp.1669-1677, 1994.

[8] R. Kosztaluk, M. Loboda, D. Mukhedkar. "Experimental Study of Transient Ground Impedances", IEEE Trans. Vol. PAS-100, No. 11, pp.4653-4660, 1981.

[9] N. Mohamad Nor, A. Haddad, and H Griffiths, "Performance of Earthing Systems of Low Resistivity Soils", IEEE Trans. Power Delivery, Vol.21, No.4, pp. 2039-2047, 2006.

[10] N. A. Idris, H. Ahmad and M. N. Isa, "Impulse Impedance Tests on Laboratory Model Earth Electrode", 2005 Asia-Pacific Conference Proceedings, pp.157-161, 2005.

[11] N. Mohamad Nor, A. Haddad, and H Griffiths, "Determination of Threshold Electric Field Ec of Soil Under High Impulse Currents", IEEE Trans. Power Delivery, Vol.20, pp. 2108-2113, July. 2005.

[12] N. Mohamad Nor, A. Haddad, and H Griffiths, "Characterization of Ionization Phenomena in Soils Under Fast Impulses," IEEE Trans. Power Delivery, Vol.21, pp. 353-361, Jan. 2006.

[13] Bok-Hee Lee, Seng-Chil Lee, "The Major Fundamental Technics for Grounding Systems", 2nd ed, Uijae, 1999, pp.37-104.

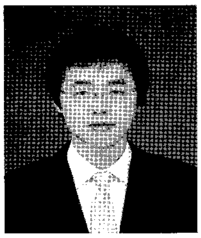
[14] KS C IEC 60060 Std, Part 1 - Guide on High-Voltage Testing Techniques, pp.23-26, 2002.

[15] S. Sekioka. M. I. Lorentzou, M. P. Philppakou, and J. M. P rousalidis. "Current-Dependent Grounding Resistance Model Based on Energy Balance of Soil Ionization", IEEE Trans. on Power Delivery, Vol.21, No.1, pp.194-201, 2006.

[16] V. Cooray, M. Zitnik, M. Manyahi, R. Montano, M. Rahman, and Y. Liu, "Physical model of surge-current characteristics of buried vertical rods in the presence of soil ionization", J. Electrostatics, Vol.60, pp.193-203, 2004.

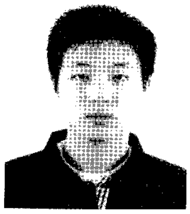
Bok-Hee Lee

He was born in Korea on June 29, 1954. He received his B.S. degree in Electrical Engineering from Inha University in 1980 and his Ph.D. degree in Electrical Engineering from Inha University in 1987, respectively. He joined the Department of Electrical Engineering at Inha University, Incheon, Korea as an Assistant Professor in 1990, and became a Professor there in 1999. From 1988 to 1989 he was a post-doctoral research fellow at the Institute of Industrial Science, University of Tokyo. From Apr. 1999 to Feb. 2000, he was a Visiting Professor at the University of Cincinnati. Since Oct. 2002, he has been a Director in the Research Center for High-voltage and Power Technology, Inha University. His research interests are in the area of lightning, lightning protection, grounding systems, surge protection, high voltage engineering and electromagnetic compatibility. Tel. 032-860-7398, Fax. 032-863-5822.



Geon-Hun Park

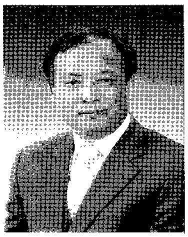
He received his B.S. degree in Electrical Engineering from Inha University in 2007. He is currently pursuing his M.S. degree in the School of Electrical Engineering at Inha University. His research interest is in the area of grounding systems.



Hoe-Gu Kim

He received his B.S. degree in Electrical Engineering from Korean Educational Development Institute in 2007. Currently he is pursuing his M.S. degree in the Dept. of Electrical Engineering at Inha University. His research interest is in the area of grounding systems.

Kyu-Sun Lee



He received his B.S. degree in Electrical Engineering from Korean Educational Development Institute in 2004 and his M.S. degree in the Dept. of Electrical Engineering at Inha University. Currently he is pursuing his Ph. D degree in the Dept. of Electrical Engineering at Inha University. His research interests are in the area of lightning protection and grounding systems.