Effective Impulse Impedances of Deeply Driven Grounding Electrodes

Bok-Hee Lee†, Dong-Cheol Jeong*, Su-Bong Lee* and Keun-Chul Chang*

Abstract - This paper presents the characteristics of transient and effective impulse impedances for deeply driven grounding electrodes used in soil with high resistivity or in downtown areas. The laboratory test associated with the time domain performance of grounding piles subjected to a lightning stroke current has been carried out using an actual-sized model grounding system. The ground impedances of the deeply driven ground rods and grounding pile under impulse currents showed inductive characteristics, and the effective impulse ground impedance owing to the inductive component is higher than the power frequency ground impedance. Both power frequency ground impedance and effective impulse ground impedance decrease upon increasing the length of the model grounding electrodes. Furthermore, the effective impulse ground impedances of the deeply driven grounding electrodes are significantly amplified in impulse currents with a rapid rise time. The reduction of the power frequency ground impedance is decisive to improve the impulse impedance characteristics of grounding systems.

Keywords: Grounding, Grounding electrode, Ground potential rise, Ground resistance, Impulse current, Impulse ground impedance, Lightning protection, Revised fall-of-potential method.

1. Introduction

Fault currents in power systems and lightning stroke currents flowing through a ground system lead to a rise in the possibility of grounding electrodes and the incidence of injury occurring in the vicinity of related equipment. It is imperative to determine precisely the resulting ground conductor potential and the distribution of ground surface potential in the region of the grounding electrodes. The effects of an improper grounding system can range from erratic operation of electronic devices to minor physical harm or damage to electrical equipment. An effective grounding system that limits hazardous voltages and electromagnetic disturbances is essential to ensure personnel safety, protection and stable operation of microelectronic equipments such as computers, medical instruments and communication facilities. The aim of a grounding system is to lower the grounding system potential developed by power frequency fault currents or lightning current surges. Moreover, modern micro-electronic circuits and devices have low signal levels and are very sensitive to transient overvoltages. The effective grounding systems with low transient impedance to electromagnetic disturbances such as lightning surges or electronic noises in microelectronics and high-technology branches are strongly required. It is highly desirable to evaluate the effective impulse ground impedances as a measure of performance of grounding systems in which lightning and switching surge currents with fast rise time and high frequency flow. [1-4]

Impulse grounding system impedances play an important role in the protection of electrical installations against lightning. A systematic approach employing the measurement and analysis of impulse grounding system impedance in the fields of lightning protection systems and communication center buildings has been studied. The impulse behaviors of grounding systems subjected to lightning stroke currents are dependent on various factors such as soil resistivity, depth, shape and size of grounding electrodes, parameters of lightning stroke currents, etc. However, in due consideration of all these factors, it is very difficult to evaluate the impulse behaviors of grounding electrode systems. Little is actually known about the impulse characteristics of grounding system impedances, especially real-sized large grounding systems. In particular, the protecting performance of lightning surge arresters is affected by impulse grounding system impedances. If transient grounding system impedances are too high, the protecting performance of lightning surge arresters will be decreased. Therefore, the influence of transient grounding system impedances should be considered deliberately, and the effective impulse impedance of grounding systems must be evaluated.

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Received April 12, 2004; Accepted August 30, 2004

In order to analyze the dynamic impedance characteristics of actual-sized lightning and surge protection grounding systems, the present work is oriented on the analysis of the physical phenomena and transient characteristics that may occur when a lightning stroke current passes through a grounding system. The experiments were carried out in the deeply driven grounding electrodes of 12, 30 and 48 m lengths and the commercial grounding pile of 30 m in length using lightning impulse currents at the testing site of Inha University in Incheon, Korea. The transient ground impedances of the model deep-driven grounding electrodes as a function of the length of grounding electrodes were measured. Furthermore, the dependence of the effective grounding system impedances on the rise time of impulse current was analyzed.

2. Experiments

2.1 Experimental set-up

The laboratory experiments have been carried out using actual sized-grounding electrode systems. The conventional fall-of-potential method is a fundamental means for measuring the ground impedance of large-sized grounding systems, but in the cases of the impulse injection current and high frequency test current, a considerable problem results in relation to significant measurement errors caused by electromagnetic coupling between the current injection line and the reference potential probe wire or other interferences. Thus in this work the revised fall-of-potential method recommended by IEEE 81.2-1991 was employed. [5] The current injection line was extended at an angle of 90° with respect to the potential probe wire to reduce the effect of the electromagnetic coupling between them as shown in Fig. 1.

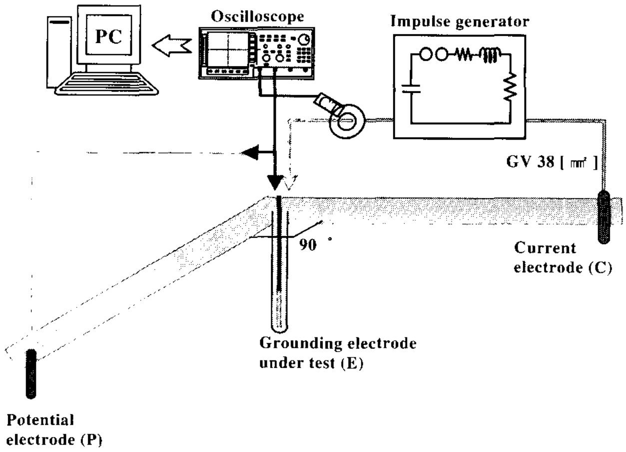


Fig. 1 Circuit diagram for measuring the ground impedance

The spacing between the grounding electrode under test E and the remote potential grounding electrode P was 60 m and the remote potential ground electrode was a vertical ground rod of 1.2 m. The return current electrode is a set of ground rods 2.4 m in length, placed at a distance of 60 m from the grounding electrode undergoing testing. The long copper-pipe grounding electrodes with the length of 12, 30 and 48 m were vertically installed on the ground surface, and their diameter was 150 mm.

2.2 Measurements

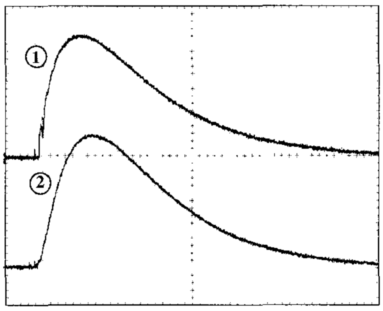
The combination wave generator is operated with an R-L-C series circuit in impulse current generator mode. The capacitance and maximum charging voltage of energy storage capacitor are 30 μF and 10 kV, respectively. The test current was measured by a current transformer with a frequency bandwidth of 400MHz. Also, the potential rise of the grounding electrode was measured by an active voltage probe with a high input impedance and a frequency bandwidth of 75 MHz. The waveforms of the injected impulse currents and grounding electrode potential are observed by digital storage at 500 MHz, 2.5 GS/s sampling rate oscilloscope, and the detected signals are registered on a personal computer.

3. Results and Discussion

3.1 Ground rod potential due to impulse currents

The apparent soil resistivity at the point of installation was measured using the Wenner four point method and was found to be equal to approximately 70 Ω·m. The measured ground resistance of the model grounding electrodes of 12, 30 and 48 m in length were 7.6, 6.8 and 4.7 Ω, respectively. The ground resistance is almost identical to the power frequency ground impedance. The test current is injected between the grounding system undergoing testing and the return current electrode 60 m away from the tested grounding system. When the trigger switch of the impulse current generator is closed, the test impulse current flowed through the grounding system. Then the waveforms of the injected current and grounding electrode potential are measured simultaneously. The lightning impulse current is injected into the top of the deeply driven grounding electrode. Figure 2 shows typical waveforms of the injected impulse current and the grounding electrode potential developed at the input point for the deeply driven grounding electrodes of 30 m in length.

The peak amplitude and rise time of the injected impulse current are 180 A and 8 μs, respectively. This current presents a relatively slow rise time. The rise time of p grounding electrode potential is shorter than that of the injected impulse current. This is not surprising since the waveform of the grounding electrode potential is a blend of resistive and inductive components. It is considered that the difference between the rise times of the injected impulse current and grounding electrode potential are due to the inductance of elongated grounding electrodes.

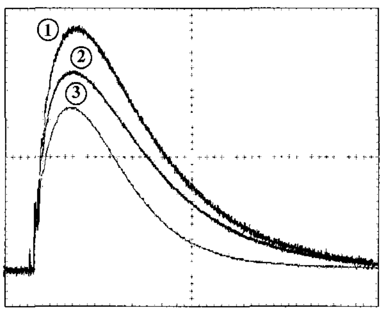


① : Potential rise 500 [V/div], 10 [μs/div]

② : Applied current 50 [A/div], 10 [μs/div]

Fig. 2 Waveforms of the injected impulse current and potential rise of the grounding electrode of 30 m in length

The waveforms of grounding electrode potential measured as a function of the length of grounding electrode are displayed in Fig. 3. It is obvious that the rise time and amplitude of the injected impulse current and grounding electrode potential are dependent on the length of the grounding electrode undergoing testing. Lengthier ground electrodes lead to low ground resistance and large inductance of the test circuit. The peak amplitude of impulse current of the combination wave generator is mainly determined by both the charging voltage of the capacitor and the inductance of the test circuit. Due to this reason the peak value of grounding electrode potential decreases with an increase in the length of the grounding electrode.



① : 250 [V/div], 10 [μs/div]

② and ③ : 200 [V/div], 10 [μs/div]

Fig. 3 Waveforms of the potential rise according to the length of the grounding electrode (Length of grounding electrode; ①: 12 m, ②: 30 m, ③: 48 m)

Generally, the rise time of impulse current waveform in the R-L-C series circuit multiplies with increasing inductance. However, in grounding systems, the ground resistance decreases and the inductance of the grounding electrode increases as the length of the grounding electrode becomes greater. The waveform parameters of the injected impulse current and grounding electrode potential are dependent on both the ground resistance and the inductance of the grounding electrode. The rise time of grounding electrode potential is gradually diminished with an increase in the length of the grounding electrode as shown in Fig. 3.

The transient ground impedance is calculated from the ground rod potential divided by the injected current. Figure 4 shows the transient ground impedances (*Z-t* curves) as a parameter of the length of the grounding electrode. The transient ground impedances decrease exponentially to steady-state levels up to the time of 15 μs. In general, the nonlinearity of the transient grounding system impedances depends on a number of factors such as the length and diameter of the grounding electrode, the resistance and inductance of the grounding electrode, the peak value and the rate of change of the lightning stroke currents, and etc. [6] Some factors affecting the transient grounding system impedances present difficulties when evaluating the transient behaviors of grounding system impedances. It is inferred that the effect of reduction of ground resistance combined with an increase in the length of the grounding electrode is pronounced in these experimental conditions. Furthermore, the measured grounding electrode potential was a relatively low voltage of less than 2 kV, causing no ionization of soil around the grounding electrode undergoing testing. The symptom of ionization of soil around the grounding electrode did not appear in any waveforms of the injected impulse current and grounding electrode potential.

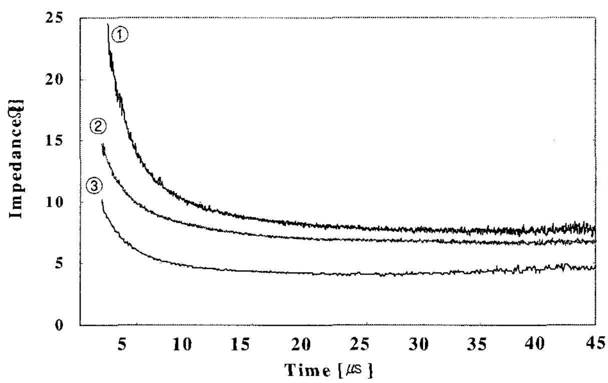


Fig. 4 *Z-t* curves as a parameter of the length of the grounding electrode (Length of grounding electrode ①: 12 m, ②: 30 m, ③: 48 m)

The upturning of the transient ground impedances in the time ranges of less than 15 μs is pronounced. This indicates that the inductive component of transient ground impedances is dominative. The transient ground impedances decreases with time and then becomes almost constant. In detail, after 15 μs the transient ground impedances are nearly flat due to the dull rates of change of the injected current. This implies that the resistive component is also included in the transient ground impedances.

Moreover, as the length of the grounding electrode increases, the transient ground impedance decreases. The transient ground impedances are much greater than the ground resistance. The *Z-t* curves of the grounding electrodes of 12 and 30 m in length appear in the inductive aspects, but the *Z-t* curve of the grounding electrode of 48 m in length appears delicately in the capacitive aspect. The ground impedance is drastically decreased over time within the time range of 8 μs and its change is insensitive over the time range of more than 8 μs. The results confirm the statement that longer grounding electrodes have greater reduction factors for transient ground impedances in soils of low resistivity.

3.2 Dependence of the effective impulse ground impedance on the rise time of impulse current

Due to the above-mentioned reasons, it is very difficult to investigate the impulse ground impedance under test conditions of the same injected impulse current. Furthermore, the essential purpose of a grounding system is to reduce the grounding system potential developed by fault currents or lightning stroke currents. The impulse ground impedance at the instant of the peak potential of the grounding systems is significant. Thus, it is essential that the effective impulse characteristic of grounding system impedances should be evaluated. [7-9] The effective impulse ground impedance $Z_{\rm eff}$ is calculated from the following formula:

$$Z_{eff} = \frac{V_{\max}}{I} \quad (1)$$

Where $V_{\max}$ is the peak value of grounding electrode potential and I is the magnitude of the injected impulse current at the time instant when $V_{\max}$ has been reached, as shown in Fig. 5.

Vital factors in the determination of transient grounding system impedances are the ground resistance, the resistance and inductance of the grounding electrode, the ground capacitance, etc. [10, 11] The transient ground impedance is significantly dependent on the self and mutual inductance of the grounding electrodes. Thus, the grounding electrode system can be modeled by the electrical equivalent circuit consisting of ground resistance, as well as inductance of the grounding electrode and the ground capacitance. Usually, for grounding systems installed in low resistivity soil, the effect of capacitance can be neglected. The grounding system is simulated by an R-L series circuit, then, the ground rod potential can be expressed as follows:

$$V(t) = Ri(t) + L\frac{di(t)}{dt} \quad (2)$$

Where R is the sum of the ground resistance and resistance of the grounding electrode and L is the inductance of the grounding electrode.

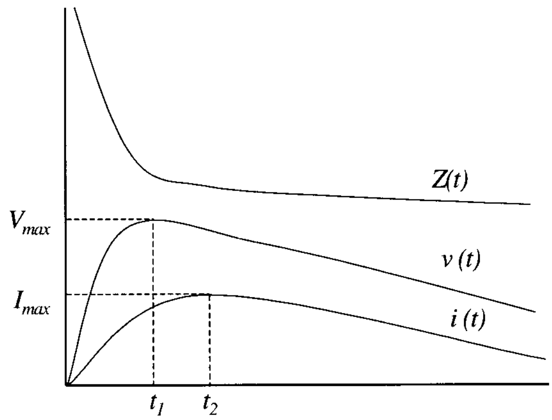


Fig. 5 Definition of the effective impulse ground impedance

The ground resistance R decreases and the inductance of grounding electrode L increases as the length of the grounding electrode is increased. i.e., in the case of extended grounding electrodes, the resistive component of grounding electrode potential is decreased and the reactive component of grounding electrode potential is increased. The ground resistance is principally determined by the soil resistivity and the size of the grounding electrode. Overall, both the ground resistance and the effective impulse ground impedance are lessened with an increase in the length of the grounding electrodes. This tendency indicates that the decrease in the resistive component of the grounding electrode potential is more dominant than the increase in the reactive component with respect to the amplification of the length of the grounding electrode. Also, the effective impulse ground impedances in all experimental conditions are greater than the ground resistance due to the inductive component caused by the rate of change of injected impulse current. It can be concluded that the deeply driven grounding electrodes in the areas of relatively low soil resistivity of our test site are effective to reduce both the ground resistance and the effective impulse ground impedance.

The effective impulse ground impedances of the deeply driven grounding electrodes were measured as a function of the rise time of the injected impulse currents. Figure 6 indicates the dependence of the effective impulse ground impedance on the rise time of the injected impulse currents as a parameter of the length of the grounding electrode.

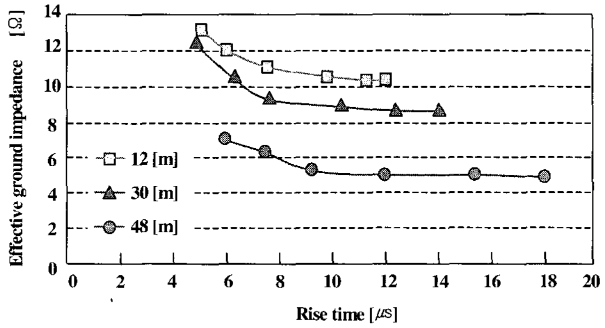


Fig. 6 *Z-t* curves as a parameter of the length of the grounding electrode

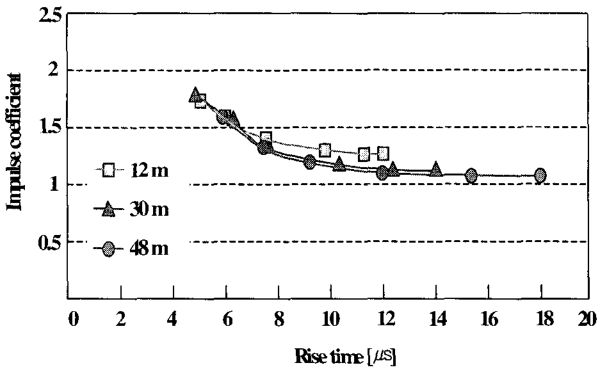


Fig. 7 Curves of the impulse coefficient versus rise time of the injected impulse current

The rise time of impulse currents is limited by the inductance of the test circuit including the length of the grounding electrode as well as return current line and ground. The comparison of the impulse coefficients of the grounding electrode systems as a function of the rise time of the injected impulse currents is depicted in Fig. 7. Here, the impulse coefficient of grounding system impedance is defined as the ratio of the effective impulse ground impedance to the ground resistance. The effective impulse ground impedances were approximately 1.1~1.8 times greater than the ground resistance of the grounding system. The dependence of the impulse coefficient of the grounding system impedance on the length of the grounding electrode can be negligible.

The effective impulse ground impedance is relatively less sensitive to the rise time of the impulse currents as the length of the grounding electrode increases. The steady state and transient characteristics of a grounding electrode of 48 m in length is satisfactory, and this result is mainly due to the low ground resistance of the grounding electrode of 48 m in length. It was well known that the reduction of ground resistance is essential to diminish the effective impulse ground impedance of the grounding systems. The results obtained in this work indicate that the effective impulse ground impedance depends on the rise time of the injected impulse current and the length of the grounding electrode.

3.3 Improved deeply driven grounding pile

Recently, deeply driven grounding piles have been commonly used in soil with high resistivity or in downtown areas, due to limited space availability. The transient and effective ground impedances were measured using the real-sized experimental set-up of the commercial grounding pile. Figure 8 indicates a cross-sectional view of the improved deeply driven grounding pile. A specifically designed ground rod of 3 m in length with copper needles was installed in a hole of 30 m in depth and 15 cm in diameter. An annealed copper wire of 100 ㎟ was connected to the ground rod. The soil resistivity reducing filler plays a decisive role in lowering the ground resistance of the grounding pile. The ground resistance of the grounding pile was about 2.1 Ω.

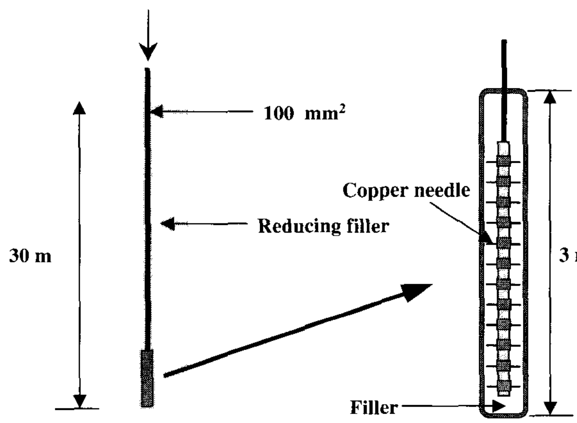
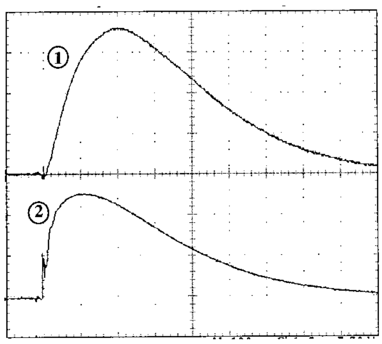


Fig. 8 Measurement circuit associated with various types of system grounding

The impulse currents are injected into the grounding electrode being tested by way of the return current electrode. Measurements of a wide rise time range of effective impulse ground impedances were made using the rise time of injected impulse currents. Figure 9 illustrates a typical relationship between the instantaneous value of the impulse current flowing from the ground electrode being tested to the return current auxiliary electrode and the instantaneous value of the potential rise developed by the impulse current because of the ground resistance and ground electrode inductance.



① : Injected impulse current [50 A/div, 10μs/div]
② : Grounding electrode potential [200 V/div, 10 μs/div]

Fig. 9 Waveforms of the injected impulse current and grounding electrode potential

As may be seen in Fig. 9, the peak value of the potential rise developed on the grounding electrode being tested precedes the crest value of the injected impulse current. This indicates that the grounding electrode potential consists of both resistive and inductive components developed by the injected current. Figure 10 indicates the *Z-t* curve of the grounding pile together with that of the copper-pipe grounding electrode of 30 m in length.

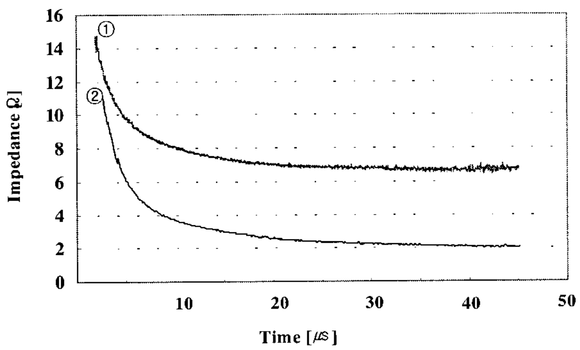


Fig. 10 Z-t curves for the improved grounding pile and copper-pipe grounding electrode (①: Copper-pipe grounding electrode, ②: Improved grounding electrode)

There is no abrupt variation on the transient ground impedance curves related to the ionization of soil. The ionization of soil occurring in the change of transient ground impedances can generally be neglected for the surge arrester discharge currents due to lightning surges [9]. Under a shorter time domain, the reactive components of the transient ground impedances are no longer negligible, and the variation of transient ground impedance for the improved grounding pile is more pronounced than that for the copper-pipe grounding electrode. Most of the transient ground impedances are inductive component. A comparison of the effective impulse ground impedances for the improved grounding pile and copper-pipe grounding electrode are shown in Fig. 11. As well, Figure 12 presents the dependence of the impulse coefficient of the grounding pile on the rise time of the injected impulse current.

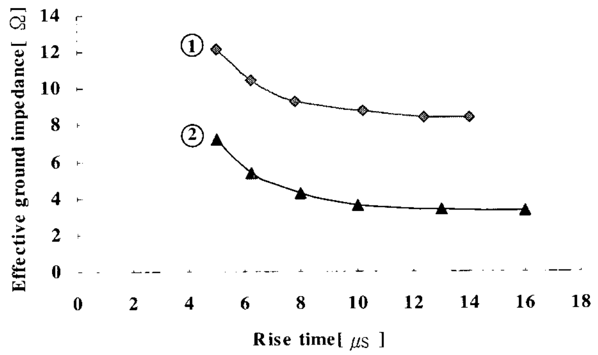


Fig. 11 Comparison of the effective impulse ground impedances of the improved grounding pile and the copper-pipe grounding electrode (①: Copper-pipe grounding electrode, ②: Improved grounding electrode)

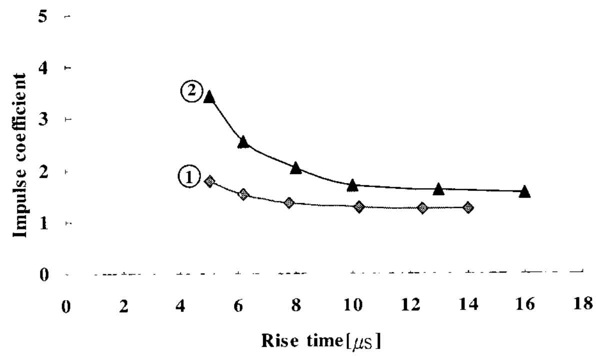


Fig. 12 Curves of the impulse coefficient versus rise time of the injected impulse current for the grounding pile (①: Improved grounding electrode, ②: Copper-pipe grounding electrode)

The transient impedance of the grounding pile depends considerably on the rise time of the test impulse current. The effective impulse ground impedances of the improved grounding pile are much lower than those of the copper-pipe grounding electrode. It is considered that the main cause is the grounding electrode potential rise developed by the inductance and the rate of change of injected impulse current. The impulse coefficients of the grounding pile are much greater than those of the copper-pipe grounding electrode. The effective impulse ground impedances are reliant on the rise time of the impulse current and are as high as about 2-3.5 times the ground resistance. This result was brought about by the low ground resistance of the grounding pile compared to that of the copper-pipe grounding electrode.

It is inferred from this result that the ground resistance may not provide proper protection against lightning. The effectiveness of lightning protection provided by a grounding system depends on the transient ground impedance and not on the ground resistance. The determination of impulse ground impedance is an effective method of evaluating the lightning performance of the grounding systems. The behaviors of grounding systems to impulse currents are significant in predicting the performance of lightning protection systems. Therefore, a grounding system for lightning protection should be designed and installed so as to provide low effective impulse ground impedance.

4. Conclusion

A detailed time domain analysis of ground impedances of the deeply driven grounding electrodes and grounding piles subjected to impulse currents with relatively slow rise time has been presented. The impulse ground impedance characteristics of the actual-sized grounding electrodes and grounding piles were experimentally studied. As a consequence, the results could be concluded as follows:

The fine waveform of grounding electrode potential to the impulse currents was measured without electromagnetic coupling effects by using the modified fall-of-potential method. The effective impulse ground impedance of deeply driven grounding electrodes is much greater than the ground resistance and decreases with an increase in the length of grounding electrodes under all of our experimental conditions. The effective impulse ground impedance is a decisive criterion in evaluating the protection performance of grounding systems against lightning. Furthermore, the most effective way to obtain the fine transient impedance behaviors of deeply driven grounding electrodes is to reduce the ground resistance and the inductive component of the grounding electrodes.

Acknowledgement

This work was financially supported by MOCIE through the EIRC program.

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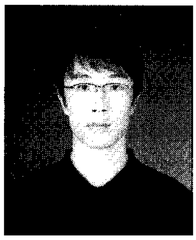

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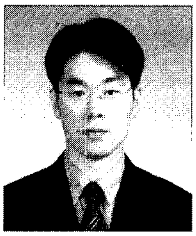

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