Journal of the Korean Institute of Illuminating and Electrical Installation Engineers Vol. 23, No.7, pp. 41~48 July 2009 (23-7-6)

High Frequency Grounding Impedances of Vertically-Driven Ground Rods

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Abstract

Grounding impedance depends on the frequency of current flowing into a grounding system. Lightning in particular has a broad frequency spectrum from some tens of Hz to a few MHz. So the grounding impedance related to transient currents such as lightning should be measured. In this paper, the grounding impedances of vertically-driven ground rods of 10, 30 and 48[m] long are measured and analyzed as functions of the frequency of injected current and the feeding point. As a result, the longer the ground rod is, the lower the steady-state ground resistance is. However the grounding impedance of a vertically-driven ground rod at a high frequency is significantly increased. It is not always true that low grounding impedance follows from a low steady-state ground resistance. It is important to evaluate the high frequency performance of grounding systems for protection against lightning.

Key Words : Ground rod, Ground resistance, Grounding impedance, High frequency performance of grounding system, Protection against lightning

1. Introduction

An effective grounding system which limits hazardous voltages and electromagnetic disturbances is very important to ensure personnel safety, protection and stable operation of microelectronic equipments such as computers. An effective grounding system having a very low resistance to electromagnetic disturbances such as lightning surges is strongly required in microelectronics and communication facilities [1-2].

Guidelines for the design of such grounding systems are usually based on their low frequency resistances using the Korean standard. For example, the steady-state ground resistance measured at low frequency is being used at present to determine the performance of a grounding system for protection against lightning [3]. The grounding impedance at power frequencies and their harmonics components in large scale grounding systems is primarily resistive and relatively low, but due to the inductive component of grounding electrode

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Date of submit : 2009. 4. 3
First assessment : 2009. 4. 6
Completion of assessment : 2009. 6. 3

conductors, the grounding system impedance at high frequency could be much larger than the steady-state ground resistance. It is important to note that the performance of a grounding system appears to transient events as grounding impedance rather than a ground resistance [4-6]. Also transient behaviors of grounding electrode systems subjected to lightning current impulses are dependent on various factors such as soil resistivity, buried depth, shape and size of grounding electrodes, and parameters of lightning current impulses, etc. All these factors influence the ground surface potential rise and grounding impedance [7-8].

The most common type of grounding electrode is the driven ground rod. In this study, in order to evaluate accurately the frequency-dependent impedance of grounding systems for protection against lightning, the grounding system impedances of an actual sized vertical grounding electrode were measured as a function of frequency for the test current. Therefore, this study focuses on the analysis of the frequency dependence of grounding system impedance characteristics of deeply driven ground rods which are used in highly resistive soil and in downtown areas. The experiments were carried out with ground rods of 10, 30 and 48[m] in length buried at the test site of Inha University in Incheon, Korea. The high frequency performance of the vertically-driven ground rods were analyzed with respect to the variable frequency current in the ranges from 10[kHz] to 20[MHz] and the feed point. This approach makes available the evaluation of frequency response characteristic of the grounding system for protection against lightning.

2. Experiment

2.1 Experimental setup

The laboratory experiments in this study were carried out using actual-sized grounding electrode systems. The conventional fall-of-potential method is the fundamental method for measuring the impedance of large-sized grounding systems, but it is very important to remove the measurement errors caused by mutual coupling between the current injection line and the potential measuring probe wire in the case of high frequency test current. Thus, in this study the revised fall-of potential method recommended by the IEEE 81.2-1991[9] was employed. The current injection line was extended at an angle of 90°with respect to the potential probe wire to minimize the effect of ac mutual coupling between them (Fig. 1).

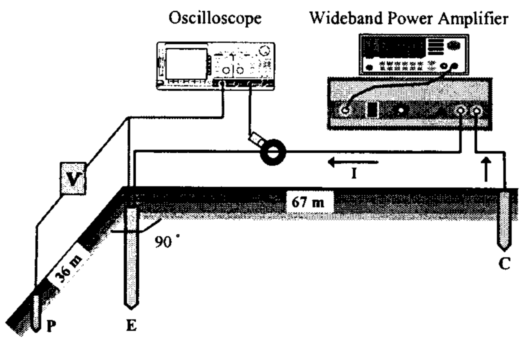


Fig. 1. Schematic diagram of the experimental setup and measurement devices.

The grounding electrode systems being tested in this experiment are driven ground rods. Pipe-style ground rods 10, 30 and 48[m] in length and 54[mm] in diameter were vertically installed and the test current feed point were located at the upper, middle and lower end of each ground rods (Fig.2).

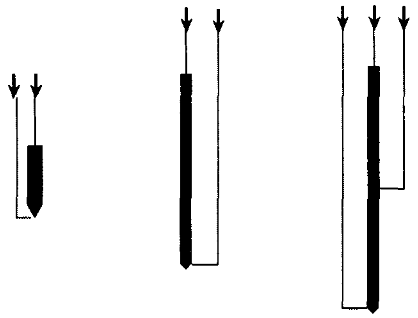


Fig. 2. Profile of the test grounding electrodes

The return current electrode is a set of ground rods placed at a distance of 67[m] from the ground rod being tested. The remote ground potential electrode is a 0.2[m] long vertical ground rod placed at a distance of 36[m] from the ground rod under measurement.

The measured steady-state ground resistances of the 10, 30 and 48[m] long vertically driven ground rod were 8.2, 11.52 and 5.8[Ω], respectively. The steady-state ground resistance of the 30[m] long ground rod is greater than that of the 10[m] long ground rod. Thus, steady-state ground resistance is dependent on both the dimensions of the ground rod and soil resistivity. At the test site, the steady-state ground resistance is more dependent on soil resistivity than the length of the ground rod.

2.2 Measurements

A wideband power amplifier capable of producing sinusoidal voltage ranging from DC to 250[MHz] was employed, and its maximum output power was 75[Watts]. A variable frequency current ranging from 10[kHz] to 20[MHz] was supplied between the ground rod being tested and a current auxiliary electrode. The injected current was measured by a current probe with a frequency bandwidth of 400[MHz]. The potential rise of the ground rod under test was measured by a differential probe with a frequency bandwidth of 100[MHz].

The waveforms of the injected currents and ground rod potential rise were recorded by a 4 channel digital storage oscilloscope with a frequency bandwidth of 1[GHz] and sampling time of 2[Gs/s]. The detected signals of the injected current and the potential rise of ground rods are registered at a personal computer. The grounding impedance is determined as the ratio of the voltage developed at the feeding point to the injected current as a function of frequency.

3. Results and discussion

The frequency content of lightning current extends along a wide domain. Components with large amplitude lay in a frequency interval around 10[kHz] for the lightning current of both first and subsequent strokes. However, the frequency range of the first stroke current has a superior limit around 200[kHz], while this limit is above 1[MHz] for the subsequent stroke [10]. Measurement of steady-state ground resistance with conventional built-in ground testers working a frequency of less than 600[Hz] might not provide accurate data that are indicative of the ground response to a lightning surge. A grounding designed for personnel safety in power systems is not always the best way to carry away transient currents such as lightning and surges. In order to evaluate the performance of grounding systems for protection against lightning, the grounding impedance should be considered rather than its steady-state ground resistance. Thus, in this paper, frequency-dependent grounding impedances of vertically-driven ground rods are measured and analyzed.

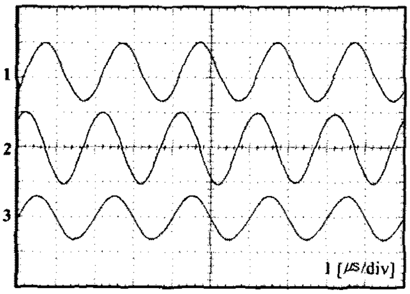
Because the wideband power amplifier could not inject high currents into the vertically-driven ground rods, it does not perfectly represent the behavior of the grounding system under high lightning current such as soil ionization and breakdown phenomena. The high frequency grounding impedance can be evaluated as a measure of response behavior of grounding systems against lightning current. The grounding impedance Z is defined as the ratio of the grounding electrode potential to a remote ground to the injected current. The amplitude, resistive and reactive components Z, R and X of the grounding impedance can be simply expressed as:

$$Z = R + jX = |Z| \cdot (\cos\theta + j\sin\theta) \tag{1}$$

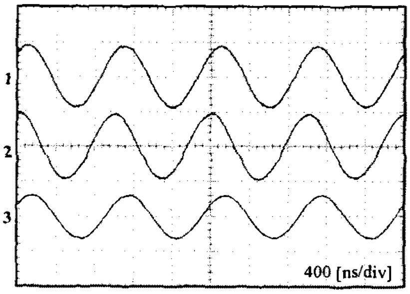
$$|Z| = V / I \tag{2}$$

$$R = |Z| \cdot \cos\theta, \quad X = |Z| \cdot \sin\theta \tag{3}$$

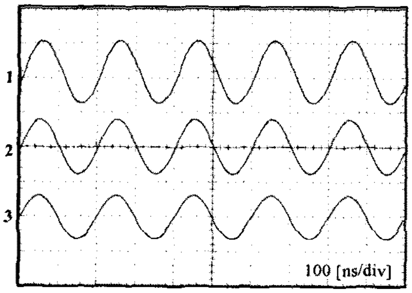
Low-impedance large grounding systems used in high-voltage power systems may require higher test current than the built-in 5~40[mA] test current sources provided by commercial ground testers. When the grounding grid potential rise due to the test current must be high enough to overcome poor connection or nonlinearities in the grounding system, the test current magnitude should range from 0.1 to 100[A] [9]. The impedance measurements in all experimental conditions were made at the injected current magnitude of 0.35[A] with consideration of the output capacity of the power amplifier and the estimated impedance. Also, measurement errors caused by earth mutual resistance due to current flow through the earth from the test grounding grid to the current auxiliary electrode was evaluated. With the measuring arrangements employed in this experiment, a measurement error of less than 5[%] due to earth mutual resistance is estimated.



(a) 500(kHz)



(b) 1(MHz)



(c) 5(MHz)

1: Applied voltage (50(V/div))
2: Ground potential rise (5(V/div))
3: Injected current (1(A/div))

Fig. 3. Waveforms of the applied voltage, the injected current and the potential rise of the 30(m) ground rod as a function of frequency

Figure 3 shows the typical waveforms of the applied voltage, the injected current and the potential rise of the 30[m] ground rod with respect to the frequency. The amplitude and phase angle (θ) of the grounding impedance are calculated from the potential rise at the feeding point and the injected current waveforms. Also, the resistive and reactive components are computed from the magnitude and phase angle of grounding impedance.

Figs. 4-6 show the variation of parameter values Z, R and X of the grounding impedances for different lengths of ground rods and feed points of test current.

Figure 4 shows the amplitude resistive and reactive components of the grounding impedance for the 10[m] ground rod as a function of frequency. When the test current was injected at the upper end of the 10[m] ground rod, the grounding impedance below the frequency of 100[kHz] was 8.2[Ω]. This was in accordance with the steady-state ground resistance measured by the conventional ground meter. The grounding impedances act as inductive behavior at high frequency. The grounding impedance is gradually increased with the frequency in the range of 100[kHz] to 1[MHz], was then rapidly increased to 5[MHz] and is considerably greater than the steady-state ground resistance. The grounding impedance also gives oscillatory variation over frequency ranges above 5[MHz]. Resonance phenomena can be seen at the frequency of 5, 7 and 10[MHz]. The reason for this behavior is not clear, but it is considered that this variation is due to the capacitive effect of the soil with respect to frequency.

For example the grounding impedance at 1[MHz] is 42[Ω], more than about 5 times the steady-state ground resistance. The performance of this ground rod is significantly changed when a lightning current is applied. The potential rise of the ground rod is drastically increased and a flashover can occur. The high frequency performance of a long ground rod will not be as favorable as originally expected with a low steady-state ground resistance.

When the test current was injected at the lower end of the ground rod, the variation of the grounding impedance as a function of frequency is similar to that of the current applied to the upper end. However, the inductive behavior at the frequency of less than 1[MHz] is pronounced because of the effect of the inductance of the connection lead. Consequently, the grounding impedance of vertically-driven ground rods strongly depends on the current feed point. It can be concluded that the high frequency performance of the long ground rod displays a good result as the current feed point is installed at the upper end

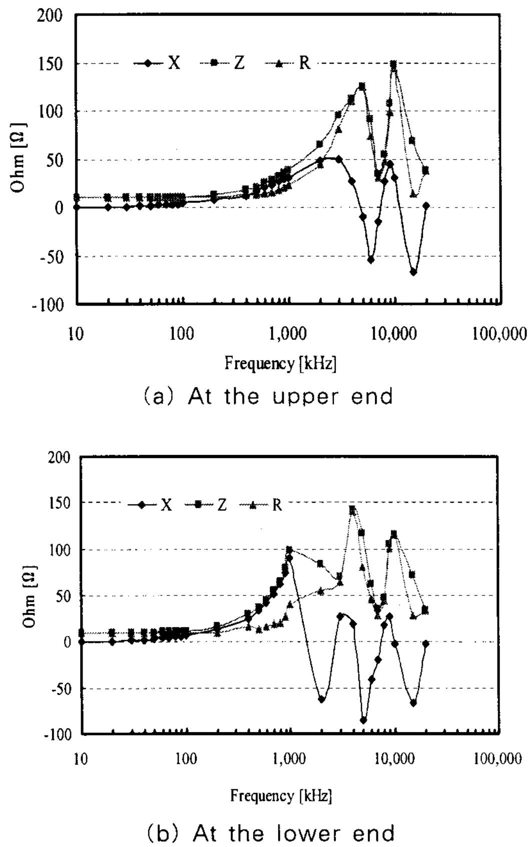
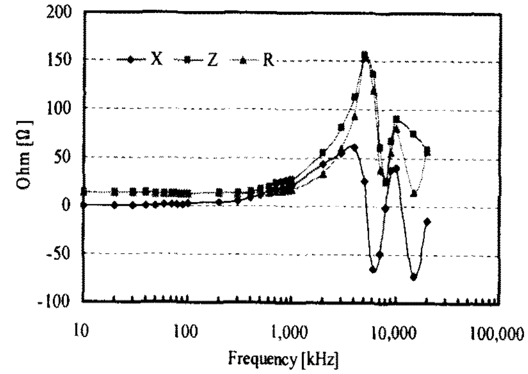
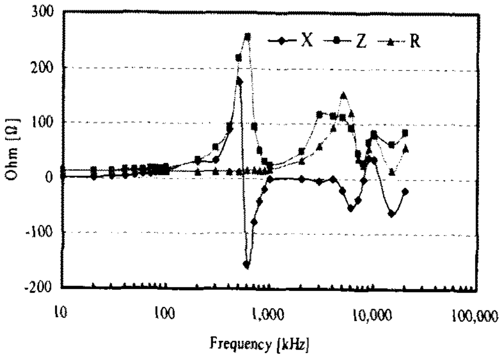


Fig. 4. Grounding impedances of 10[m] ground rod as a function of the frequency in relation to the feed point of test current

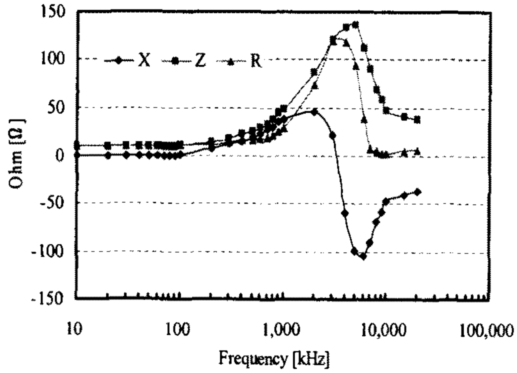


(a) At the upper end

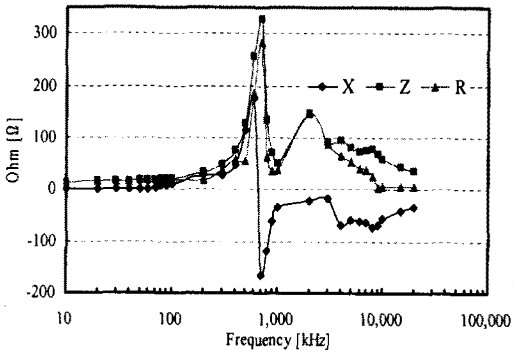


(b) At the lower end

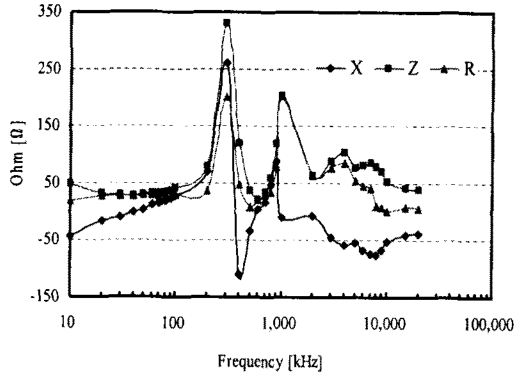
Fig. 5. Grounding impedances of the 30[m] ground rod as a function of the frequency in relation to the feed point of test current



(a) At the upper end



(b) At the middle



(c) At the lower end

Fig. 6. Grounding impedances of the 48[m] ground rod as a function of the frequency in relation to the feed point of test current

of the ground rod.

A grounding system that protects against lightning with a steady-state ground resistance of less than 10[Ω] is often required for international or national standards which do not deal with high frequency grounding impedances as the equipment to measure them is rare. The high frequency grounding impedances differ considerably from the ground resistance measured by a conventional ground resistance meter. The grounding impedance of long ground rods at high frequencies acts as inductively. The specified ground resistance misleads the high frequency performance of grounding systems for protection against lightning. Thus the high frequency performance of protective grounding systems needs to be examined when designed and installed.

Generally the grounding impedances of ground rods employed in this study are equal to the steady-state ground resistance in a frequency range of less than 100[kHz]. The grounding impedances appear inductively over a frequency range of a few hundred [kHz] and increase with frequency. The steady-state ground resistance of the 48[m] ground rod was 5.8[Ω] and was smaller than that of the 10[m] long ground rod. However, the grounding impedances of the 48[m] ground rod at a frequency above a few hundred [kHz] are greater than those of the 10[m] ground rod. That is, the ground resistance of the 48[m] long ground rod at low frequency is small and the grounding impedance increases with frequency appearing as dominant inductive behavior. Thus the 48[m] ground rod is not satisfactory when compared to the 10[m] ground rod for lightning protection systems. A single long ground rod with a high inductance is improper for use in proactive grounding systems.

In order to obtain a low steady-state ground resistance, a large dimension ground rod is required. However, a large dimension ground rod leads to a higher value of its high frequency grounding impedance due to the inductive effect [11]. It is not possible to obtain low values in both low frequency ground resistance and high frequency grounding impedance with long ground rods. Grounding systems with low steady-state ground resistance may or may not give a low value of high frequency grounding impedance. That is, an increase of the length of ground rod is not always followed by a decrease of grounding impedance. Further evaluation of the high frequency performance of grounding systems for protection against lightning is needed as well as further study of approaches to improve the high frequency performance of long ground rods.

Ground rods with a feed point at their lower end are similar to the grounding system of actual lightning protection systems connected to grounded terminations by one down-conductor. Since a lightning rod is connected to the grounding termination through down-conductors, the potential rise of the upper part of down-conductor is significantly increased when lightning is injected to lightning rod, and flashover can occur in the installation. The high frequency performance of actual lightning grounding systems is degraded with frequency because of the down-conductor. The transient performance of a grounding system including grounding conductors is a measure of the system ability to disperse transient energy into the ground. Thus, the high frequency performance of a grounding system is the most important factor in determining the effectiveness of a lightning or surge protection system.

4. Conclusion

High frequency grounding impedances of vertically driven ground rods were examined and the conclusion could be summarized as follows:

Firstly, the grounding impedance at low frequency was almost equal to the steady-state ground resistance, but increased considerably over the frequency range of a few hundreds [kHz], due to induction. Secondly, the high frequency grounding impedance of vertically-driven ground rods is strongly dependent on the lengths of the ground rod and the current feed points. Low grounding impedance is not always followed from a low steady-state ground resistance. A grounding system designed for personnel safety at commercial frequency power systems is not always adequate for carrying away transient currents such as lightning or switching surges. The transient performance of a grounding system is a measure of the system ability to disperse transient energy into the ground. Therefore, it is important to evaluate the high frequency performance of grounding systems for protection against lightning and to determine the optimal dimensions of grounding systems with low values of high frequency grounding impedance.

Acknowledgements

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

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