GROUNDING SYSTEM DESIGN AND MEASUREMENTS FOR CRITICAL INSTALLATIONS

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Abstract

A key parameter in the design of lightning protection systems for critical or sensitive installations is the impedance of the grounding system. In this paper we will show that grounding impedance data gathered using high frequency techniques better characterizes the lightning response of grounding systems and is a much better indicator of the probability of sideflashes and internal arcing due to lightning than that obtained from low frequency measurements presently in use.

In addition, the high frequency results simplify ground system testing. Many have expressed concerns about the safety and reliability aspects of disconnecting grounding electrodes in order to obtain a valid resistance-to-earth measurement and for some older structures such isolation is not possible. Without such isolation, the measurement would reveal the parallel resistance of all items connected to the system; including some, such as the electrical power distribution system resistance, that may not be a factor during a lightning impulse. The inductive reactance of these remote parallel paths can be identified and discounted by a high frequency measurement.
This paper will examine the responses of selected grounding electrodes mathematically and compare those findings with actual measurements of certain electrode configurations at frequencies up to 1 MHz. A simple test methodology using high frequency signal injection, similar to the Wenner method presently in use, will be discussed. It will also discuss the possibility of using measurements of up to 1 MHz to characterize the response of grounding systems without the need to disconnect any grounding electrodes or isolating discrete grounding subsystems.

Introduction

An earth electrode emplaced in soil has the electrical property of resistance, measured by the familiar Wenner, or fall-of-potential, method. Resistance is a common figure of merit for earth electrodes. Resistance is one component of the total impedance of any electrical circuit. Consider that the property of resistance is only dominant when dealing with direct current or low frequency current. In any conductor or circuit as the frequency increases, inductive and capacitive reactances may become dominant. During a lightning event (or a fault current surge) the earth electrode receives a pulse of current that is largely comprised of higher frequency components. Consequently, the electrical behavior of the earth electrode under these conditions is different than when it is exposed to direct

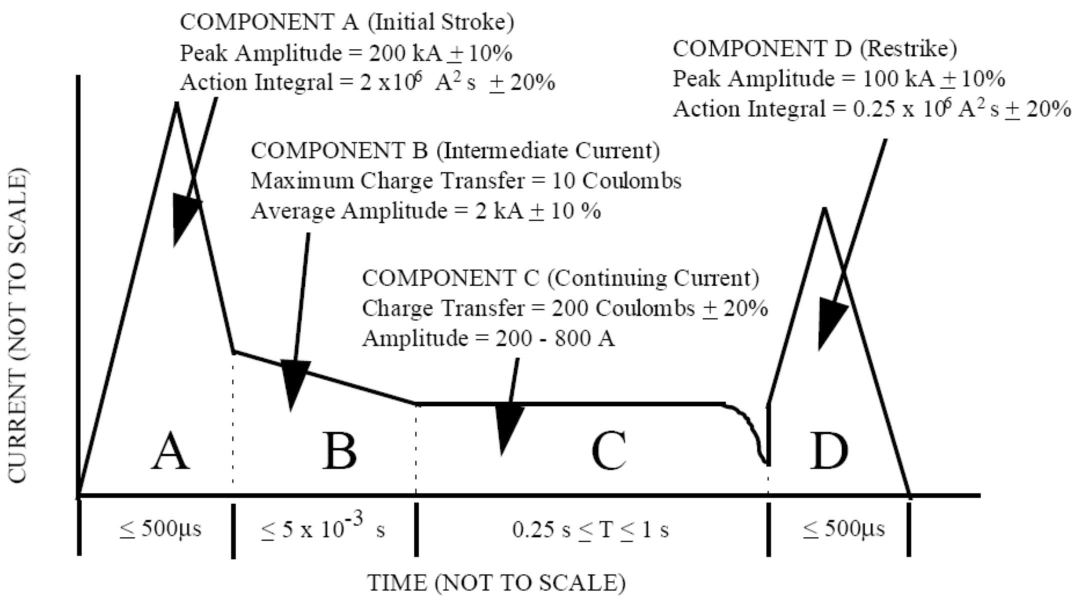

Figure 1. Representative lightning waveform. (After MIL-STD-464.)

current or low (power) frequencies.

A representative lightning event (Figure 1) is characterized by an initial fast risetime peak (A-component) followed by a direct current (Components B&C). Several cycles of B&C components can occur after the D-component, which is a follow-on fast risetime event. Components of this waveform with fast risetime emulate an alternating current with a frequency. To consider only the direct current components of the lightning waveform ignores the reactances that arise from the A and D-components.

In order to properly assess these effects in grounding electrodes we must consider the impedance of the earth electrode. The impedance of the earth electrode system is the sum of the resistance, inductive reactance and capacitive reactance. Each of these depends upon frequency. The resistance of any conductor increases as frequency increases due to skin effect. At high frequency or during a fast-risetime event, most of the current in a conductor will tend toward the surface. Since resistance is inversely proportional to cross section, the resistance increases simply because there is less material for the current to pass through.

Inductive reactance is commonly considered in lightning protection. Additional voltage drop along a conductor arises due to the inductive reactance as a function of the rate of change of current with respect to time. Often, the inductive reactance can exceed the resistance during the A and D-components of a lightning event. Typical value considered for such an inductance is 1µH/m. A possible result is sideflash or arcing in lightning protection systems. Inductive reactance exists in grounding electrodes as well. Evidence suggests that it is responsible for rejection of the lightning current to the surface rather than conduction by the grounding electrode.

Capacitive reactance, however, is not commonly considered in lightning protection systems or in earth electrode systems. Yet, it is present and can be a significant contributor to decrease the impedance of the whole grounding system. [1] In fact, a common earth electrode application, the single ground rod, is demonstrated to have some capacitive reactance.

Given these considerations, measurement of the impedance is a better figure of merit for earth electrodes used in lightning protection systems.

Application

Our method measures the impedance of the grounding system by the injecting signals into a Wenner-type test arrangement at frequencies ranging from the 79 Hz to the 1 MHz range. Recall that a lightning event is characterized by a fast risetime, high current pulse followed by a direct current component, represented in Figure 1. [2]

It is well known that an impulse function, like that of the lightning event can be resolved into frequency components by use of the Fourier theorem. Performing this calculation on a typical lightning waveform, one finds that most of the A-component energy is contained in frequencies greater than 100 kHz, up to 1 MHz. Thus, by sampling the frequency response of the earth electrode system under test at these successive frequencies, the lightning (impulse) impedance can be accurately measured.

Results

The impedance of a standard 8-foot horizontal ground rod electrode is plotted at Figure 2.

Note that the low frequency measurements that would normally include 60 Hz and several harmonics (60 Hz, 120 Hz, 180 Hz) remain constant at approximately 60 ohms, reactance effects arise at 20 kHz. Much of the A-component lightning energy is contained in frequencies above 100 kHz. Examining the impedance at those frequencies, we note that it is as much as three times the power frequency impedance.

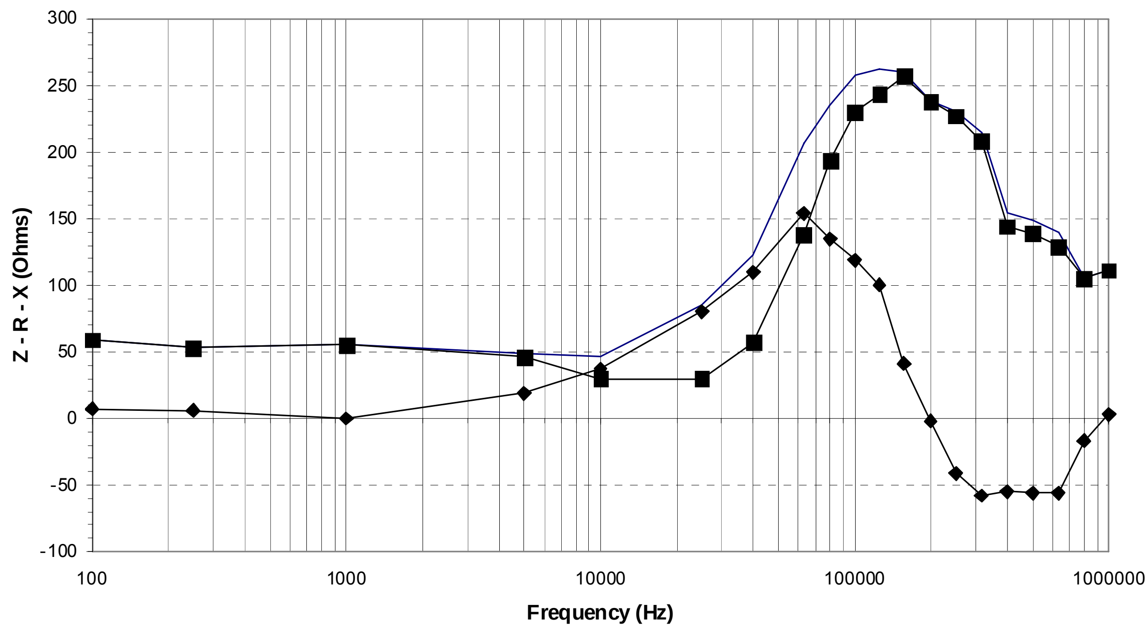

Figure 2. Single Ground Rod Impedance, Resistance and Reactance. Key: Impedance (-), Resistance (■) and Reactance (◊) as a function of frequency. (Data released courtesy of NEETRAC / Georgia Tech Management Board, Project No. 06-209).

Information can also be gained from the shape of the curve. We expect the resistance and reactance to increase linearly with frequency. However, the impedance reduction after approximately 100 kHz implies a capacitive effect. This is verified by the reactance curve. Once the reactance curve becomes negative at 200 kHz in Figure 2, capacitive reactance becomes dominant over inductive reactance.

Advantages of High Frequency Grounding System Testing

There are several advantages offered by the use of high frequency grounding system measurements. There is a significant amount of information contained in a plot of the impedance of the grounding system in the spectrum between DC and 1 MHz. This information is of benefit to those attempting to determine the adequacy of an existing grounding system to a lightning current pulse, to those trying to confirm the content of an existing grounding system and determine what measures to improve the grounding system. Information in the frequency dependent impedance charts is useful to for calculation of withstand current requirements for surge protective devices, as well.

The use of grounding system impedance measurements can also be of significant advantage in grounding system inspection and maintenance. With some additional study, we envision the possibility of eliminating the need to isolate grounding electrodes for grounding system testing. This benefit will save a significant amount of time, reduce potential hazards resulting from failing to reconnect the grounding electrodes and provide a technique for grounding system quality evaluation for those structures where isolation of grounding electrodes is not an option.

Grounding Impedance Measurements in Maintenance and Inspection Applications

As discussed earlier in this paper, the capacitance of a grounding electrode and inductance of grounding system conductors can have a significant influence on the overall impedance of a grounding system, particularly at frequencies greater than 60 kHz. For example, Figure 3 depicts the results of a measurement of a ground mat consisting of 200 feet of cable at a telephone switching site. The impedance to earth (dominated by the resistive component) measured at frequencies below approximately 20 kHz was below 10 ohms. However, it can be seen that at frequencies above 20 kHz, the impedance increases significantly to a peak value of 60 ohms at 1 MHz. Resistance increases due to skin effect. Inductive reactance (positive reactance) increases due to the cable used in the ground mat.

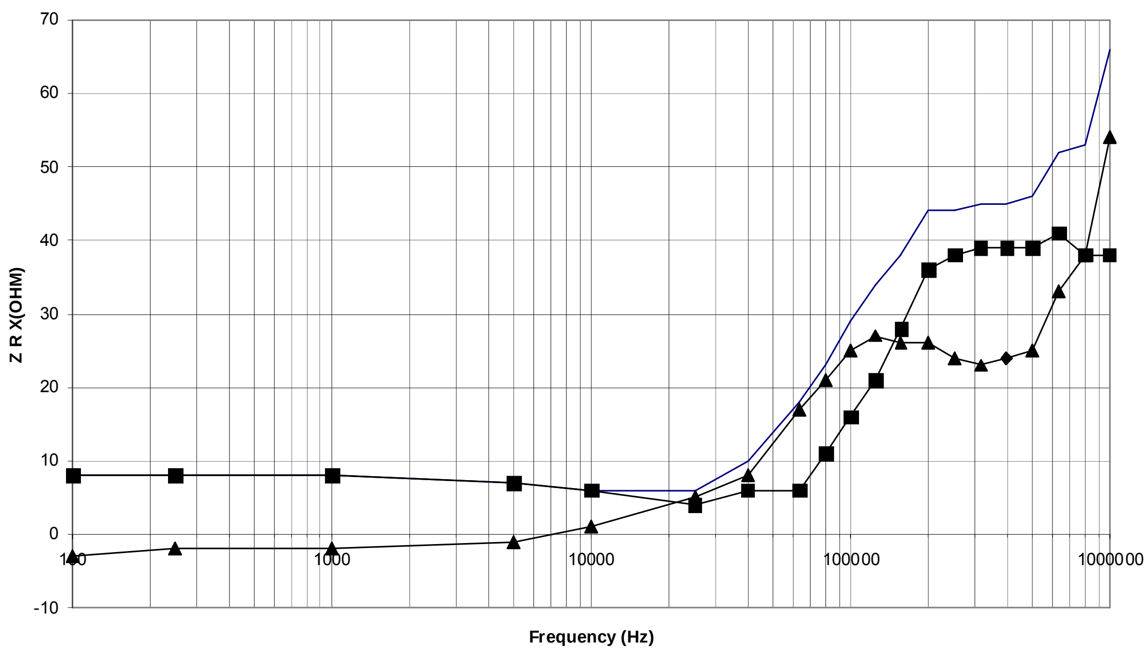

Figure 3. Impedance versus frequency plot for a ground mat consisting of 200 foot of 2/0 cable. Key: Impedance (-), Resistance (■) and Reactance (◊) as a function of frequency.

In a more complex example, Figure 4 depicts measurement data from a counterpoise for a 230 kV transmission line. The straight line depicts impedance with the overhead ground wire connecting this tower to adjacent towers removed. Triangular markers depict measurement data from the same counterpoise with the overhead ground wire connected. It is evident that the resistance to earth at low frequencies is reduced by a factor of approximately two with the overhead ground wire connected while at higher frequencies up to 1 MHz, the reduction is just over 20 percent. We conclude increasing inductive reactance (due the wire's length) and increasing resistance (due to skin effect) of the interconnecting overhead wire tends to isolate adjacent towers at higher frequencies. It shows that there is some real effect of the connection of the remote ground but at the same time quantifies its effect.

There has been significant technical discussion concerning proper figures of merit and acceptance criteria that would be applicable for the use of grounding impedance measurements in areas where the functioning of the grounding system is critical. Literature from International Conference on Lightning Protection (ICLP) and the International Symposium on Lightning Protection (SIPDA) suggests that an average of the data between 60 kHz and 1 MHz could be used as a comparison figure of merit. [3, 4] Others have suggested that higher frequency values or values weighted to the frequency distribution in a representative lightning strike should be used. The acceptable range in either case would most likely have to be increased from the 10 to 25 ohm value currently used for resistance to earth. The debate for an appropriate figure of merit is ongoing but Rousseau and Gruet [4] indicate that a review of a significant amount data gathered taken over a number of different earth grounding arrangements suggest that a high frequency resistance in the range of 30 to 40 ohms is acceptable.

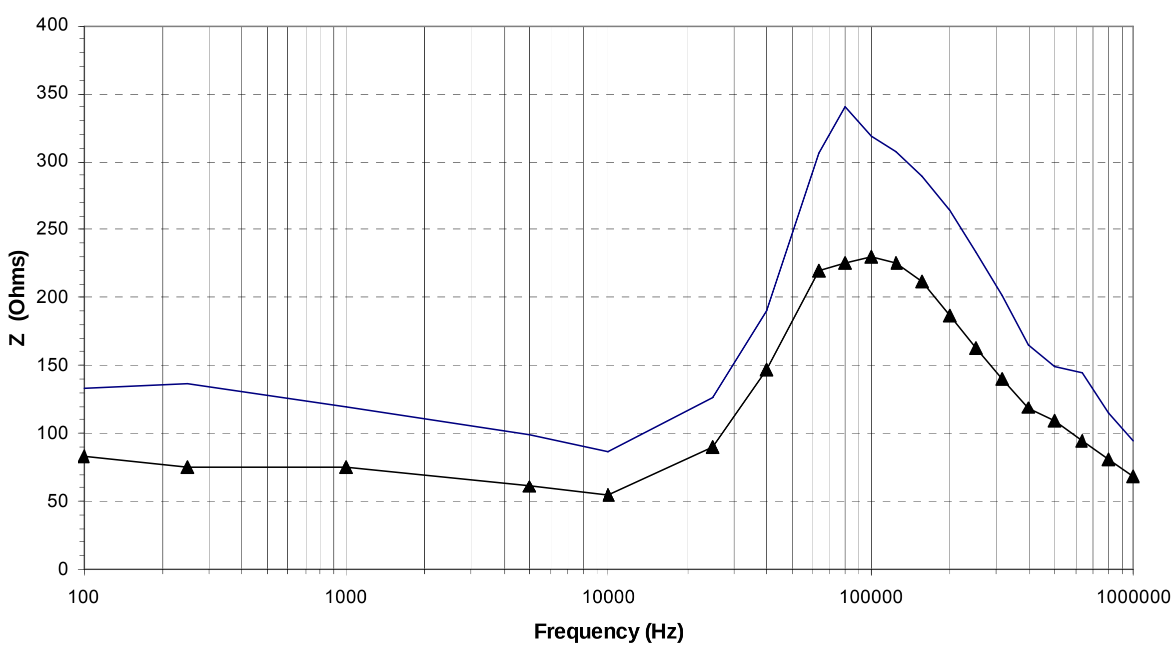

Figure 4. Impedance versus frequency for a 230 kV transmission line counterpoise with the overhead ground wire disconnected (straight line) and connected. (▲) (Data released courtesy of NEETRAC / Georgia Tech Management Board, Project No. 06-209.)

Conclusions

Impulse current and low-frequency/direct current behaves differently in grounding electrode systems due to capacitive and inductive reactance effects that arise. These reactances arise because the impulse current from the lightning event is comprised of high-frequency components up to 1 MHz, as predicted by Fourier theorem.

Consequently, impedance rather than only the low-frequency resistance is a better figure of merit for the determination of earth ground quality for lightning grounding applications. Values for these figures of merit are under consideration.

Emerging results from high frequency earth ground electrode measurements are making it possible to distinguish individual electrodes of multiple electrode grounding systems by examining the frequency-dependent impedance curve. An important consequence of these results is the ability to distinguish the contributions of these individual electrodes without isolating them.

Results from testing performed to date are yielding new insights on earth grounding system design with the expectation of lowering the high frequency impedance. Development of design guidance will soon be possible that will further minimize sideflash and arcing that result from the increased high-frequency reactances.

Acknowledgements

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References

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