論文の内容の要旨
Abstract of Dissertation

Electrical Transient Characteristics of Grounding System Incorporating Long Buried Conductor

（長い埋設導体を含む接地電極系の電気的過渡特性）

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One of the principal roles of a grounding system is to dissipate lightning current or fault current effectively into ground, and thereby to prevent the damage of installations. Thus, the lightning performance of any power systems is influenced by the proper designing and functioning of the grounding systems. In order to reduce the damage due to lightning, the grounding has to be designed efficiently from the scope of lightning protection and electromagnetic compatibility (EMC).

Long grounding conductors are frequently used to obtain low steady-state grounding resistance at highly resistive soil. Lightning performance of a large grounding system depends on the propagation characteristics of current pulse along grounding conductors. Lightning impulse current is characterized by a pulse of single polarity having rise time from less than one μs to few tens of μs with the duration of few hundred μs. Therefore, characterization of propagation of lightning surge having such properties along a grounding conductor is necessary for economical and effective design of a large grounding system. Various studies both theoretical and experimental have been carried out to investigate lightning surge response of concentrated grounding systems; however, the propagation characteristics of current pulse and distribution of electric field along a grounding conductor and its influence on the transient characteristics of a large grounding system have not been fully understood yet.

There have been three representative approaches to evaluate the transient characteristics of a grounding system as follows: (i) circuit approach, (ii) transmission line approach and (iii) electromagnetic field analysis approach. Circuit approach and transmission line approach are based on equivalent circuits and their validity may be limited in a highly lossy medium such as soil. It is also difficult to incorporate coupling between different parts of a complex grounding system using circuit approach or transmission line approach. In a numerical electromagnetic analysis, coupling is automatically incorporated, and this approach can handle electromagnetic fields in a lossy medium. So, three-dimensional numerical electromagnetic analysis is a useful tool to analyze such problems. In this thesis, numerical electromagnetic analysis is applied to analyze the lightning surge characteristics of a grounding system.

Since the electromagnetic field analysis solves Maxwell’s equations and constitutive equations, it can model the physical conditions of the system without much postulation within the limits of constitutive equations. Of many available codes of electromagnetic analysis, Numerical Electromagnetics Code (NEC-4) based on the Method of Moments (MoM) and Virtual Surge Test Lab (VSTL) based on the Finite Difference Time Domain (FDTD) method are chosen for the present work. Before applying these methods to transient analysis of grounding systems, verification of the accuracy of analysis is essential, since these codes have been verified mainly for electromagnetic fields in the air. The applicability of NEC-4 and VSTL to the electromagnetic analysis of grounding response is verified through comparison with a recent measurement on a buried conductor.

The transient response of a long horizontal grounding conductor buried in a variety of soil is computed using NEC-4 and VSTL. Applicability of these methods for transient analysis of a long grounding conductor is discussed. The maximum difference of initial peak voltages of grounding conductors for injection of lightning impulse current calculated by these methods is less than 8%. The response of long grounding conductor after several tens of μs when the response almost stabilizes, NEC-4 results agree to the steady-state values calculated by Sunde's analytical formula whereas VSTL results show 10-20% lower values. For a simple case like a single grounding conductor, both NEC-4 and VSTL can be used to analyze the transient response. In the condition close to steady-state, NEC-4 results seem to be dependent only on the space coordinates of the conductor, which may be the reason of agreement of NEC-4 results and analytical results in the time range of several tens of μs.

Then the applicability of NEC-4 and VSTL to analyze transient response of a large and complex grounding system is discussed. It is found that, though NEC-4 is applicable to analyze a simple grounding conductor, it tends to become unstable in calculating the transient behavior of a complex grounding system. VSTL turns out to be more stable than NEC-4, however, similar to the case of a single grounding conductor, it is also found that VSTL analysis shows 10-20% lower value than NEC-4 results when the response almost stabilizes. Since VSTL is more stable in the transient analysis, VSTL is employed for investigating transient behavior of large and complex grounding systems in this thesis.

The propagation characteristics of current pulse and distribution of electric field along a buried bare conductor have been studied using VSTL. In a lossy medium like soil, the apparent propagation velocity of a current pulse depends not only on the permittivity but also on the resistivity of the medium. The apparent propagation velocity of a current pulse along a buried bare conductor is slower in soil of lower resistivity and is not uniform throughout the length of the conductor. As the measuring point moves away from the current injection point the apparent propagation velocity of a current pulse become slower and this tendency is more significant in lower resistivity soil. The wave front of current is deformed (become slower) when it propagates through a buried bare conductor, and deformation is more significant in lower resistivity soil. The elongation of wave front is nearly proportional to the distance from the current injection point.

Radial electric field corresponds to radial current, and its distribution accounts for the deformation of the current waveform along a buried conductor. When the apparent propagation velocity of a current pulse is slower than that of electromagnetic wave, the values of radial current from a unit section of a vertical bare conductor, evaluated from the dissipating current from the conductor or from the radial electric field integrated over the cylindrical surface around the conductor, are consistent. In this time range, the apparent propagation of current is dominated by relaxation of charge. The spatial distribution of electric field along a grounding conductor is initially spherical and concentrated near the current injection point, and is later guided by the grounding conductor. In two-layer soil, the resistivity of the layer where the buried bare conductor is embedded dominates the electrical characteristics of grounding. When the conductor is embedded in the upper layer and its resistivity is low, the bottom llayer largely alters propagation characteristics of a current pulse and distribution of electric field along a grounding conductor.

There is the issue of the effective length of a buried bare conductor on its performance at the injection of lightning impulse current. Because lightning impulse current reaches its maximum in few microseconds, there is maximum length of a buried conductor which effectively suppresses the peak voltage at the current injection point, which depends on the impulse current waveform and the soil resistivity. The peak voltage is influenced by the reflection of a travelling current pulse at the end of the buried conductor, therefore, circuit models or travelling wave analysis have often been employed to evaluate the effective length of grounding conductors. In the circuit approach, selection of the circuit parameters is essential, and wrong selection leads to wrong results, which sometimes happened. It is more straightforward to numerically analyze fields directly to cope with this subject. As a result, a simple experimental formula to evaluate the effective length of grounding conductor from the rise time of a current pulse and ground resistivity is proposed. The proposed formula is applicable to evaluate the effective length of grounding conductors in uniform soil having resistivity from 100 Ωm to 2000 Ωm and injection current having front time from 0.25 μs to 10 μs.

IEC TR61400-24 recommends interconnection of the grounding of wind turbines in a wind farm through horizontal electrodes, either by insulated or bare conductors, to achieve low steady-state grounding resistance; however, the transient behavior of an interconnected wind turbine grounding system remains to be discussed. The transient response of interconnected wind turbine groundings is analyzed using VSTL to show the effectiveness of interconnection of wind turbine groundings. It is effective at highly resistive soil and when the lightning current having rise time more than few μs is injected. Effectiveness of interconnection using a buried bare conductor is also consistent with the evaluation of the effective length.

If for any reason interconnection is made by a buried insulated wire or an overhead wire, they are also effective, though their effectiveness is limited by their surge impedance. The surge impedance of a buried insulated wire or an overhead wire initially limits the current in the interconnection wires. It gradually increases through several reflections between the groundings where the ends of the interconnection wire are attached. As the distance between turbines increases, the effectiveness of inter-connection using a buried insulated wire or an overhead wire decreases, as the travel time between turbines increases. Nevertheless, for lightning protection of wind turbines in the winter lightning area of Japan, interconnection is always useful, as the dangerous lighting current in winter is characterized by long duration and large charge transfer.