Time-Domain Simulation of Complex Grounding Devices Considering Soil Ionization

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Abstract —It is important to identify the impulse impedance of tower grounding device for lightning protection. Soil ionization greatly affects the character of the grounding device. This paper derives a time-domain numerical approach considering soil ionization based on electromagnetic field and circuit theory. The simulation result is critically closer to the actual measured one.

I. INTRODUCTION

The lightning impulse performance of grounding system plays an important role in the lightning protection. If a lightning current is injected into the grounding system, because of the high impedance in the grounding conductor at high frequency, the electric field surrounding the grounding electrodes near the current injected point may exceeds the critical breakdown value and the soil will be ionized [1, 2]. The affected portion of the soil will become a good conductor, which is equivalent to expanding the radii of the electrodes as Fig. 1 shows. The equal radius is time-varying and nonlinear.

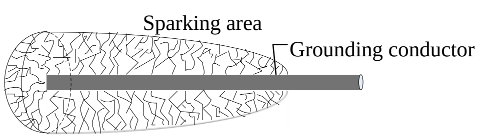

Fig. 1. Soil ionization imposed by impulse current

Usually when the impulse performance of grounding system is calculated, the dynamic and non-linear ionization phenomenon is often omitted [3-5]. Several authors have studied the simple grounding device considering soil ionization [1, 2], but the grounding device is not complex. Some have done the research by using of the transmission line approach [1, 6], but the mutual couplings among conductors especially due to the radial current cannot be taken into account. This paper derives a numerical method to analysis the impulse response of the complex grounding device in the time-domain based on electromagnetic field and circuit theory.

II. GROUNDING SYSTEM ANALYSIS

A. Modeling and Analysis in Time-Domain

Consider two buried conductor segments. As to anyone of them, there are axial current I_l, radial current I_e and electric charges Q along the conductor. There exists three coupling mechanisms, namely, capacitive coupling C, conductive coupling G, inductive coupling M between them accordingly. What's more, the self-parameters like self-resistance R and self-inductance L are also distributed along each segment. Among these parameters, because the multi-inductance is much smaller than the self-inductance, the capacitive coupling is much smaller than the conductive coupling, they can be neglected.

As to a complex grounding device, let it be cut into K segments and M nodes. Suppose the axial current I_l of each segment is centralized on the axis and the radial current I_e of each segment flows out from its central point. Fig. 2 shows these currents on the k-th segment, and Fig. 3 shows the equivalent circuit.

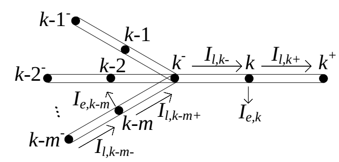

Fig. 2. A part of a grounding grid

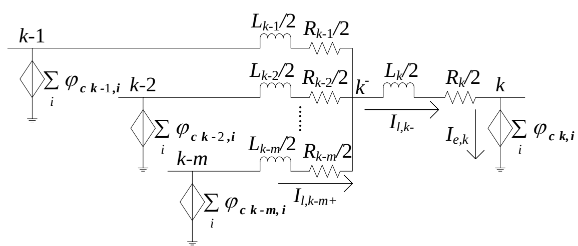

Fig. 3. The equivalent circuit of Fig. 2

The voltage φ_c at the central point of each segment due to all the radial currents in the soil can be regarded as controlled voltage sources by all the radial currents, which obeys the following relationship:

$$\varphi_c = \boldsymbol{G}^{-1}\boldsymbol{I}_e \tag{1}$$

where $\boldsymbol{\varphi}_c$ is a column matrix of the potentials at the surfaces of the central points of the segments, $\boldsymbol{G}^{-1}$ is a mutual resistance matrix with order of K whose entry G^{-1}_{ij} is equal to the potential at the surface of the central point of segment i caused by a unit current leaking from segment j [7]. Thus, a circuit model is established. In consideration of the convenience for Kirchhoff's voltage law, state equation of inductance in the time domain can be derived.

The transient process of the linear inductance shown in Fig. 4 (a) can be described by

$$u_L(t) = u_k(t) - u_m(t) = L \cdot di_{km}/dt \tag{2}$$

From (2) we can derive that

$$i_{km} = [u_k(t) - u_m(t)]/R_L + I_L(t - \Delta t) \tag{3}$$

where

$$\begin{aligned} R_L &= 2L/\Delta t \\ I_L(t-\Delta t) &= i_{km}(t-\Delta t) + [u_k(t-\Delta t) - u_m(t-\Delta t)]/R_L \end{aligned} \tag{4}$$

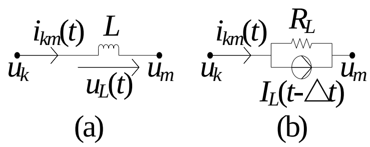

Fig. 4. An inductance component and its equivalent model

Thus, the inductance in the circuit shown in Fig. 3 can be replaced by the model shown in Fig. 4 (b). Now we can use Kirchhoff's voltage law to derive a state equation (5):

$$\boldsymbol{I_l}(t) = \boldsymbol{Y}\boldsymbol{A}^T\varphi - \boldsymbol{I_L}(t-\Delta t) \tag{5}$$

where $\boldsymbol{I_l}(t)$ is the axial current column at t with order of $2K$, which consists of I_{l+} and I_{l-}; $\boldsymbol{Y}$ is the conductance matrix of the model; $\boldsymbol{A}$ is the connection matrix; $\boldsymbol{I_L}(t\text{-}\Delta t)$ is an equivalent current source column derived from previous status as (3) shows; $\boldsymbol{\varphi}$ is the potential column at t with order of $(K+M)$, which consists of the segments' central potential column $\boldsymbol{\varphi_c}$ and the nodes' potential column $\boldsymbol{\varphi_n}$:

$$\begin{aligned} \varphi_c(t) &= \boldsymbol{G}^{-1}\boldsymbol{I}_e(t) = \boldsymbol{G}^{-1}[\boldsymbol{I}_{l-}(t) - \boldsymbol{I}_{l+}(t)] \\ \varphi_{n+}(t) &= \varphi_c(t) - [\boldsymbol{I}_{l+}(t)(\boldsymbol{R}+\boldsymbol{R}_L) - \boldsymbol{I}_{L+}(t-\Delta t)\boldsymbol{R}_L]/2 \\ \varphi_{n-}(t) &= \varphi_c(t) + [\boldsymbol{I}_{l-}(t)(\boldsymbol{R}+\boldsymbol{R}_L) - \boldsymbol{I}_{L-}(t-\Delta t)\boldsymbol{R}_L]/2 \end{aligned} \tag{6}$$

where $\boldsymbol{R}$ is the matrix of self-resistance, $\boldsymbol{R_L}$ is the matrix of equivalent self-inductance derived from (4). And as to one node, $\boldsymbol{\varphi_{n+}}$ and $\boldsymbol{\varphi_{n-}}$ should be included only once in the column $\boldsymbol{\varphi}$, whose order is $(K+M)$. Thus, $\boldsymbol{\varphi_c}$, $\boldsymbol{\varphi_n}$, $\boldsymbol{I_l}$ and $\boldsymbol{I_e}$ at t can be evaluated by solving equation (5) and (6).

B. Soil Ionization

If the electric field strength exceeds the limit for soil ionization, the equivalent radius can be obtained by:

$$J_i(t) = E_c/\rho = \Delta i_i(t)/(2\pi r_i(t)\Delta l_i) \tag{7}$$

where E_c is the critic electric field strength for soil ionization, Δl_i is the length of segment i, r_i(t) is the equivalent radius, J_i(t) is the current density, and Δi_i(t) is the radial current.

The axial current mainly flows inside the conductor, so neither the conductors' self-resistances nor self-inductances are affected by soil ionization, which means the matrixes $\boldsymbol{R}$ and $\boldsymbol{L}$ (or $\boldsymbol{R_L}$) in (6) do not vary with the development of soil ionization. Only the mutual resistance $\boldsymbol{G}^{-1}$ in (6) is changed because the real segments' radiuses are replaced by the equivalent radius. The current diffusion at time t can be calculated by iteration following the steps as Fig. 5 shows.

III. VALIDATION AND APPLICATION

The approach is verified by field test. An impulse current was imposed to a steel cross with a leg-length of 10 m, a radius of 9 mm and a depth of 0.8 m. The soil has two layers. The resistivity and the thickness of the above layer are 15.8 Ωm and 6.2 m. The resistivity of the bottom layer is 2.6 Ωm. The critic electric field strength for soil ionization is 270 kV/m. A 7 kA impulse current with wave shape of 8/20 μs is injected at the central point of the cross. As shown in Fig. 6, the result by the approach in this paper has a considerably satisfied uniformity with the test result.

IV. CONCLUSION

A numerical method is developed to analyze the transient performance of grounding systems taking account of the effect of soil ionization based on electromagnetic field and circuit theory in the time domain. The method can take into account the mutual couplings between different conductors in the grounding. And the method is verified by field test.

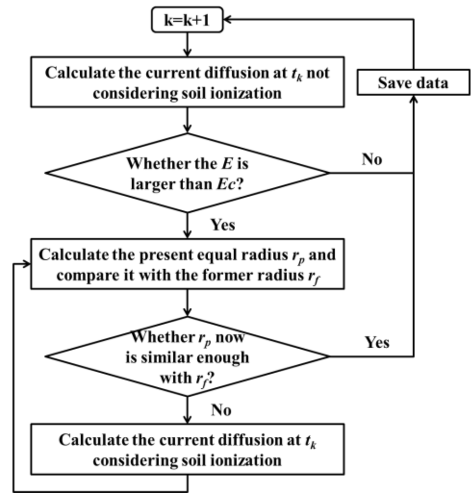

Fig. 5. Iterative steps while considering soil ionization

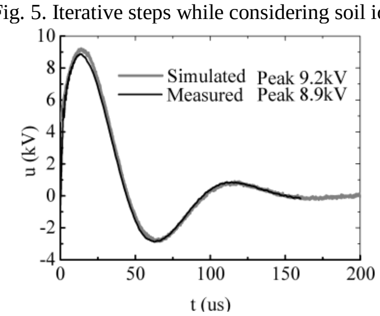

Fig. 6. Simulation result compared with field test

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