Analysis on Impulse Characteristics of Independence Grounding Devices for Lightning Protection

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Abstract—Based on the circuit theory, this paper adopts the analysis model for the impulse characteristics of grounding device considering the nonlinear soil ionization phenomena in the soil neighbouring the grounding conductors. The impulse characteristics of a typical independence grounding device for lightning protection of electronic and electrical systems inside structures is discussed and the impacts of interval and length of vertical rods, and soil resistivity are also compared by the use of this model. Suggestions for the layout of this grounding device are proposed according to the calculated results.

I. INTRODUCTION

With the development of buildings, the function of impulse grounding for lightning protection device is more and more prominent. Since the impulse characteristics of the device determine the lightning protection effect, grounding devices should be emphasized during the processes of design, construction and maintenance. The correct impulse analysis is the basis of lightning protection of structures. Nevertheless, the simulation using a lumped resistance with designated value is still adopted in large part of analysis, which does not conform to the practical situation. In fact, the grounding resistance is various with time under the impulse current. It represents complex non-linear characteristics.

Soil ionization around the grounding device makes the impulse characteristics of grounding device nonlinear. So how to consider the actual soil ionization process around the grounding devices is very important in the lightning protection analysis.

There have been many papers on the performance of grounding systems. And several models have been proposed to analyze and predict the behaviour of grounding systems [1]-[12]. The dynamic and non-linear ionization phenomenon is often omitted because this complicated physical phenomenon is too difficult to be modelled, but this was considered in a recent paper [13].

In this paper, based on the circuit model of distributed time-variable parameters proposed in [13], the lightning impulse performances of grounding devices are analyzed.

II. GROUNDING DEVICE MODEL CONSIDERING SOIL IONIZATION

Under the impulse current, a transient electrical field is generated around the grounding device. The field intensity is

\[ E = J \rho \]  

where \( J \) is current density and \( \rho \) is soil density. With the amplitude of impulse current increases, the field density in soil becomes larger. If the electrical field intensity around the grounding device exceeds the critic breakdown value, spark discharge is generated and soil will breakdown. The spark discharge makes both the electrical field intensity near the grounding conductor and the soil resistivity in the discharging region decrease extraordinarily. Generally, the potential fall of discharging region is ignored in the calculation of grounding device. That is, the resistivity of ionization soil can be simply assumed as zero, this means the size of grounding conductors is enlarged. The radius of discharging region in soil near grounding conductor can be considered as equivalent radius of grounding conductor in transient process.

The performance of grounding device under large impulse current is quite different from that in lower frequency which can be explained by the remarkable inductance effect of grounding device compared to resistance due to the high frequency current. The inductance effect would obstruct the impulse current flowing to the far-end of ground device, this makes the distribution of current and potential along grounding conductors extremely unbalanced thus leading to the extent of spark discharge and equivalent radius various along grounding conductors.

The current density in the soil, where is much closer to the feed point, is much larger. So the ionized zone of the soil around the conductor is not cucumiform but pyramidal as shown in Fig. 1. With respect to the complexity of mathematical model, the used model in this paper is shown in Fig.2 [13], the conductor is represented by a set of cylindrical zones to simulate the soil ionization phenomena as illustrated in Fig.2. \( a_i \) in Fig.2 is the equivalent radius of the ith segment, which is time-variable when an impulse current is injected; and \( a \) is the radius of the metal conductor. \( a_i \) is chosen to be large enough that the electric field at the edge of the ionized zone is below the critical value, which is time-variable.

![Fig.1. The Shape of spark discharging region around a grounding conductor.](image1)

![Fig.2. Modelling of a grounding electrode.](image2)
A horizontal grounding electrode buried in soil under lightning impulse current can be considered as a distributed network as shown in Fig.2. For a conductor segment, it is composed of series resistance \( r_i \), series inductance \( L_i \), shunt conductance \( G_i \) and shunt capacitance \( C_i \).

\[
\begin{align*}
\frac{1}{r_1} + r_2 + r_3 + r_4 + r_5 &= \frac{1}{L_1} + L_2 + L_3 + L_4 + L_5 \quad \text{(4)} \\
G_1 + G_2 + G_3 + G_4 + G_5 &= C_1 + C_2 + C_3 + C_4 + C_5
\end{align*}
\]

Fig. 3. Representation of a ground electrode with no uniformly lumped parameters.

The spark discharging region around grounding device changes according to the impulse current. In order to simulate the nonlinear discharging, the equivalent radius of different elements of grounding device should vary with time, so are the electrical parameters which have close connection with the radius.

The electric field intensity on the boundary of ionized zone is the critical value of soil breakdown. The equivalent radius for each segment can be obtained by

\[
J = \frac{E_c}{r} = \frac{\Delta i}{2 \pi r \Delta l}
\]

where \( J \) is current density and \( \Delta i \) is current of the \( i \)th segment respectively; \( \Delta l \) is the length of every conductor. Equation (2) can determine the equivalent radius which is time-variable and all parameters in Fig.3 can be obtained by the formulas in [13], thus voltages on all nodes can be calculated.

III. THE ANALYSIS AND RESULT OF IMPULSE CHARACTERISTICS OF GROUNDING DEVICE SIMULATION

This paper mainly discusses a typical independence impulse grounding device for lightning protection for electrical and electronic systems inside structures as shown in Fig. 4.

Fig. 4 Sketch diagram of an independence impulse grounding devices.

In the simulation of this paper, the lightning impulse current waveform is simulated by 2.6/50\( \mu \)s dual exponential wave with the amplitude of 10kA.

Assume that the soil relative dielectric constant is 9 and soil resistivity \( \rho \) is 100 \( \Omega \)-m. The soil critic breakdown field intensity \( E_c \) is 300 kV/m. The length of grounding device is 30 m with radius of 10 mm and burial depth is 0.8 m. The influences of the span and length of vertical rods and soil resistivity are discussed in the following.

A. The Influence of Vertical Rods’ Span and Length

The impulse grounding resistances of vertical rods with different span and length are calculated and the results are shown in Fig.5.

The impulse grounding resistance of a grounding structure is defined as the ratio of the maximum impulse voltage to the maximum impulse current in the lightning injecting point. The impulse grounding resistance does not have any physical meaning, but if the lightning current is possibly known, then we can use it to estimate the potential of the grounding structure, this is very important in lightning protection.

From Fig. 5, it is obvious that impulse grounding resistance decreases with the decrease of rod span and the increase of vertical rod length. Nevertheless, these two impacts have their own characteristics.

With the decrease of the rod interval, the impulse resistance decreases a little when the number of conductors increases a little, though the rod interval decreases a lot. The case is with the rod interval changing from 30 m to 15 m. On the contrary, when interval changes from 7.5 m to 5 m, the resistance has a significant decrease. Therefore, it can be seen that the number of vertical rods is the key influential factor for impulse grounding resistance. This can be explained that with the increase of number of vertical rods, current spreading area increases proportionally. Therefore, within the effective length of horizontal conductor, the impulse resistance decreases accordingly. When the rod interval comes to 2.5 m, the impulse resistance reaches a satisfactory value. In the consideration of economical requirement, it does not make huge different to shorten the rod interval or increase the number of vertical rods. It is relatively ideal to make the rod interval between 2.5 m and 5 m.

With the increase of the length of vertical conductor, the impulse resistance decreases firstly, however, when the length reaches 10 m approximately, the grounding resistance has an obvious saturated trend. On the one hand, the current spreading area enlarges due to the increased length which is similar to the impact of number of vertical conductors. On the other hand, the conductor inductance increases with the rise of rod length, which leads to no uniformity of current distribution along the grounding device. As a result, the incremental part of the grounding device is not facilitated efficiently. These two aspects lead to this saturation, that is to say vertical conductor has an effective length \( L_e \) under impulse current. According to Fig. 5, from the aspect of efficiency of current distribution and construction cost, it is reasonable to choose the length of vertical rod as 10 m.

B. The Influence of Vertical Rods’ Span and Length on Transient Grounding Resistance

![Fig. 5. The relationship between the impulse grounding resistances and the length of vertical rod](image-url)
The potential and transient resistance of the injected point varied with time are calculated. Setting the length of vertical rod is 10 m and the rod interval is 15 m, 7.5 m, 5 m and 2.5 m respectively. The analysis results are shown in Figs. 6 and 7.

From Fig. 6, it is obvious that with the decrease of rod interval, the potential of the injected point decreases extraordinarily. It is very efficient to lower the peak voltage by narrowing the rod interval. From Fig. 7, it can be seen that with the decrease of rod interval, the transient grounding resistance of the injected point has a little decrease, though it is not as apparent as voltage. From the resistance of power frequency, it is clear to see the impact of the decrease of rod interval.

From Fig. 8, it can also be seen that with the decrease of rod interval, the equivalent radius of the injected point decreases extraordinarily. In addition, the time that radius reaches the original radius is getting shorter. This demonstrates that the decrease of rod interval has a great effect on soil ionization.

Set the interval between two vertical rods as 5 m and the length of vertical rods as 5 m, 7.5 m, 10 m and 12.5 m respectively. The respective analysis results are shown in Figs. 9 to 11.

From Fig. 9, it is obvious that with the increase of vertical rod length, the potential of the injected point decreases extraordinarily. It is very efficient to lower the peak voltage by increasing the rod length. This feature is quite similar to the impact of the decrease of rod interval. However, when the rod becomes longer such as 10 m, there is a saturation trend. The reason can be explained by the effective length, which is discussed above.

From Fig. 10, it can be seen that with the increase of rod length, there is a little decrease of the grounding resistance of the injected point, though it is not as apparent as voltage. Due to the invisible decreasing trend, it does not show much saturation.

From Fig. 11, it can also be seen that with the increase of length, the equivalent radius of the injected point decreases extraordinarily. In addition, the time that radius reaches the original radius becomes shorter. This demonstrates that the decrease of interval has a great effect on soil ionization. These features are similar to the impact of the decrease of rod interval. What is different from the saturation of voltage is that though the radius embodies saturation when the length comes to 10 m, the time that the equivalent radius reaches the original radius is still shorter without saturation.
under the cases with the vertical rod length of 5 m, 7.5 m, 10 m, and 12.5 m.

C. The Impact of Soil Resistivity for Impulse Grounding Resistance

Set the length of vertical conductor 10m and different intervals, the impact of soil resistivity for impulse resistance can be discussed under different soil resistivity such as 50, 100, 200 and 300 $\Omega$·m respectively. The impulse grounding resistance calculated is shown in Fig. 12.

[Graph showing the relationship between the impulse grounding resistance and the soil resistivity under different rod span.]

It is known that impulse grounding resistance decreases with the decrease of rod interval which can be observed clearly from Fig. 12. Moreover, in the range of soil resistivity calculated in this case, the impulse grounding resistance grows linearly with the increment of soil resistivity. That can be explained that soil conductivity performs better if soil resistivity decreases, thus making it easier to dissipate current into soil. At the same time, when the soil resistivity is relatively low, the increase of soil resistivity has a little impact on the electrical field around grounding resistance and the thickness of ionized soil. In this way, the soil ionization does not have too much impact, thus the impulse resistance increases linearly with the soil resistivity. Also, when the rod interval becomes shorter, the extent of impulse resistance grows with the increase of soil resistivity is less. This trend can be seen from Fig. 12 that the increasing rate of the curve decreases with the increase of the rod interval. It can be explained that the increase of vertical rod number leads to the increase of current dissipating region, thus the function that the decrease of soil resistivity plays is more insignificantly.

[Graph showing the relationship between the impulse grounding resistance and the soil resistivity under different rod span.]