Impact Characteristic Analysis of Grounding Devices under High Energy Lightning

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Abstract. In this paper, the research progress of soil discharge phenomenon is comprehensively analyzed from three aspects: soil discharge imaging technology, soil impact breakdown mechanism and calculation method of grounding device impact characteristics. It is urgent to collect the important image data of soil discharge in order to study the regional structure model of soil discharge, and then accurately calculate the electrical parameters of soil discharge characteristics, and apply it to the calculation of transient model. Compared with the numerical calculation methods of grounding device, the electromagnetic field method is recommended for the calculation of impact characteristics.

1. Foreword
When the high amplitude impulse current enters the ground, some field strengths in the soil exceed the soil critical breakdown field strength, resulting in intense soil discharge phenomenon [1-3], and the soil resistance is significantly reduced[4]. Soil discharge characteristics under different conditions can be effectively analyzed by using soil discharge imaging technique to observe soil discharge area. Therefore, it is of great significance to study the technology of soil discharge imaging for analyzing the phenomenon of soil discharge, establishing an accurate soil discharge model and helping to realize the accurate evaluation of the impact characteristics of grounding devices.

2. Soil discharge imaging technology
As early as 1999~2001, scholars of Wuhan University studied the soil discharge imaging by using conductive paper[5] and monochrome photosensitive film method[6]. The image is blurred and difficult to deal with and analyze. In addition, the drop point distribution of discharge channel at the bottom of the test tank can only be obtained by conductive paper method, and the internal situation of soil discharge channel can not be observed. The observed results are shown in figure 1 and figure 2.
Figure 1. Discharge channels of soil recorded by conducting paper.  

Figure 2. Discharge channels of soil recorded by light-sensitive film.

In 2004, Tsinghua University scholars carried out simulation experiments with rod-rod and rod-plate electrodes placed horizontally. X-ray film imaging method was used to observe the soil discharge area [8,9]. The image was clear, but it could not be digitalized, and the X-ray film buried in the soil also had some influence on the discharge process. As shown in figure 3.

In 2005, Liew AC used high speed camera to observe the discrete discharge channel of high resistance wet sand surface under the action of high amplitude impulse current in the process of soil surface impact discharge using suspended electrode[7]. But in fact they observed flashover along the interface between soil and air, as shown in figure 4.

The shock discharge process of transparent glass foam was observed by A. Elzowawi in the UK in 2015 through a high-speed camera. The results show that the breakdown channel is an obvious narrow and long path, as shown in figure 5. Rakov in the United States has also found that the actual soil discharge channels grow along one or more narrow paths through field excavation experiments[11]. At the same time, when the soil discharge channels develop near the underground pipelines, they cause obvious burns to the pipelines, as shown in figure 6. The results show that the soil discharge channel tends to develop along the low resistance region and further reduce the grounding resistance[12].

Figure 3. Discharge channels of soil recorded by X-ray films.  

Figure 4. Photograph of spark discharge of soil surface from the top of a vertical driven rod.

Figure 5. Synchronized video frames of discharge channels recorded by high speed camera.
3. Soil discharge imaging technology

3.1. Study on Soil Discharge Model
Since 1942, many scholars have assumed that the soil impact discharge area of a single vertical earth pole is a cylindrical or hemispheric discharge model with a ground pole symmetry axis. It is considered that the residual resistivity in soil discharge area is similar to that of metal. As shown in figure 7.

In 1974, A. C. Liew decomposed the soil discharge region into non-free region, free region and detached region, corresponding to the regions a, b and c of figure 8. In 2011, Sima Wenxia and Li Jingli of Chongqing University improved on the basis of this model, considered the different degree of free region, and put forward a new four-zone soil discharge model.

In 1999, A.Geri proposed a time-varying piecewise cylindrical soil discharge model, as shown in figure 9[10]. Gao Yanqing of Tsinghua University in China also published a paper in 2005 to support this model, and proposed a distributed parameter circuit calculation model based on this model for horizontal grounding electrode[21].
Almost all of the above models are artificial hypothetical models. It is considered that the soil discharge region is a symmetric structure with grounding conductor as the symmetry axis, and there is a lack of effective observation means to verify the accuracy of the model. Due to the inhomogeneity of the actual soil, it is almost impossible for the soil discharge area to be distributed in axisymmetric structure, but similar to the lightning breakdown channel in the air, forming a discharge path from a certain point of the grounding pole and developing outward.

3.2. Study on Electrical Parameters of Soil Discharge Characteristics

3.2.1. Soil critical breakdown field strength
As early as 1929, the critical breakdown field strength of gravel was calculated by H.M. Towne. It is suggested that the critical breakdown field strength is 29kV/m~104kV/m when the soil resistivity is 130Ω·m≤686Ω·m[7]. In 1987, E.E. Oettle proposed that the functional relation between soil critical breakdown field strength and soil initial resistivity was as follows:

$$E_c = 241\rho^{0.215}$$  \hspace{1cm} (1.1)

In 1994, Mousa hypothesized the discharge region model of hemispherical electrode and single vertical earth pole, and proposed that the critical ionization gradient of soil is 300kV/m. In 2005, on the basis of assuming that the radius of soil discharge region is equal to the radius of grounding pole, the soil critical breakdown field strengths of hemispherical electrode under the action of positive and negative polar impulse currents are 550kV/m and 660kV/m, and that of parallel plate electrode are 790kV/m and 900kV/m, respectively. In China, He Jinliang of Tsinghua University and others put forward that the soil critical breakdown field strength is between 341kV/m and 991kV/m in 2005.

3.2.2. Residual resistivity in soil discharge area
From 1942 to 1988, Bellaschi found that the soil resistivity decreased greatly. In 2003, on the basis of assuming that the soil discharge region is hemispherical or cylindrical structure, Y.Q. Liu calculated that the residual resistivity in soil discharge area is 1.7%~47% of the initial resistivity, and the geometric mean is the residual resistivity in soil discharge area.

The soil critical breakdown field strength calculated by different scholars has a wide range of variation, which is mainly due to the difference of the soil discharge model adopted. For the residual resistivity in soil discharge area, the calculation process is also based on the hypothetical soil discharge model. Therefore, how to observe the soil discharge area effectively in order to establish an accurate soil discharge model is an urgent problem to be solved at present.

4. Calculation Method of Grounding Device Impact Characteristics
At present, through the summary and classification of the numerical calculation methods of grounding devices at home and abroad, there are three main types.
4.1. Circuit Method
There are two types of considerations:
(1)When the length of the grounding conductor is much smaller than that of the working electromagnetic wavelength, it is assumed that the current flowing into one terminal of the two-terminal element is equal to the current flowing out from the other end, and the voltage between the two terminals is a single value, then the grounding conductor is regarded as a circuit composed of several finite impedance and admittance, and solve it according to Kirchhoff's law.
(2)When the length of grounding conductor is close to the working electromagnetic wavelength, the distribution of parameters must be taken into account. The potential and current of the two adjacent points in the circuit are different at the same moment, then the transmission line model based on distributed parameters is used instead of the physical model of grounding device.

4.2. Field-circuit Method
The circuit model is established by using the basic circuit theory, the parameters are calculated by the physical and mathematical derivation process of the classical electromagnetic field theory, and then the model is solved. In the process of calculation, the complex mirror method is often used to improve the calculation efficiency. If the lightning current frequency is not more than 106Hz, the calculated results of the field-circuit combination method can often obtain ideal results. The field-circuit combination method can conveniently deal with the frequency characteristics and mutual coupling effect of grounding conductors, and the calculation speed also retains the advantages of circuit method. But in dealing with soil discharge phenomenon, field-circuit combination method is often difficult to consider.

4.3. Electromagnetic Field Method
The transient electromagnetic field is produced when the lightning current flows through the grounding device and scatters in the ground. So the process of soil dispersion can be analyzed from the point of view of electromagnetic field. The Maxwell equation in the form of differentiation or integration is used to describe the scattered flow process, and the reasonable boundary conditions are set up to establish the equations describing the scattered flow process. Then the finite element method (FEM) and the finite-difference time-domain method (FDTD) are used to solve the equations.

The finite element method (FEM) based on Maxwell differential equation has a good calculation speed in analyzing the transient performance of grounding device, and the influence of current characteristics and other factors can be considered at the same time. Compared with the simplified circuit method and the field-circuit method, the accuracy of the calculation results is higher when the actual dispersion process is simulated in the form of electromagnetic field.

At present, as long as the discharge area is hypothetical, it will undoubtedly be different from the actual soil discharge area. So the accuracy of the numerical calculation model will be reduced. It can be seen that the current research results lack a convincing theory to explain the mechanism, whether it is the soil impact breakdown mechanism or the accurate calculation of the impact characteristics of the grounding device. Therefore, the research on soil impact discharge can not only make up for the shortcomings in the field at home and abroad, but also lay a solid experimental and theoretical basis for evaluation of impact dispersion performance of grounding devices in the future.

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