



Research of Influence Pattern of Lightning Current on Impulse Characteristic of Ground Device for Pole and Tower

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Abstract—A majority of failures in power transmission line are due to trip-out in power transmission line as a result of lightning strike on power transmission line or pole and tower, how to reduce trip-out rate in transmission line becomes focus of attention in electric power system at the present time. The paper has established model for lightning current amplitude and impulse coefficient of ground device of pole and tower. X-ray photograph platform for spark discharge in soil shall shoot the gradual change process of spark discharge in soil from light lightning current to heavy lightning current; spark discharge is process pattern from spot, sphere, streamer to arc channel, the equivalent conversion pattern of impulse characteristic parameter of ground device for high and light lightning current is obtained based on research of spark coefficient and inductance coefficient so as to achieve the method to know impulse characteristic of ground device under the action of heavy lightning current by light lightning current impulse testing, in which small portable type impulse ground impedance tester is adopted to carry out testing of impulse ground impedance of pole and tower precisely, which shall play a guidance role in lightning protection design, evaluation, construction and renovation of power transmission line.

Keywords- Lightning current; ground device for pole and tower; X ray photograph platform; spark discharge; spark coefficient; inductance coefficient

I. INTRODUCTION

At present, the method adopting lumped parameter resistance with given value to simulate ground device to carry out analysis and measurement of lightning protection power transmission line is one of the main causes for big difference between analysis result of lightning protection and statistical data of practical operation[1-2]. Establishment of dynamic impulse characteristic parameter model and measurement of impulse ground resistance of ground device for power transmission line in a precise way are the foundation for analysis and design of ground performance and lightning protection of power transmission line[3-5].

Trip-out accident as a result of lightning strike on pole and tower is the result under the combined action of inductance effect of ground device and spark discharge effect in soil in the surrounding[6-8]. Inductance effect of high frequency lightning current through ground device is a relatively stable process conforming to electrical pattern; and the spark discharge effect in soil is a high-frequency, time-varying and complex physical process. Given test means restriction, its process model is still unclear for the time being[9-11].

In addition, with rapid development of power electronic technology, the small portable type impulse impedance tester applied to testing of impulse resistance of ground device for pole and tower comes into being[12-13], however, there is no definite model for equivalent relation between impulse impedance of ground device obtained by light lightning current testing within the range from hundreds of amperes to thousands of amperes and impulse impedance of ground device obtained under the action of heavy lightning current from tens of thousands of amperes to several hundreds of thousands of amperes in practical lightning process, the reason for which is that there is no accurate relation pattern between spark discharge processes generated in soil by lightning currents with different amplitudes, therefore, the result of measurement by portable type impulse impedance tester is subject to in-depth study, being a balk to its popularization and application.

The paper presents research on influence pattern of different lightning currents on ground device for pole and tower based on model for impulse process by lightning current with different amplitudes and spark discharge pattern in soil photographed by X ray and equivalent conversion relation between heavy lightning current and light lightning current in terms of impulse impedance of ground device in testing so as to offer theoretical basis for application of portable type impulse impedance tester.

II. ESTABLISHMENT OF MODEL

A. Ground calculation model under the action of lightning current

Whether there is spark discharge in soil around ground device under lightning current impulse may be determined by determining whether field density in soil is in excess of critical breakdown field intensity when ground connector is dispersing current[14], but the park discharge range is very complex, therefore, it is difficult to model spark discharge based on computer simulation to carry out simulation of impulse characteristic of ground device.

The resistivity in soil in spark discharge area is much smaller than that in no spark discharge area, the most common modeling assumptions in spark discharge area is that the resistivity in the soil in the area is considered to be very small and close to resistivity of ground connector, therefore, being equivalent to increase in ground connector or electrode dimension, the resistivity in soil in spark discharge area may be considered to be equivalent to resistivity of conductor, considering that spark discharge area is relatively regular, accordingly, spark discharge area is considered as a coaxial cone centering around conductor axis, with hemispheric discharge area at tip as shown in figure.1.

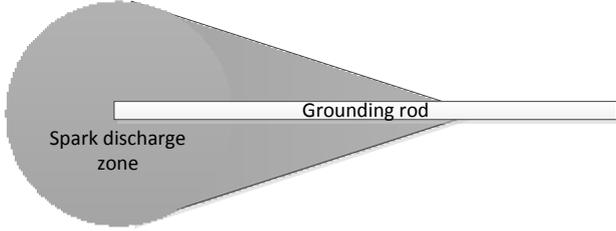


Figure 1. Spark discharge area around ground device

After segmentation of ground connector, the spark discharge area of every segment of conductor is considered to be equivalent to a cylinder, if conductor is segmented as small as possible, the spark discharge area in entire conductor shall be more approximate to cone. The boundary of cylinder in every segment of conductor shall be obtained by formula (1)-(4).

$$\frac{E_c}{\rho} = J = \frac{I}{2\pi r^{eq} L} \quad (1)$$

$$r^{eq} = \frac{I\rho}{2\pi L E_c} \quad (2)$$

In case of conductor endpoint, the radius of hemisphere is

$$\frac{E_c}{\rho} = J = \frac{I}{2\pi (r^{eq})^2} \quad (3)$$

$$r^{eq} = \sqrt{\frac{I\rho}{2\pi E_c}} \quad (4)$$

Where, E_c is critical breakdown field intensity of soil, ρ is soil resistivity, J is dispersion density of conductor, r^{eq} is radius of boundary of spark discharge around conductor, L is length

of conductor segment, I is leakage current of conductor or tip point.

In case of spark discharge, although the equivalent radius of conductor is increased, axial current is still circulating in metallic conductor other than circulating in soil in spark discharge, even if skin effect of conductor is taken into consideration, the resistivity of metallic conductor is still much smaller than resistivity in ionized soil, axial current is still circulating in metallic conductor, with only radial leakage current left in spark discharge area, therefore, when it comes to calculation of axial resistance and self inductance and mutual inductance of conductor, the calculation is still performed according to radius of metallic conductor.

B. Characteristic parameter model for ground device under the action of lightning current with difference amplitudes

Under the condition of spark discharge effect and inductance effect, the characteristic parameter of ground device under the action of lightning current with different amplitudes is subject to simulation, given the ground device composed of 15m square tower base and 4 horizontal rays, the current amplitude dependent impulse coefficient curve of ground device is obtained by change of lightning current amplitude as shown in figure.2.

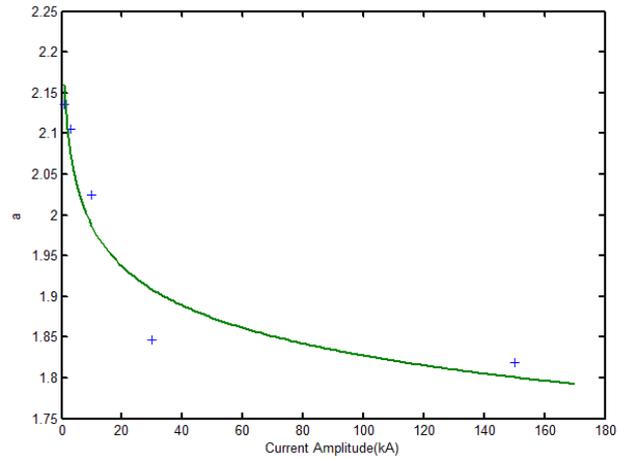


Figure 2. Current amplitude dependent impulse coefficient curve of ground device

It observed from the curve that the relation between impulse coefficient and current amplitude is in accordance with exponential function to a greater extent. The formula $\alpha = b \times I^{-c}$ is adopted for fitting to obtain $b = 2.1594$, $c = 0.0363$, therefore $\alpha = 2.1594 I^{-0.0363}$.

III. RESEARCH OF SPARK DISCHARGE UNDER THE ACTION OF DIFFERENT LIGHTNING CURRENTS

A. Building of test platform for X-ray photograph for spark discharge

In order to research spark discharge due to different lightning current, the X-ray photograph platform for spark

discharge in soil is developed as shown in 3, in which 3 (a) view of platform and 3 (b) inside view of platform.



(a) View of platform



(b) Inside view of platform

Figure 3. X-ray photograph platform for spark discharge in soil

There are 4 PTFE rollers at the bottom of the platform, with steel frame structure used as chassis, oblong trough made of organic glass as top test chamber, inside buried into soil according to practical situation, the entire test platform is covered with full light shading plastic clothing, with four corners sealed with adhesive tape. Test electrode is bar-plate electrode, with negative plate buried into soil, being vertically against inner wall of trough and vertical plate of ground conductor horizontally buried into soil. Prior to testing, the ground conductor and X-ray film are buried into soil in dark room according to preset process, after being sealed with light shading cloth, they shall be pushed to test hall for spark discharge photographing; after test, the test trough is pushed back to dark room again to take out X-ray film to develop the film in red light till X ray develops film in spark discharge channel.

B. Research of test on spark discharge in soil around ground device under the action of lightning current with different amplitude

Relative position drawing of ground bar, X-ray film and negative plate is as shown in fig.4, in which bar electrode is copper bar with diameter of 3cm, plate electrode is copper plate being 0.2cm in thickness, 43.5cm in length and 21cm in width, film is medical X ray sensitive film.

Bar electrode is buried along the direction vertical to plate electrode, being 50cm in length and 11cm in depth, the bar is 17cm away from the bottom of trough; film is buried along the direction parallel to the axial direction of bar, being 5cm apart,

the number and position of films in testing shall be adjusted according to impulse current amplitude, the reason for which is that the light current shall result in spark discharge on a small scale, only requiring 1 film buried at the tip of bar electrode, heavy current shall bring spark discharge on a large scale, requiring 3 films buried at the tip of bar electric; plate electrode center is 20cm away from bar electrode end, the resistivity of test soil is $1492\Omega\cdot m$, the waveform of impulse current is set to be 8/20 μ S lightning current.

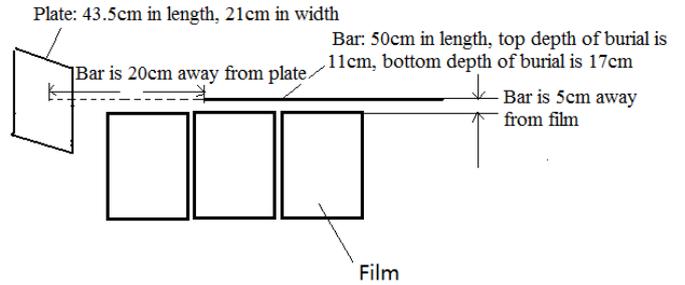


Figure 4. Relative position drawing for ground bar, X-ray film and plate

100kA lightning current generator is used for heavy lightning current, 1kA lightning current generator is used for heavy lightning current. Figure.5 is Lightning current waveform in test .

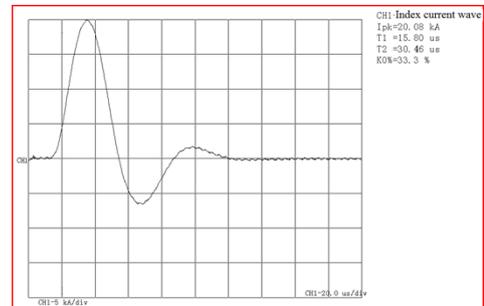
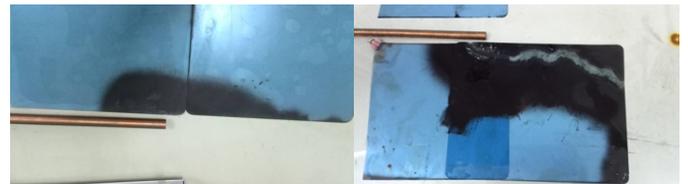


Figure 5. Lightning current waveform in testing



(a) 1kA

(b) 8kA



(c) 10kA

(d) 16kA

Figure 6. Spark discharge channel in soil under the action of lightning current with different amplitude

Fig.6 shows spark discharge channel in soil under the action of lightning current with different amplitude photographed by X-ray film, in which, (a) when lightning current is 1kA, there is spot-shaped and slightly convex spark discharge in soil at the tip of electrode, the exposed part on the left of the film is due to improper operation in film development; (b) when lightning current is 8kA, there is circular spark discharge area around electrode tip, with spark discharge dispersing in all directions from electrode tip as center; (c) when lightning current is 10kA, spark discharge channel extends to negative plate from bar electrode tip in the form of streamer; (d) when lightning current is 16kA, the gap between bar electrode and plate electrode is broken-down, forming spark discharge channel, it is observed from fig that the film showing arc channel is burned due to high arc energy.

It is observed from testing that spark discharge in soil under the action of lightning current with different amplitude is a process pattern from spot, sphere, streamer and arc channel, the equivalent relation between light lightning current and heavy lightning current may be established by modeling.

IV. RESEARCH OF EQUIVALENT CONVERSION RELATION BETWEEN HEAVY LIGHTNING CURRENT AND LIGHT LIGHTNING CURRENT IN TERMS OF IMPULSE CHARACTERISTIC PARAMETER OF GROUND DEVICE

A. Impulse coefficient decoupling

Since the power frequency ground resistance is the most available for measurement in actual field measurement, therefore, the impulse ground resistance of ground device is obtained by impulse coefficient correction[15], and the impulse coefficient defined in procedure is obtained by simulation test in sand pit, namely the impulse characteristic and its pattern of ground device are subject to research by measurement of waveform of current and voltage based on scaled-down model for ground device to which lightning impulse current is applied[16]. The method to measure impulse coefficient in sand pit is able to simulate spark effect but fails to simulate inductance effect related to dimension of ground device, which is the root cause for error in testing impulse resistance.

Therefore, inductance effect and spark discharge may be subject to decoupling, namely adopting the following expression to express relation between impulse ground impedance and power frequency ground resistance:

$$R_1 = K_1 K_2 R_2 \quad (5)$$

$$R_1 = K_1 R_3 \quad (6)$$

Where, K_1 and K_2 are spark correction coefficient and inductance correction coefficient; R_1 and R_2 impulse ground impedance under heavy current and ground resistance under power frequency; $R_3 = K_2 \times R_2$, express impulse impedance under light impulse current.

Therefore, the conversion relation between impulse resistances of ground device under the action of different lightning currents may be obtained by inductance effect and spark effect decoupling, namely, the inductance correction

coefficient may be obtained by simulation calculation based on software such as CDEGS according to lightning current, size, shape and material of ground device and then spark correction coefficient may be obtained based on procedure or simulation test in laboratory, and then the impulse impedance of ground device under the action of high impulse current may be obtained by formula 5 in a precise way, conversion relation between impulse resistances of ground device under the action of lightning currents may be obtained by change of simulation parameter and parameter in procedure.

B. Test verification

In testing, on the premise that inter-electrode distance is 1m, soil resistivity is $6033\Omega\cdot m$ and average soil resistivity is $1523\Omega\cdot m$. the "crisscross" ground device with 30m in length of ray is adopted and buried 0.6m below ground, the power frequency ground resistance measured in test is 28.3Ω as shown in figure. 7. During testing, 4kA lightning current with $8/20\mu s$ waveform is injected for measurement; the impulse ground resistance under the action of the ground current by actual measurement is 11.9935Ω .

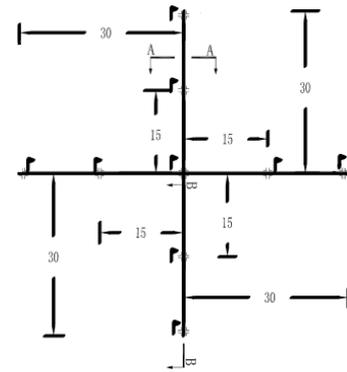


Figure 7. Ground device in test

According to procedure, injected current amplitude is 4kA, the total length of ray is 120m, the soil resistivity is $6033\Omega\cdot m$, it is recommended that $\alpha = 1.16\rho^{-0.4}(7.1 + \sqrt{L})[0.78 - \exp(-2.3I_t^{-0.2})]$ given in formula be adopted to calculate spark correction coefficient, substituting the above mentioned parameters to calculate and obtain that the spark correction coefficient K_1 is 0.3874.

Ground electrode model and soil resistivity parameters are entered in CDEGS to calculate inductance correction coefficient of the ground electrode in such an edaphic condition, during calculation, current wave front parameter is set based on actually measured data, being 8us. Finally, the impulse ground resistance calculated out is 30Ω , accordingly, the inductance correction coefficient is:

$$K_2 = 30/28.3 = 1.06 \quad (7)$$

It is observed that adopting formula 5 may figure out impulse ground resistance $R_{\text{impulse}} = K_1 \times K_2 \times R_{\text{Power}}$ Frequency = $0.3874 \times 1.06 \times 28.3\Omega = 11.62\Omega$, compared with actual impulse ground resistance, the error between which is 3%, verifying that the method to decouple inductance effect and spark effect may obtain precise impulse impedance of ground device and may be applied to figuring out conversion of

impulse resistance of ground device under the action of different lightning current.

V. CONCLUSION

The paper presents research of spark discharge and inductance calculation model for ground device under the action of lightning current and makes a study of spark discharge pattern in soil around ground device under the action of different lightning current as well as conversion method for impulse resistance of ground device under the action of different lightning current and comes to the following conclusions:

- Model for impulse coefficient of ground device under the action of lightning current with different amplitude has been established.
- Test platform for spark discharge in soil around ground device based on X-ray photograph has been developed and the process pattern from spot, sphere, and streamer to arc channel of spark discharge in soil around ground device according to lightning current value under the action of different lightning current has been obtained by testing.
- It is observed from theoretical and test verification that the method to decouple inductance effect and spark effect may obtain precise impulse impedance of ground device and may be applied to figuring out conversion of impulse resistance of ground device under the action of different lightning current.

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