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Influence of impulse breakdown delay of soil on lightning protection characteristics of transmission line

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ABSTRACT

The impulse breakdown characteristic of soil is significant for evaluating the lightning trip-out rate of transmission lines. Firstly, this paper examined the impulse breakdown delay characteristics of soil through considerable experiments. Then the influence of the impulse breakdown delay phenomenon of soil on the lightning protection characteristics of transmission lines with different rated voltages is analyzed through the numerical calculation. Based on the results, the lightning electromagnetic transient process of transmission line considering the impulse breakdown delay was discussed. The analysis results indicate that the lightning withstand level has a decreasing trend with the increase of the soil impulse breakdown delay. The influence of the impulse breakdown delay on the lightning protection characteristics of transmission lines become weaker as the rated voltage level of transmission line increases.

1. Introduction

The impulse characteristics of grounding devices for transmission line are mainly decided by impulse performance of the soil around the grounding devices. When a high impulse current is injected into the grounding device, it produces a transient electric field around the grounding device. In the circumstance that the electric field is higher than the initial breakdown electric field strength, the surrounding soil is penetrated and the spark discharges occurs. As a result, the resistivity of the ionized soil decreases obviously, and the impedance of the grounding device also reduces significantly.

The breakdown delay of soil is an important parameter to describe the impulse breakdown of soil. For any dielectric medium, when an impulse voltage high enough is applied, there is always a delay until the breakdown occurs instead of an immediate penetration. This is called the impulse breakdown delay. The impulse breakdown delay of soil is significant for evaluating the lightning trip-out rate of transmission lines, which is related to the potential on the tower top when a lightning strikes on it. The potential on the tower top is given as

$$u_t = R_i i_t + L_t \frac{di_t}{dt} = \beta \left(R_i i + L_t \frac{di}{dt} \right), \quad (1)$$

where u_t is the potential on the tower top; i_t is the current flowing through the tower; L_t is the equivalent inductance of the tower; i is the lightning current; β is the shunt coefficient of the tower to the lightning current applied on the tower, which is the ratio of the tower current and the whole lightning current; R_i is the transient grounding resistance of tower grounding device.

In premise that other parameters stay unchanged, the tower top potential and the lightning trip-out rate of transmission line are completely determined by the impulse characteristics of tower grounding device. Usually, the transient grounding resistance of tower grounding device, which is the ratio of the impulse voltage on the grounding device and the impulse current injecting into the grounding device synchronously, obviously varies with time and is used to measure the impulse characteristics of tower grounding device [1].

Many papers have discussed the phenomenon and mechanism of soil breakdown [2–14]. More studies have been made to identify the critical breakdown electric field strength E_c [8–14], which ranged from tens to thousands kV/m. Oettle [9] proposed a relationship between the critical breakdown electric field strength E_c and the resistivity of soil. Mousa analyzed the tests results in literatures, and suggested 300 kV/m as the value of E_c [10]. But few literatures can be founded discussing the impulse breakdown delay.

This paper is the extended and improved version of [15]. In this paper, the impulse breakdown delay characteristics of soil are examined through considerable experiments [16]. Then the influence of the impulse breakdown delay phenomenon of soil on the lightning protection characteristics of transmission lines with different rated voltages is analyzed through the numerical calculation.

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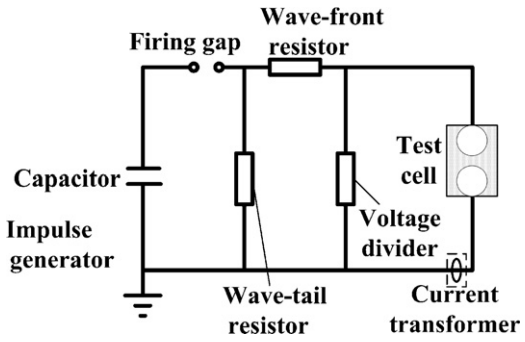

Fig. 1. The experimental arrangement and test cell of sphere-to-sphere electrode.

2. Impulse breakdown delay of soil

2.1. Test method

The experiment arrangement is shown in Fig. 1 [16], including the container of soil sample and electrodes. The impulse voltage generator can generate the 1.2/50 μs standard lightning impulse voltage, which is applied on the soil sample placed between two electrodes. The screened fine sand is selected as soil sample, whose particle size is smaller than 0.9 mm. The diameter of the sphere electrodes defined as D is 11 cm, and the distance of soil gap between two electrodes defined as d ranges from 0 to 5 cm. During the tests, d is fixed as 4 cm. Since the ratio of D to d is consequently higher than 2, the electric field between electrodes is relatively uniform.

2.2. Typical waveforms of impulse current and voltage

When an impulse voltage is applied, the soil gap will be penetrated after a certain delay, and the voltage and current waveforms will be chopped. The chopped waves of voltage and current are shown in Fig. 2, where U_m is the peak value of impulse voltage, U_c is the value at the chopping moment, t_b is the soil impulse breakdown delay [16]. In the tests, the breakdown can occur asynchronously due to different impulse voltage applied. When the value of the impulse is low, the breakdown occurs at the wave tail, while when the value is high, the breakdown occurs at the wave front before the voltage rises to the peak. The voltage remains a low value after breakdown due to the residual resistivity of the soil.

2.3. Analysis of Soil Impulse Breakdown Delay

The impulse peak voltage U_m is inapplicable to plot with the impulse breakdown delay, because U_m is indeterminate if the breakdown occurs at wave front; situation is the same with the

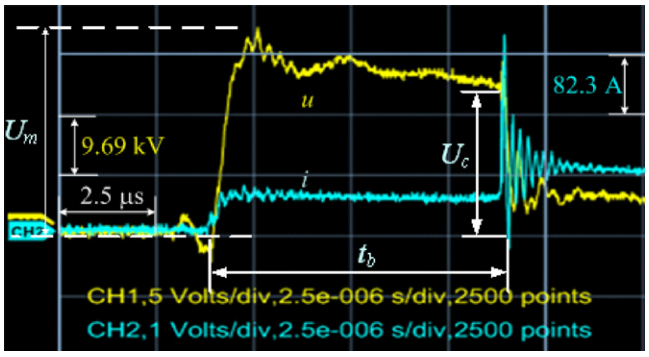

Fig. 2. The voltage and current waveforms under the sphere-to-sphere electrode.

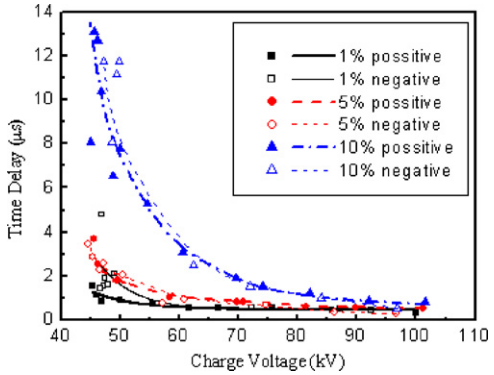

Fig. 3. The influences of the soil moisture on soil impulse breakdown delay at normal temperature.

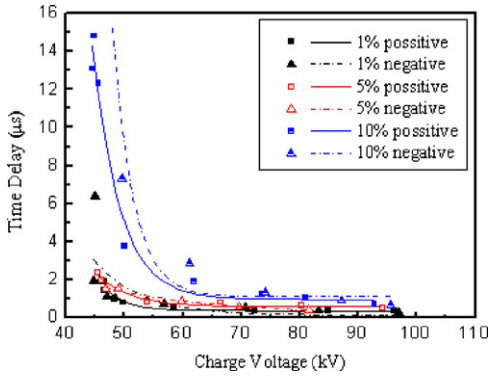

Fig. 4. The influences of the soil moisture on soil impulse breakdown delay at 0 °C.

voltage U_c at the chopping moment, because if it is adopted, the breakdown at wave front and wave tail cannot be plotted orderly, and the delay of higher chopping voltage may be longer than that of lower chopping voltage. Considering the above conditions, we use the charge voltage of the impulse generator to analyze the influence of the impulse voltage on the breakdown delay.

The soil impulse breakdown delays under the circumstances of various soil temperatures and moisture and both impulse polarities are shown in Figs. 3–7.

As shown in Figs. 3–7, for the same voltage, the soil impulse breakdown delay under the negative impulse is slightly higher than that under the positive impulse. This is because the gas discharge under a positive impulse is easier than that under a negative impulse. Thus the critical breakdown voltage under positive impulse is relatively low [12–14], and the gap between the soil

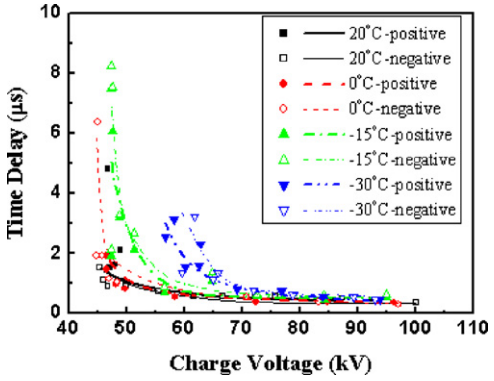

Fig. 5. The influences of the temperature on the impulse breakdown delay of the soil with 1% water content.