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Experimental Research on Impulse Breakdown Characteristics of Soil

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Abstract: The electrical breakdown characteristics of different types of soil samples have been measured. It is shown that the threshold soil breakdown strength is affected by many factors, such as types of soil, grain size, and soil compaction. The breakdown process in the test soil samples appears to be due to air ionization in the voids between the soil particles. The results have been compared with the relevant experimental results of other researchers.

Keywords: Grounding resistance, Ionization, Lightning, Soil breakdown, Threshold breakdown strength

1. Introduction

The lightning protection effects of substations or transmission lines are related to the impulse characteristics of grounding systems. As already evidenced by many researches, the large impulse currents can generate complicated soil ionization surrounding the grounding conductors, which makes the transient characteristic typically non-linear. The non-linear transient behavior depends upon many electrical and geometrical parameters. Furthermore, the evolution of soil ionization in the time domain is very difficult to predict.

Thus, the investigation into the characteristics of electrical breakdown and discharge processes in soil forms part of a project concerned with the impulse characteristics of grounding systems [1-3].

Of all of the transient models of grounding systems considering the soil ionization, the threshold soil breakdown strength E_0 is an important and pivotal parameter. The choice of a suitable value of E_0 has a significant influence on the transient characteristics of grounding systems. Unfortunately, E_0 is a parameter about which very little is presently understood. The soil ionization will assist in reducing the value of grounding resistance of the ground system. This fact was first stated by Towne in 1929 [4]. The E_0 in his measurements was in the range of 160-520 kV/m. Loboda et al [5, 6] present the results of experimental investigations concerning the electric properties of different soils injected by current pulses. The E_0 was calculated to be in the range of 560-900 kV/m. In the investigations of Oettle [7] and Chisholm [8], which covered several types of soil, the E_0 was found to be in the range of 600-1850 kV/m. Mousa [2] has suggested that the threshold soil breakdown strength is equal to 300 kV/m, by using a large number of reliable impulse resistance measurements, carried out by several researchers. The value of 400 kV/m is used by CIGRE [9] without any other explanation.

This study of the breakdown processes in soil was performed in order to reach a better understanding of the actual physical processes in soil under high voltage and high current density. We hope that this work will lead to a superior model describing the soil discharge process resulting in a more reliable method of estimating E_0.

2. Experiment Arrangement

The experimental set-up is shown in Fig. 1. The impulse generator consisted of a capacitor, resistors and inductive component included in the circuit to adjust the waveform of the impulse current. When the circuit is short, an impulse current having a front time of 1.2 μs and a half time of 50 μs is generated. The soil sample is placed between the two large hollow spherical cupreous electrodes. When the thickness of soil sample d is less than half of the diameter of the electrodes ϕ ($d \leq 0.5\phi$), the electric field in the center of the soil sample is believed to be fairly uniform. The surface of the two cupreous electrodes was burnished prior to the test. The sifted soil sample between the two electrodes was compressed manually and evenly in order to ensure sufficient contact between the soil sample and the metal. The soil sample was subjected to about 15 times of high voltage impulses to determine its threshold breakdown strength with the voltage up-down procedure.

The curves in Fig. 2 are the typical voltage and current

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waveshapes before and after a soil breakdown. When the impulse is first turned on, the voltage across the soil sample increases with the rise time of impulse voltage. When the breakdown occurs after the delay time, td, the current increases rapidly while the voltage drops sharply.

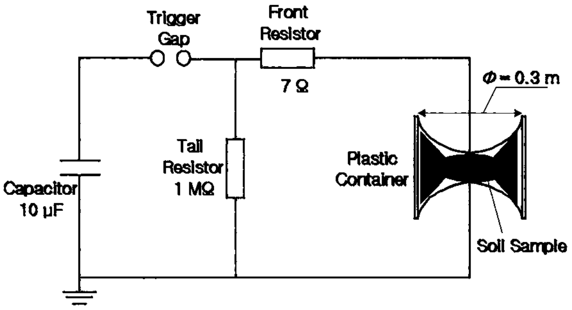

Fig. 1 Set-up for experiment

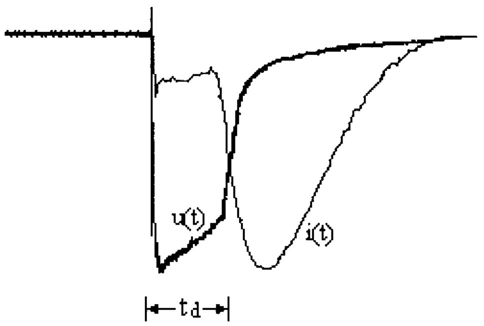

Fig. 2 Typical voltage and current waveshapes when soil breakdown occurs

3. Threshold Breakdown Strength for Different Types of Soil

A number of tests were performed to compare the threshold breakdown strength for different types of soil. Four types of soil (sand, clay, sand-clay and humus soil) were chosen for the experiments. The variation of the threshold breakdown strength versus different types of soil is presented in Table 1 and Fig. 3. Where, $\overline{E}$ is the average value of the threshold breakdown strength; S is the standard deviation, which is defined in (1).

Table 1 Threshold breakdown strength for different types of soil [kV/cm]

N	1	2	3	4	5	6	7	8	9	10	$\overline{E}$	S
Humus soil	3.47	3.38	3.42	3.43	3.37	3.39	3.47	3.35	3.42	3.4	3.41	0.04
Clay	5.21	5.09	5.09	4.89	5.02	5.11	5.01	5	4.97	5.04	5.04	0.09
Sand-clay	6.12	5.98	6.01	6.05	6.04	5.9	5.95	6.04	6.08	6.01	6.02	0.06
Sand	10.13	9.61	9.84	9.76	10.19	9.88	9.64	10.08	9.98	9.97	9.91	0.20

$$S = \sqrt{\frac{\sum_{i=1}^{n}(E_i - \overline{E})^2}{n-1}} \tag{1}$$

From the curves in Fig. 3, the threshold breakdown strength was found to be in the range of 3-10 kV/cm. The E_0 is very different for dissimilar types of soil. As well, the E_0 for any soil type will always be much less than that of the air, which is approximately 30kV/cm under atmospheric conditions.

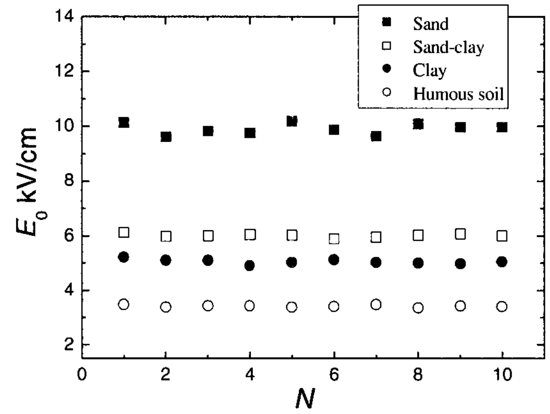

Fig. 3 Threshold breakdown strength for different types of soil

4. Influences of Grain Size on the Threshold Breakdown Strength

In this section, three types of dry beaded glass were adopted to simulate the actual soil, allowing us to study the influences of the size of soil particles on the threshold breakdown strength. It effectively eliminated the influences of other facts on the experiment result, such as the existence of organic and man-made debris in the soil.

The soil sample has been classified into three types (A, B and C) according to their grain size, as shown in Table 2. Sample D is a mixture of sample A and sample B with the proportion of 50% respectively. The threshold breakdown strength for the four types of soil samples with the same moisture content has been shown in Table 3 and plotted in Fig. 4.

Table 2 Types of soil sample

Sample Type	Particle Diameter (mm)
Sample A	1.5-3
Sample B	0.8-1
Sample C	<0.4
Sample D	Mixture of A and B

Table 3 Threshold breakdown strength for soil with different grain size [kV/cm]

N	1	2	3	4	5	6	7	8	9	10	$\overline{E}$	S
Sample A	15.8	15.8	15.9	15.8	15.8	15.7	15.6	15.7	15.8	15.8	15.8	0.08
Sample B	16.2	16	16.2	16.1	16.1	16	16.2	16.2	16.1	16	16.1	0.09
Sample C	17.2	17.3	17.2	17.1	16.9	16.9	16.6	16.6	16.6	16.7	16.9	0.28
Sample D	14.2	13.9	14.1	14.2	14	13.9	14.1	13.9	14	13.8	14	0.14

From the curves in Fig. 4, we can see that the threshold breakdown strength of the soil sample with larger grain size is lower than that of the soil with smaller grain size.

The average size of the air voids within the soil will depend on the grain size of the soil samples. The soil sample with a larger grain size will have a larger air void. For example, soil consisting of very fine particles will have smaller sized voids, while soil with coarse particles will have larger sized voids. The breakdown in soil is due to avalanche ionization of the air in the voids between the soil particles, where the electrical field is enforced discontinuously. With equivalent moisture content, it is more easily developed into continuous discharge channels for the soil sample with larger grain size, which leads to a lower threshold breakdown strength. The threshold breakdown strength of sample D, which is the mixture of sample A and sample B, is markedly lower than that of sample A or sample B. The main reason for this is that the nonuniformity of the grain size for sample D leads to the nonuniformity and irregular shape of the size of air voids. As a result, it partially enforces the maximal electrical field in the air voids, which causes the soil to breakdown more easily.

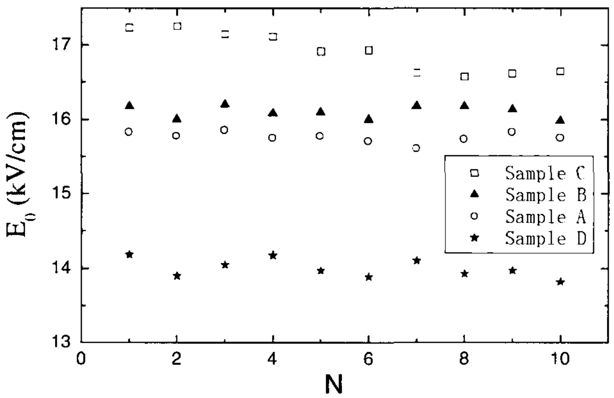

Fig. 4 Threshold breakdown strength for soil samples with different grain sizes

5. Influences of Soil Compaction on the Threshold Breakdown Strength

In the case of clay soil, the compaction can be changed by manual compression and twisting, which will have influence not only on the soil resistivity but also on the threshold breakdown strength, as shown in Table 4. The soil resistivity decreases with the increase of soil density. The contact among the soil particles is tighter and closer for soil with higher density, which enhances the capability of current-conduction. The soil sample with higher density will have tighter contact of soil particles and smaller size of air voids among soil particles. As a result, in the case of soil with high density, it is difficult to develop into continuous discharge channels, which leads to a higher threshold breakdown strength.

Table 4 Threshold breakdown strength for soil with different density

υ (kg/m^3)	ρ (Ω m)	E_0 (kV/cm)
1024.9	195.2	5.04
1176.5	129.9	5.29
1323.5	136.7	5.83
1470.6	85.5	6.29
1691.5	23.9	6.58

6. Breakdown Mechanism of the Soil

Two different mechanisms have been proposed to explain the electrical breakdown process in soil. The first explanation suggests that avalanche breakdown in the air voids leads to soil breakdown when the electrical field becomes large enough to ionize the air [1]. Another explanation is that the breakdown mechanism is primarily a thermal process in the water contained in the soil [10].

The experimental result in Part 4 indicates that for the same dry soil samples, the air voids between soil particles have great influence on the threshold breakdown strength. This conclusion strongly supports the following opinion: soil breakdown is produced by the air ionization between the soil particles. Kirkici studied the electrical breakdown of a simulated lunar soil in a high vacuum environment [11]. Experimental results showed that the breakdown in electrical strength is about 60kV/cm for the simulant soil, which is much higher than the values of 3-10kV/cm in this study. It is obvious that the air voids between soil particles have great influences on the soil breakdown.

7. Conclusion

The soil types have great influence on the threshold breakdown strength E_0. The majority of the values of E_0, for different types of soil can differ from 3-5 kV/cm (clay and humus) to 9-10 kV/cm (sandy), which are much lower than the breakdown strength of air. The influences of grain size on the threshold breakdown strength were investigated. The soil with larger grain size has a larger size of air voids between soil particles, which leads to a lower threshold breakdown strength.

The electrical breakdown for different types of soil was investigated. In addition, the breakdown mechanism of soil was discussed in this paper. The result of the experiment suggests that the ionization of the air trapped in the voids of the soil is the mechanism by which breakdown of the soil occurs.

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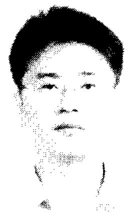

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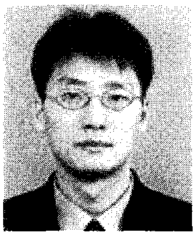

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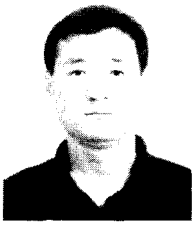

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