

Mason's equation application for prediction of voltage of oil shale treeing breakdown

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Abstract. The application of the formula, which is used to calculate the maximum field at the tip of the pin-plane electrode system was proposed to describe the process of electrical treeing and treeing breakdown in an oil shale. An analytical expression for the calculation of the treeing breakdown voltage in the oil shale, as a function of the inter-electrode distance, was taken. A high accuracy of the correspondence of the model to the experimental data in the range of inter-electrode distances from 0.03 to 0.5 m was taken.

1. Introduction

Electrical treeing, which is the formation of tree-like channel structures, is observed in the low conductive materials under high voltage. In [1], the treeing phenomenology for polymeric insulation materials is widely described. It is ascertained that the growth of channel structures called dendrites occurs due to degradation of the material by partial discharges (PD). Many treeing diagnostic methods are based on measurement of the partial discharge characteristics [2, 3].

Depending on the dielectric material and its molecular structure, the dendrites can be conductive and nonconductive [4, 5]. In the case of non-conductive dendrites, the treeing is going on due to an increased voltage within the dendrite. The main part of the PDs is concentrated in the area of the dendrite base. The PDs have a relatively large apparent charge, which increases by lengthening of the dendrite. The structure is lengthened when the discharge streamers reach the tips of the dendrite. This forms a hollow channel structure with dielectric walls. In this case, the intensity of partial discharge weakens by the growth and branching of the structure.

In the case of conductive dendrites the structure lengthening occurs due to the increased voltage, in the material near the tips of the dendrites. The PDs act mainly on the tips of the dendrite branches and extend it by a thermal effect of the partial discharge. The PDs have a relatively low apparent charge, which is almost independent of the size of the dendrite. The structure lengthens more rapidly than in the case of non-conductive dendrites. By the growth and branching of the tree, the intensity of the PDs increases. The channel structure is coated with a low-ohmic layer of products of a dielectric thermal destruction [4].

The partial discharges and treeing can occur in the carbonaceous rocks, such as the brown and black coal and the oil shale. [6], leading to the breakdown of large interelectrode distances at relatively low voltage. This effect can be used for breakdown and underground heating of solid fuels formation



in the technologies of in situ processing [7]. However, we need to know the voltage required for the breakdown of a given inter-electrode distance.

In dielectrics with the non-conductive dendrites, the breakdown moment can be predicted with the help of the apparent charge value [2, 3]. In dielectrics with the conductive dendrites, the PD characteristics do not correlate with a breakdown time. The reason can be that in the structures with the conductive dendrite, the PDs arise mainly on the tips of the tree, so the discharge characteristics depend a little on the size of the tree.

We observed treeing in solid fossil fuels (the black coal, the brown coal, the oil shale) and its correlation with the characteristics of the partial discharges. Observations of treeing in the solid fuels showed the following features. At a constant value of the applied voltage, the dendrite growth is going on for some time, after which the intensity of partial discharge is reduced. As far as the voltage is increasing, the intensity of the PDs rises again and continues for a while, then decreases again. This behavior is related to the fact that the voltage change on the electrodes will affect the value of the field concentrated at the tips of the dendrite. The Mason's article [8] presented a formula that describes the field at the tip of the electrode in the tip-plane electrode system. Use of this equation can help to determine the field on the tips of the dendrites.

The article describes a model, which can be used to predict the treeing breakdown voltage in the solid fossil fuels, as a function of the inter-electrode distance, using the Mason's formula.

2. Experimental setup and results

In the experimental setup, the dependence of the treeing breakdown voltage on the distance between the electrodes was investigated (Figure 1).

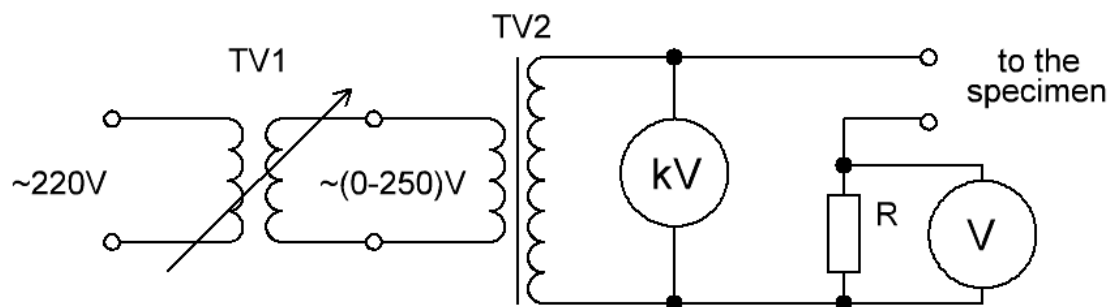


Figure 1. Experimental setup circuit

In the setup, the voltage ~ 220 V is regulated by a transformer with a variable magnetic coupling over the voltage range from 0 to 250 V. This voltage supplies a step-up transformer with an output voltage up to 100 kV. The measured parameters in the experiments were the voltage at the sample and the current flowing through this sample, which were detected using a resistive shunt. The electrodes were made of a steel rod and inserted into the rock in 5-10 cm, to provide an electrical contact of the electrodes with an interlayer cut for an efficient dendrite growth.

In the experiments, the voltage was gradually raising till the moment of breakdown. During the experiment, the growth of dendrites was diagnosed by the presence of current spikes caused by a large number of short pulses in the circuit, which is typical for partial discharges. It was noticed that at a constant value of the applied voltage, the treeing stopped after some time, as if reaching a potential barrier. When the voltage increased, the treeing was detected again, but after some time, stopped. The voltage increasing rate was 100 V/min. This rate was enough for treeing processes to complete and reduce the activity, waiting for a further increase of the voltage.

The voltage of the treeing breakdown, as a function of the inter-electrode distance, for the oil shale of Huadian deposit (China) is shown in Figure 2.

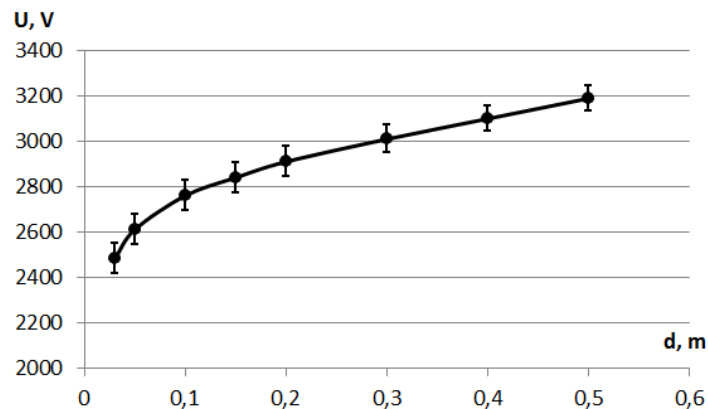


Figure 2. Voltage of treeing breakdown of oil shale as a function of inter-electrode distance

The voltage is dependent on the distance nonlinearly, as would be in the case of a pure electric breakdown. The shape of curve induces a supposition that the breakdown at large distances between the electrodes requires a relatively low voltage. This effect can be used in the technologies of in situ heating and the pyrolysis of solid fuels, where the first stage is a breakdown of the inter-electrode distance, and the second one is the heating of the formation by a joule heat in a breakdown channel [7]. In this case, the distance between the electrodes can reach tens to hundreds of meters, and the voltage, at the same time, is technically achievable.

This application of the treeing breakdown needs a way, to predict the voltage required for the breakdown of the given inter-electrode distance. If we assume that each rock can be tested in a laboratory, at small distances, the obtained characteristic can be extrapolated to larger distances. In this case, a low of approximation of the experimental data should be reasonably chosen. For the purpose of such an approximation, we have considered the use of Mason's formula for the treeing breakdown modeling. The calculations were performed for the oil shale of Huadian deposit (China).

3. Mason's equation application for breakdown modelling

The following model of treeing and treeing breakdown process was assumed for phenomena modelling. The partial discharges occur at a tip of the dendrite, as a breakdown of a small part of the material in the area, where the field is extremely high and exceeds the electrical strength of the rocks (Figure 3).

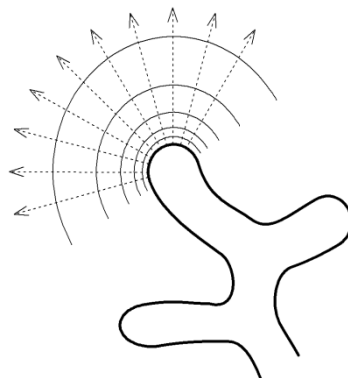


Figure 3. Field concentration near the tip of the dendrite

The maximum field near the tip can be calculated by the Mason's formula [8]:

$$E = \frac{2V}{r \ln\left(1 + \frac{4d}{r}\right)} \quad (1)$$

where E is the maximum field near the tip of the dendrite, V is the voltage between the electrodes, r is the radius of the tip of the dendrite, d is the distance between the electrodes.

When the field near the tip exceeds the electrical strength of the rock, the local electrical breakdown (i.e. a partial discharge) occurs in this fragment of the rock. Suppose that the electric strength of the rock is approximately constant at all points, and the partial discharge occurs when the maximum field at the tip E exceeds a certain amount, called a critical field E_{cr} in similar models [9]. Thus, on the basis of (1), the PDs will occur, when the voltage between the electrodes is:

$$V = \frac{E_{kp}}{2} r \ln\left(1 + \frac{4d}{r}\right) \quad (2)$$

Thus, using the formula (2), we obtain the dependence of the voltage between the electrodes, which will enough for a steady occurrence of partial discharges and treeing development, at a distance d , with a given value of the critical field E_{cr} and the tip radius r . If we assume that under this condition, the treeing development and breakdown will occur, then the (2) may be considered as a dependence of the breakdown voltage on the inter-electrode distance.

The radius of the tip of the dendrite depends on the material structure and composition. Suppose that for one rock, it is an approximately constant value. For the considered oil shale, the average radius was determined by an electron microscopy scanning and amounted to about 5 microns (Figure 4).



Figure 4. Dendrite in the oil shale

The value of the critical field E_{cr} can be determined using the approximation of the experimental data by obtained analytical characteristic. The approximation by least-squares method showed that the value of the critical field is $E_{cr} = 98 \times 10^6$ V/m (Figure 5a).

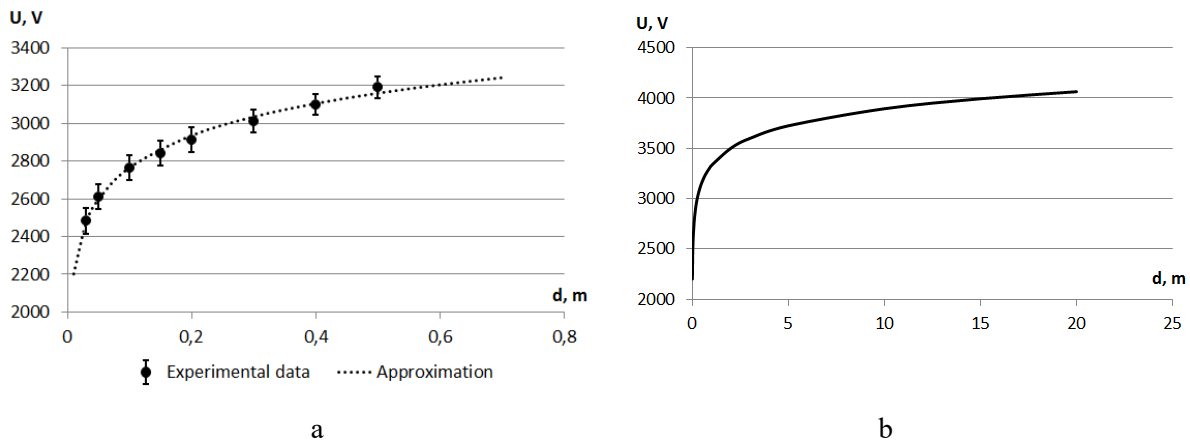


Figure 5. Curves of the experiment and the model: a) the approximation of experimental data, b) extrapolation of obtained characteristic to larger inter-electrode distances

The average error of the approximation, relative to the average value of the experimental data, is less than 1%, suggesting that there is an exact correspondence between the model and the real processes.

An extrapolation of the obtained analytical characteristic to larger inter-electrode distances (Figure 5b) showed that the breakdown of the oil shale of 20 m requires the voltage of 4060 V.

4. Summary

The proposed approximation method can be used to predict of the voltage required for the treeing breakdown of solid fuels at a given distance between the electrodes. The advantage of this approximation method are a true account of a physical principle of the electrical treeing and physical parameters of the medium. The disadvantage of the proposed model is a possible spread in the values of the critical field and the radius of the tip of the dendrite relating to an inhomogeneity of the material of fossil rocks. It was noted that the real effect of the partial discharge starts at the voltage, which is significantly lower than this estimate.

For the given oil shale, the model has correspondence to the experimental data with high accuracy at small inter-electrode distances. At large inter-electrode distances, the compliance of the model should be checked under field conditions.

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