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Incipient electric field determination for bush and streamer stage in dielectric liquid under energy balance condition

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ABSTRACT

This paper introduces a new approach for streamer advance mechanism in dielectric liquid. The existing of bush-like streamer shape early and then a tree structure shape after that has been given an over view and definition by devising a breakdown index for dielectric liquid which reach a value of 25. The deviation of streamer velocity from low values of tens of meter per second, until several kilometer per second from bush-like shape, until complete breakdown has been discussed too. These different stages have been studied on an energy balance concepts. In this paper using energy balance analysis, different critical applied fields have been obtained. These values reach 2.18 MV/cm for one branch channel in bush-like streamer shape and 21.5 MV/cm, for tree streamer. After that, the initial streamer velocities concerning these stages have been introduced. From these analysis the dissociation of dielectric liquids starts when the streamer velocity reach the sound speed in air, 331 m/s. In addition, the dissociation field depends mainly on the physical values of the dielectric medium, such as density, and permittivity have been introduced. In this paper the dissociation starts at an electric field value of 21.5 MV/cm for nearly all dielectric liquids, This result is equal to tree streamer inception value, which can be considered as a new introduced finding. A new energy equation relating injected energy electric field, velocity and new deduced breakdown index in dielectric liquid has been devised. The streamer may stop or continue its advance until complete breakdown. According to many published data for streamer, there is no clear explanation for streamer stopping and continuing it advance. In this paper, the streamer must advance ahead of the bush zone in the gap toward the opposite electrode when the prospective electric field at 66% of the gap achieves a breakdown index of 25. This result can be considered as a new criterion for streamer growth until crossing the gap. These new equations and findings have been applied to several experimental works and achieve good results.

1. Introduction

It has been clearly known that breakdown in dielectric liquids has preceded by streamer initiation. There is a good relation among the streamer structure, propagation velocity, current shape and light emission, irrespective of the polarity of the point electrode and liquid condition [1]. The velocity increase with the more filamentary streamer [1] and vice versa.

The experimental data given after [2,3] in cyclohexane using point-plane electrode system, their results indicate that for very sharp tips, the streamer initiation occurred under either of two anode modes. For first anode mode the required voltage increases with increasing point electrode radius. But for the second mode the required voltage was independent of the point radius for small values of the tip radii.

In Ref. [4], at bush-like streamer of low velocity (~60 m/s) the main mechanism is vaporization, but under filamentary streamer of high velocities (~2 km/s) the working mechanisms are dissociation and ionization. Applied voltage 35 kV, gap 2 mm, negative point, radius 3 μm, show a slow streamer, but for applied voltage 30 kV, gap 1.5 mm, positive point, radius 1.5 μm show a rapid streamer.

From previously given data, the streamer starts as a bush-like structure type. The channels in this bush region are fine [5], compared with the streamer size.

2. Breakdown criterion in dielectric liquid

The authors in this paper introduce a new visualized concept for breakdown condition in dielectric liquid. This concept can be

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realized at the instant when the injected energy at the electric tip is sufficient to empty the liquid surrounding the stressed electrode tip in so called "minimum stressed zone". Under this condition, an initial process toward breakdown is started.

2.1. Bush-like streamer mechanism

For point-plane electrode under high applied voltage, the non-uniform electric field results in initiating an energetic zone around this tip. It is assumed that the bush-like structure spread in the minimum stressed zone with 4 μm radius as given in Ref. [9], show Fig. 1. From this figure the bush zone consists of many fine branches its number can be estimated by knowing firstly the energy required to initiate one branch.

The pressure inside this branch (P_i) must be sufficient to overcome, hydrostatic pressure (P_h), surface tension pressure (P_s) and external applied pressure (P_a), according to the following equation

$$P_i = P_h + P_s + P_a \tag{1}$$

From Equation (1), P_h can be neglected, for the test cell's used and P_a can be considered atmospheric pressure, thus.

$$P_i = \frac{2\sigma}{r_o} + P_a \quad \mathrm{N}/\mathrm{m}^2 \tag{2}$$

where, (σ) is the surface tension of dielectric liquid and r_o is the channel radius.

From Fig. 1, for bush-like streamer zone, R can be assumed equal to $5r_o$ (which is acceptable value for most published data of channel radius and electric field at this stage). The total number of fine branches (N) occupying the bush zone volume, could be given as the ratio of the bush zone volume to fine branch volume i.e.

$$N = \frac{(4/3)\pi R^3}{(1/3)\ \pi r_o^2 l_o} \tag{3}$$

where, l_o is the height of fine branch cones filling the bush zone volume, see Fig. 1b. For l_o equal R. $N = 4(R/r_o)^2 = 100$ branches.

2.2. Energy balance for bush zone initiation

2.2.1. Energy required to empty the bush zone from dielectric liquid

From the above analysis, the total number of fine branches covering the bush-like streamer zone reaches 100. But actually evaporation occur in this stage. The vaporization will increase the size of these branches. This size (r_v) can reach 8 μm value at atmospheric pressure as given after [6]. Thus, the total number (n) of vapor branches which occupies the same volume of fine branches constituting the bush-like streamer zone, will be $\frac{4\pi R^2}{\pi r_v^2} = 4\left(\frac{R}{r_v}\right)^2$, and

$$n = 4\left(\frac{R}{r_v}\right)^2 \tag{4}$$

where, n is the required increased vapor volume branches to empty the bush zone from liquid and become gaseous zone, which can be considered as the breakdown criterion and n as breakdown index.

Also, the total energy required for initiating one bush branch (Wb) in this zone, can be given as

$$W_b = P_i\left(\pi r_o^2 l_o\right) \quad \text{Joule} \tag{5}$$

2.2.2. Critical applied field required for bush branch initiation

Under non-uniform high applied field in front of a point electrodes in dielectric liquids, a maximum stressed zone is intended for streamer initiation, some authors [7] gives a value of 0.5×10^{-15} $m^3$and some other authors [8] proposed a critical volume of the order 10^{-15} to 10^{-18} m^3.

In the present paper, a minimum stressed zone is considered as a sphere at the apex of stressed electrode tip (r_p) as an envelope for initiated push like streamer branches. The energy at the electrode tip required to initiate one bush–branch at a critical applied field (E_c) can be given as following, see Fig. 2.

The energy delivered to critical volume V_o at critical field E_c equal to ($1/2\ \varepsilon E_c^2$) per unit volume. This energy will be transferred to the dielectric liquid in front of the electrode tip in the form of

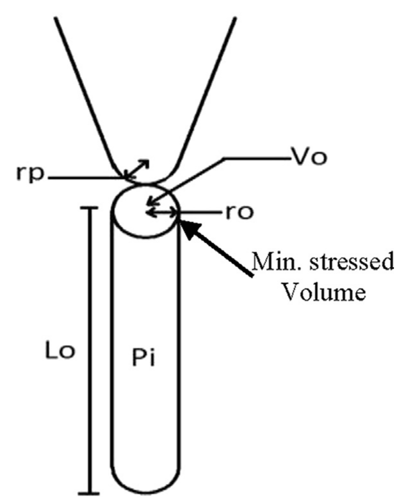

Fig. 2. Bush–Branch Pressure stability.

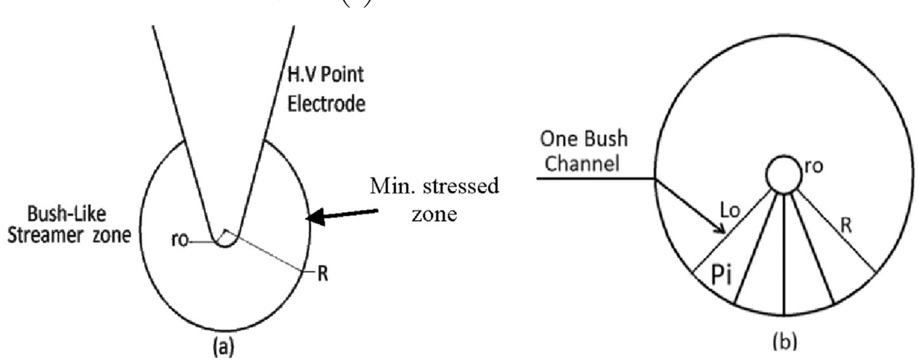

Fig. 1. Bush-like streamer structure representation.