Fractal analysis of streamer patterns in dielectric liquids under dc voltage

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Abstract

In order to investigate the streamers propagating characteristics with in a dielectric liquid, an equivalent electrical network was used to model branching streamers. Streamer patterns were computed to be applied for the fractal analysis on streamer. In this paper, the fractal dimension of streamer patterns in transformer oil was estimated based on box-counting. Streamer patterns were obtained from initiation stage to breakdown stage, in a 5, 10, 15 and 35 mm needle-to-plane gap, under a dc voltage of 30 kV and evaluated with 2D box count. Results indicate that the variation of fractal dimension with propagation times, widely different conditions of gap distance and streamer conductivity follows the similar trend to streamer length and area electrode gap.

1. Introduction

In insulating liquids, it is possible to follow the different stages leading to breakdown and to establish that the breakdown of liquids is generally preceded by some events called “streamers“, which are the consequence of streamer initiation and propagation. The term “streamer” remains widely used in liquids to designate all propagating pre-breakdown phenomena, although mechanisms are obviously different from streamers in gases. Many papers have been devoted to study the physical processes involved during streamer initiation and propagation, and they are summarized in [1-4]. A number of parameters such as current, light pulses, and propagation velocity and stopping length can be used to characterize the streamer phenomenon. Streamers could cause degradations in transformer oils and in the worst situation, completely bridge two conductors inside the transformer and lead to insulation breakdown failures. They are generally classified as slow and “bushy” for streamers emanating from the negative electrode, or fast and “filamentary” for streamers emanating from the positive electrode. Figure 1 shows image of streamers obtained in point-plane gaps under impulse voltage with the point negative [5], and the photograph correspond to shadowgraphic” image(a light source illuminates the gap and the image recorded correspond to the shadow of streamer filaments)

The characteristics (current, velocity, structure….) of these streamers depend on the chemical composition and physical properties of the liquid; pressure and temperature; the electrode geometry; the voltage magnitude, polarity, and shape; and contaminants of air, moisture, particles, and other trace impurities. The velocity and the mode of propagation of streamers depend on the electric field, the electrode geometry.

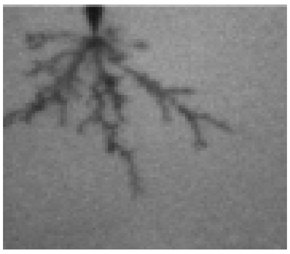

Fig. 1. Streamer propagation in insulating liquid recorded by the multichannel high speed camera.

The initial electric field at the point of a needle electrode plays an important role in the initiation phase of streamers. According to the value of this field, it could be possible to initiate different structures of streamers.

When experimental conditions are changed, streamer features do not vary uniformly. Velocity, current and light measurements show sudden transitions, strongly suggesting that different propagation mechanisms are involved. It was suggested to distinguish various “streamer modes”. Four “streamer modes” evidenced in the same mineral oil with the point positive. A transient current and a light emission is recorded while a streamer propagates. Depending on voltage and streamer mode, the current intensity may vary considerably, typically from 0.1mA (1st mode), up to more than 10A (4th mode) [6-8]. In most cases, current and light signals are made up of discrete pulses, which intensity is usually correlated.

Fractal analysis was increasingly used as an index to quantitatively describe the complexity of a pre-breakdown phenomenon, i.e. electrical treeing in solid insulating materials and creeping discharge patterns over solid insulators immersed in insulating oils [9-11].

In this paper, with the help of the equivalent electrical network modeling streamer patterns obtained for the same conditions (i.e., for the same geometry and voltage) were computed to be applied for the fractal analysis on streamer. The fractal index of streamers, i.e. fractal dimension, was estimated by using the box-counting method. Variations of fractal dimension of streamers with different propagation times,electrode gap distance and streamer conductivity were evaluated.

2. Equivalent electrical network

Assuming each streamer branch as a cylindrical channel of conductivity σ, length l and radius r_0, its resistance *Rest* per unit length will be:

$$R_{est} = l / \sigma.\pi.\ r_0^2 \qquad (1)$$

Two types of channels are considered: the '*free channels*' and '*tied channels*'. The free channels are those channels having one extremity not connected to other channels and the tied channels are those channels that have both their extremities connected to at least one channel (Fig. 2).

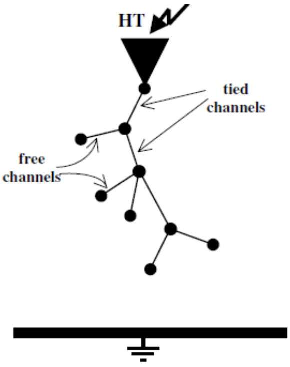

Fig. 2. Diagram representing a branching streamer

To each free channel, we associate a capacitor C_{capa} constituted of the free extremity of the channel and the opposite electrode. This capacitor is calculated using a hyperboloidal approximation and by taking into account the solid angle constituted by the streamer head (i.e., the free extremity of a free channel) and having the electrode plane as a base.

$$C_{capa} = \pi.\varepsilon_0\ \varepsilon_r\ \alpha_c(1+m_1/(1-m_2)) \qquad (2)$$

with $\alpha_c = 1 - (1 / (1+(\Phi/2d)/(1-m_2))^{1/2})$ (3)

and $m_1 = r_0/d \quad m_2 = l/d$ (4)

Where ε_r is the dielectric constant and ε_0 is the permittivity of free space. The structure so generated and the above hypotheses enable us to build an electric circuit that we can solve using the computation electrical network method.

From the topology of this system, we establish the equations of the electrical network that we then solve by a nodal method. The nodal resolution consists in constructing for each streamer jump, the *branch-node incidence matrix A*, the *primitive admittance matrix Y* and the voltage and current *source matrixes E* and *I* [12].We built equivalent electrical circuit with Matlab-Simulink [13], by computing the circuit element considering a point-plane electrode arrangement with a gap of 10 mm, immersed in a dielectric liquid of permittivity ε_r = 2 and submitted to a dc voltage of 30 kV (Fig.3).
The build an algorithm allowing us to generate stochastically the streamer lengths as follows:

$$newLength = oldLength \times \varphi(\tau) \qquad (5)$$

where

$$\varphi(\tau) = 0.25 + 0.5\tau \qquad (6)$$

$\varphi(\tau)$ is a weighting function of the variable τ distributed uniformly in the unit interval; '*newLength*' is the new length and '*oldLength*' is the previous length.
When the propagation conditions are satisfied to generate a new streamer branch, we determine the new direction of the propagation by an angle α depending on the value of a variable $\kappa 1$ also distributed uniformly in a unit interval

if $\kappa 1 \leq 0.5$

$$newDir = oldDir + \arccos(1 + \alpha \log(\kappa 1 \alpha 2 + \alpha 1)) \qquad (7)$$

if $\kappa 1 \geq 0.5$

$$newDir = oldDir + \arccos(1+\alpha \log(2-\kappa 1 \alpha 2-\alpha 1)) \qquad (8)$$

with $\alpha = 0.25 \quad \alpha 1 = \exp(-2/ \alpha)$
and $\alpha 2 = 2(1- \alpha 1\ )$

where '*newDir*' and '*oldDir*' are the newand old streamer directions, respectively.

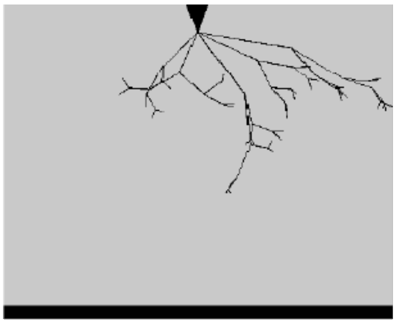

Fig. 3. Streamer obtained for a point-plane arrangement under dc voltage using the computation electrical network method.

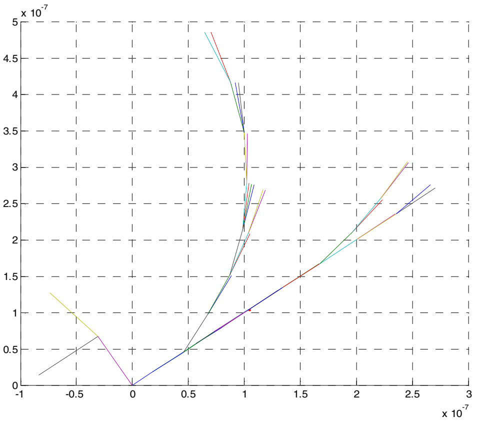

Fig. 4. Example of Simulated filamentary structure obtained for a point-plane arrangement under DC voltage after a time simulation of 30 µs point radius r_0 = 5 μm; applied voltage U_0 = 30 kV

3. Fractal Analysis by Using the Box-Counting Method

The evaluation of fractal nature of streamer patterns is achieved by using fractal dimension D_f Literally there are several methods for the estimation of fractal dimension.

However, only the box-counting method is considered in this paper, since this method is one of the most popular methods for estimating the structure of self-similar patterns and is easy to achieve by MATLAB programming. The idea of the box algorithm is to subdivide the domain into boxes, and count the number of boxes that contain observations of the data.

Firstly, color image (256 x 256) of the streamer pattern was converted to binary image by using an image processing program, as shown in Fig. 5 (a) , and (b).

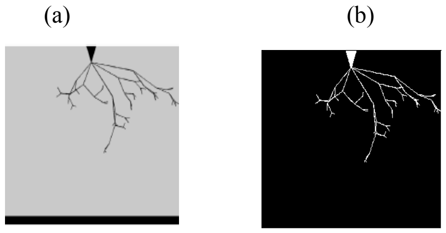
(a) (b)

Fig. 5. Color and binary images of streamer patterns.

Secondly, streamer pattern in the binary image is covered by square boxes of size *r* (*r*= 256, 128, ..., 1).

When a box of size r covers a streamer patterns, the following relationship is shown as:

$$N_r \approx r^{-Df} \qquad (9)$$

Where is N_r the number of covering boxes measured by scale rand D_f is the fractal dimension. Equation (1) can be rewritten as:

$$D_f = -\lim_{r \to \infty} (\log N_r \;/\; \log r) \qquad (10)$$

Therefore the negative slope of log N_r - log *r* curve corresponds to the fractal dimension D_f as shown in Fig. 6.

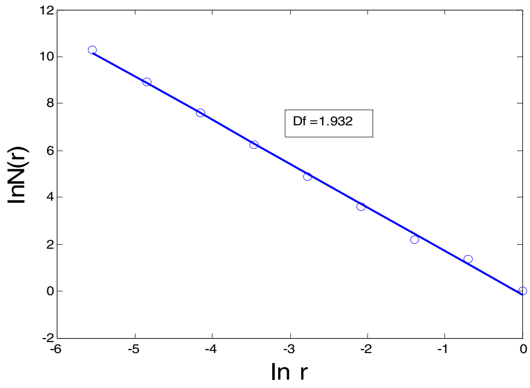

Fig. 6. Plot of log N_r - log *r* to calculate fractal dimension.

Streamer propagation length, i.e. the straight-line distance from the farthest tip point of a streamer to the needle electrode, was computed by using an equivalent electrical network model, whilst streamer area information, i.e. all the areas occupied by the streamer branches in a binary image, was measured by using MATLAB software. Relationships between fractal dimension and 2-D parameters were finally defined.

4. Results and discussions

Fractal dimension, streamer propagation length and streamer area were carried out focusing on 5, 10, 15 and 35 mm gap distance, from streamer inception under dc voltage of 30kV.

Streamer patterns obtained for a point-plane arrangement a time simulation of 30 µs; point radius 5 µm.

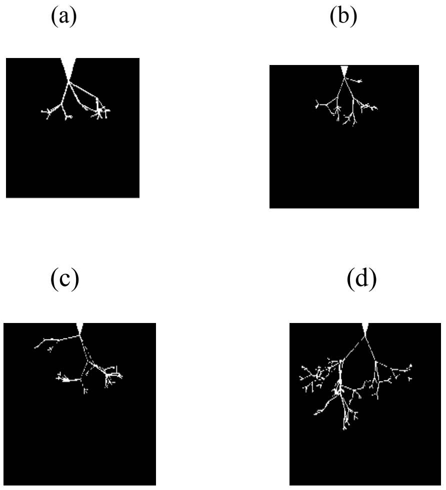
(a) (b) (c) (d)

Fig.7. Streamer patterns obtained for a point-plane electrode arrangement under dc voltage after a time simulation of 1.4 µs; gap distance 5*(a),* 10*(b),* 15*(c) and* 35*(d)* mm; r_0= 3 µm, U_0 = 30 kV.

Table 1. Fractal dimension versus electrode gap distance

Gap distance (mm)	D_f	Error
5	1.89	0.097
10	1.93	0.071
15	1.98	0.030
35	1.99	0.015

It indicates in table 1 that the fractal dimension is increasing with the increase of electrode gap distance. The increment of fractal dimension is due to the propagation of main channel of the streamer pattern and extension of micro-channels with the increase of electrode gap.

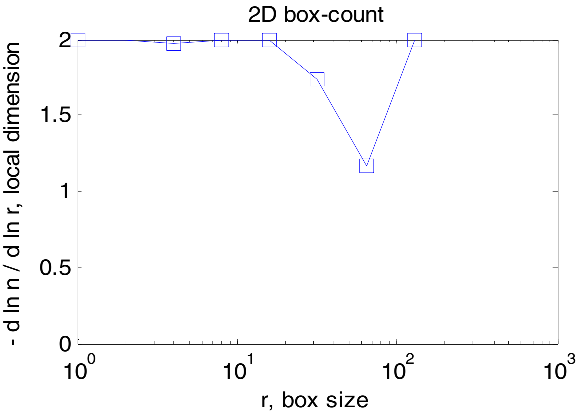

Fig. 7. The result of 2D box count

The local slope (Fig. 7) shows that the image is indeed approximately fractal, with a fractal dimension D_f= 1.9907 +/- 0.015286 for scales r < 100.

Fig. 8. Streamer patterns obtained for two values of the streamer conductivity (a) $\sigma = 5\ \Omega^{-1}.m^{-1}$ (b) $\sigma = 50\ \Omega^{-1}.m^{-1}$

Figure 8 gives examples of streamer patterns obtained for two values of the streamer conductivity, namely $\sigma = 5\ \Omega^{-1}.m^{-1}$ and $\sigma = 50\ \Omega^{-1}.m^{-1}$, and a radius of channels $r_0 = 5$ µm.
We note that the more conducting the streamer, the larger is its final length. Now let analyze the fractal dimension associated to these types of streamer. The estimated fractal dimensions are D_f= 1.94 and 1.98, for streamer conductivity of $5\ \Omega^{-1}.m^{-1}$ and $50\ \Omega^{-1}.m^{-1}$ respectively. It indicates that the fractal dimension is increasing with the increase of streamer conductivity

6. Conclusions

In this paper, the fractal dimension of streamer patterns in dielectric liquids was estimated based on box-counting method. Streamer patterns were obtained from initiation stage to breakdown stage, in a different needle-to-plane gap and under dc voltage using an equivalent electrical network which constitutes an interesting tool to model the streamers propagating. The different characteristics so simulated are quite in a good accordance with those reported in the literature. The obtained results indicate that at a fixed voltage level, the fractal dimension of streamer pattern increases gradually with the increase of time, streamer conductivity and electrode gap distance finally levels off when the streamer stops propagation.

7. References

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