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Effect of the Electrodes' Shape on the Transition between 2nd and 3rd Modes Streamer Discharge

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Keywords
Numerical Simulation, Streamer Discharge, Breakdown, transformer oil.

Abstract
The aim of this investigation is to determine how the electrode shape impacts the change from the second to the third modes of streamer discharge in transformer oil. To achieve this, three systems—rod-plate, needle-plate, and needle-sphere electrode configurations—were employed. The characteristics of the streamer, such as its beginning time, length, propagation velocity, and radius, were examined during the investigation. The results of our simulation clearly show how the characteristics of the streamer and thus, the transition to the third mode, are affected by the form of the electrodes. According to the data, the lowest applied voltage required for the electrodes (rod-plate, needle-plate, and needle-sphere) to transition to the third mode was (265,269,281) kV, respectively. For each of the three designs, the space between the electrodes was fixed at 1 mm, the anode tip's curvature was fixed at 40 µm, and the applied voltage was 300 kV. The investigation was simulated in two dimensions using COMSOL Multiphysics.

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1. Introduction

Engineers and scientists have long investigated the insulating properties of dielectric liquids, particularly transformer oils, to understand the causes underlying electrical failure and reduce the likelihood of such breakdowns [1]. This is because an insulation breakdown in a piece of electrical equipment might have serious consequences. The majority of their efforts have been focused on making electrical streamers. These are low-density conductive structures that develop in oil areas that have suffered excessive electric field stress of at least 1×10^{8} V/m. After forming, a streamer can lengthen as it moves from the place of initiation to a grounding point. A streamer cutting off the oil space between the electrodes might happen as a result of sustained overexcitation. An arc will form as a result, and an electrical breakdown will take place.

The literature on streamers in dielectric liquids has grown significantly as a result of actual research that has been done extensively on the topic, of which the

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references [2] – [9] are examples. Unfortunately, unlike both the gaseous and solid phases, liquids have more complicated molecular structures and behaviors, and even the cleanest liquids include tiny amounts of impurities, which makes it challenging to determine the exact causes of electrical breakdown [8], [9]. Researchers have shown that streamers' unique propagation characteristics—such as amplitude, polarity, waveform, duration, rise time, fall time, etc.—are substantially influenced by the geometry of the electrodes [10]–[13].

For lightning impulse voltage excitations in transformer oil, four positive streamer propagation modes have been observed and are referred to as the first, second, third, and fourth modes. The four modes start at different voltage magnitudes depending on the excitation intensity, with the first mode starting at the lowest voltage magnitude and the fourth mode starting at the highest. The third mode starts at the acceleration voltage V_a, where there is a considerable rise in streamer propagation velocity, whereas the second mode starts at the breakdown voltage V_b, which implies a 50% likelihood of breakdown [7].

As a result, the streamer's form and velocity vary considerably with increased applied voltage, becoming more risky and energetic. The first mode is frequently disregarded in pre-breakdown research because it has a low likelihood of causing breakdown [11]. On the other hand, the propagation velocities for second, third, and fourth mode streamers are, in the range of 1 km/s, 10 km/s, and 100 km/s respectively [3]–[7]. The 3rd mode area, when the streamer switches from the slower 2nd mode to the highly active 4th mode, has a smaller applied voltage range than the 2nd mode zone. Because the incredibly rapid 4th mode streamer may be produced with a small rise in applied voltage, the transitional 3rd mode streamer is risky.

To explain the procedures and circumstances that result in the third mode streamer, the mathematical model is further developed in this study. The model is solved numerically using the finite element application COMSOL Multiphysics [14]. The results confirm that Biller's qualitative model [15] accurately represents the basic physical principles behind the development of different streamer modes in transformer oil.

2. Description of the model

Based on the fluid dynamics model suggested by Morrow and Lowke [16], which consists of the Poisson equation of the electric field, which defines the formation and growth of streamer in the liquid dielectric, and three charge continuity equations (one for positive ions (ρ_p), another for negative ions (ρ_n), and a third for electrons (ρ_e)). The following equations make up the computational formula of the streamer in the liquid medium of transformer oil [17, 18, 19, 20]:

$$\frac{\partial \rho_p}{\partial t} + \nabla \cdot (\rho_p \mu_p \vec{E}) = G_F(|\vec{E}|) + \frac{\rho_p \rho_e R_{pe}}{q} + \frac{\rho_p \rho_n R_{pn}}{q} \quad (1)$$

$$\frac{\partial \rho_n}{\partial t} - \nabla \cdot (\rho_n \mu_n \vec{E}) = \frac{\rho_e}{\tau_a} - \frac{\rho_p \rho_n R_{pn}}{q} \quad (2)$$

$$\frac{\partial \rho_e}{\partial t} - \nabla \cdot (\rho_e \mu_e \vec{E}) = -G_F(|\vec{E}|) - \frac{\rho_p \rho_e R_{pe}}{q} - \frac{\rho_e}{\tau_a} \tag{3}$$

$$\nabla \cdot (\varepsilon \vec{E}) = \rho_e + \rho_p + \rho_n \tag{4}$$

q is the electron charge, ε is the relative permittivity of insulators $(\varepsilon=\varepsilon_r\varepsilon_0)$ (ε_r is the permittivity for transformer oil defined to 2.2) while ε_0 is the vacuum's permittivity, E represents the electric field as determined by Poisson's equation. (4), and G (|E|) is the dielectric fluid's ionization source term, which reacts to the electric field. In a dielectric liquid, R_{pe} and R_{pn} represent the rates at which ions recombine with electrons and with other ions. Meanwhile, μ_p, μ_n, and μ_e represent the mobilities of positive, and negative ions and electrons, respectively. A value of 200 ns, represents the electron attachment time (τ_a). An insulating fluid's molecules share electrons and are in a stable condition when no external voltage is applied. These neutral molecules become charged, shed their outermost electrons, and split into positive ions and free electrons when they are subjected to a high electric field. The Zener ionization model includes the ion source term, which is a term of the electric charge responding to a strong electric field as a charge density ratio based on the dielectric's electron tunneling action [7,21,22,23].

$$G_F(|\vec{E}|) = \frac{q^2 n_0 a |\vec{E}|}{h} \exp\left(-\frac{\pi^2 m^* a \Delta^2}{q h^2 |\vec{E}|}\right) \tag{5}$$

The following parameters are included in the equation: the density of ionizable transformer oil molecules is represented by the number n_0; a, which represents the separation among molecules; h, which represents the Planck constant; Δ which is an explanation of the electric energy needed to ionize the molecules; and m*, which represents effective electron mass. As shown in Table 1, the major parameters needed for the simulation model utilized in this study were gathered from the literature. [4], [21], [24] - 28] Additionally, it does not oppose studies that you may find in experimental plasma research, such as [25, 29].

Table 1. Basic modeling parameters [19, 25].

Symbol	Meaning	Value
n_0	Density number of molecules	1×10^{23} m^{-3}
a	Molecular spacing constant	3×10^{-10} m
m^*	Mass of the effective electrons	9.11×10^{-32}kg
$R_{pn}R_{pe}$	Recombination rate constants of ions-electrons and ions-ions inthe insulating fluid	1.64×10^{-17} m^3 s^{-1}
$\mu_p\mu_n$	Mobility of positive and negative ions	1×10^{-9} m^2 V^{-1} s^{-1}
μ_e	Mobility of electrons	1×10^{-4} m^2 V^{-1} s^{-1}
Δ	The molecule's ionization energy	8.5 eV
τ_a	Time of electron attachment	200 ns

2.1. Conditions at the boundary and the numerical

To generate the impulse voltage required by IEC 600060-1 [19], [29], the cathode electrode's potential is grounded. and the potential of the anode electrode is set to Vi, as expressed in equation (6), which is described by two exponential functions with different time constants, τ_1, and τ_2.

$$V_i = KV_0 \left(e^{-\frac{t}{\tau_1}} - e^{-\frac{t}{\tau_2}} \right) \tag{6}$$

The compensation factor is denoted by K. The "Transport of Diluted Species" module of the commercial software program COMSOL Multiphysics is utilized to solve all of the continuity equations (1) through (3) while the "Electrostatics" subsystem is solved by using Poisson's equation (4) [25]. In general, the highest value which is not necessarily one is achieved when combining two exponential functions, τ_1 the rising time and τ_2 the falling time.

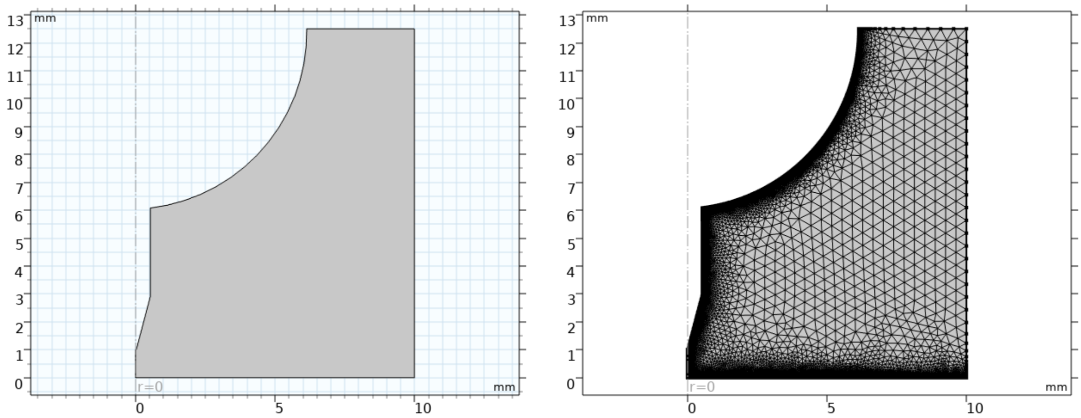
2.2. Domain for Simulation

In this investigation, the curvature of the tips' anode will be (40 μm), for each of the three systems that we will discuss below, the voltage will be fixed at (300 kV), and the distance between the electrodes will be constant (1 mm).

2.2.1 Needle-plate configuration

Figure 1 illustrates the needle-plate electrode for transformer oil discharge, according to the IEC 60897 Standard [20]. The needle electrode has a top radius curvature of (40 μm). One millimeter between the oil gaps in the simulation. The total estimated domain measures approximately r × z = 10×12.5 mm. The gradient of the electric field and the density of charged particles are very high because discharge mostly takes place in the vicinity of the symmetric axis and neighboring zone. For an accurate and effective numerical treatment of discharge events, a non-uniform spatial meshing is therefore required. The figure on the right represents the distribution of the mesh over the entire domain. This section's interlocking geometry is extremely exact to provide the accuracy and resolution of mathematical calculation. The other portions' mesh geometry, on the other hand, is insufficient to cut down on computation.

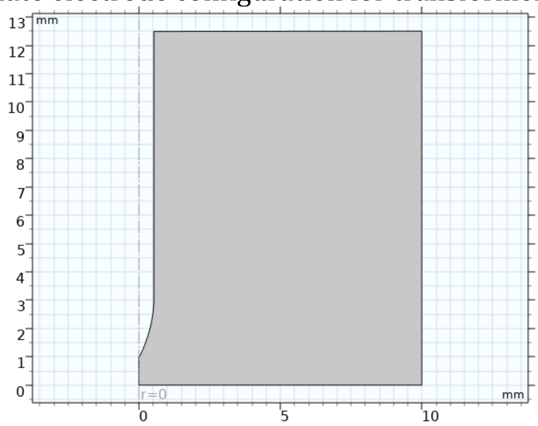
Figure 1. The needle-plate electrode configuration for transformer oil discharge, which is based on the IEC 60897 Standard [20], and the design of meshes for needle-plate electrodes.



2.2.2 Rod-plate electrode configuration

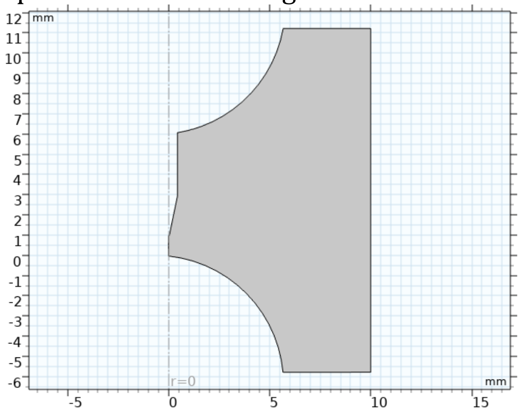
We used another configuration to study the effect of the electrodes' shape on the generation and development of the streamer and transitioning between the second and third modes, which is the rod-plate configuration, where we kept also, the distance between the electrodes fixed and about (1 mm) and the curvature of the head of the rod (the tip of the anode electrode) is (40μm), figure 2 illustrates, below.

Figure 2. Rod-plate electrode configuration for transformer oil discharge.



The third configuration, which is used to study the effect of the electrode shape on the generation and evolution of the streamer and its transition to the 3rd mode, is the needle-sphere, as illustrated in Figure 3.

Figure 3. The needle-sphere electrode configuration for transformer oil discharge.



3. Results and discussion

3.1. Needle-plate electrode

The space-time electric field contribution is used to illustrate the streamer profiles and dynamics. The simulation results in Figure 4 clearly illustrate the initiation, growth, and breakdown of the streamer, which is created by the needle-plate electrodes in the first configuration at a 300 kV applied voltage and a 1 mm gap spacing. We noticed from the data that the configuration's size and shape affect the streamer's initiation time. During our study, we found that the lowest applied voltage to obtain a change to the third mode was (269 kV) at (100ns). Through this study, also, we have noticed that the transition to the third mode starts between the two time periods (80-90 ns), figure 4 below is for the streamer during the period of (90 ns). Figure 5 shows the evolution of a streamer discharge for the needle-plate electrode at 300 kV in transformer oil.

Figure 4. The streamer discharge at the 90 ns stage, which is the beginning of the transition to the third mode. The applied voltage is fixed at 300 kV.

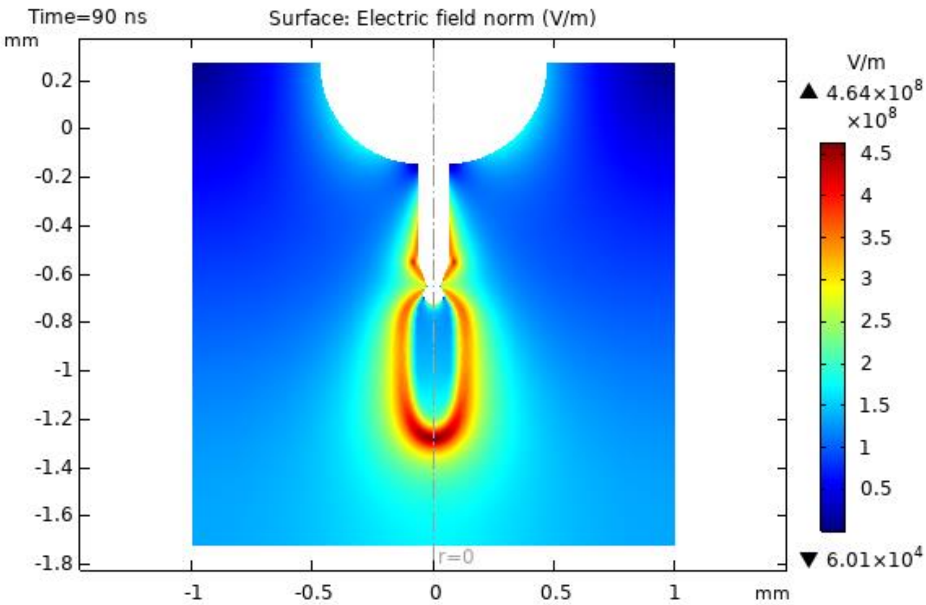
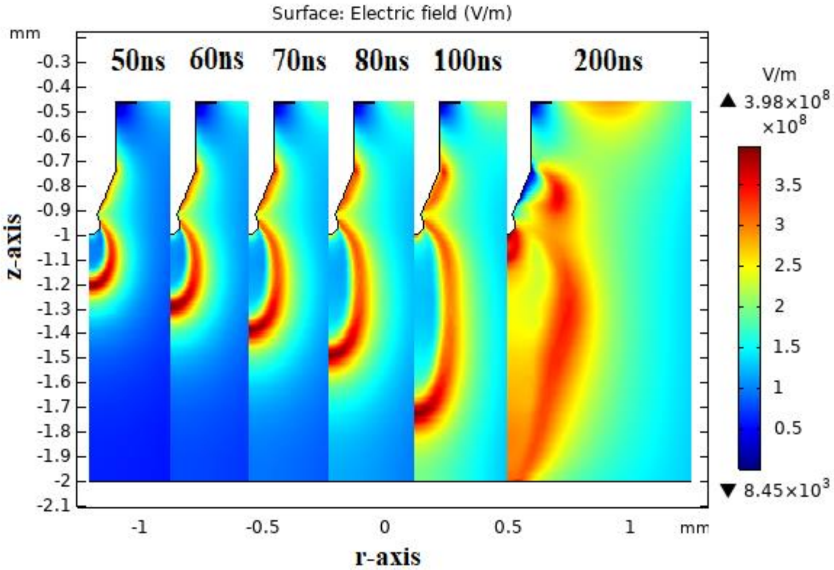


Figure 5. A streamer discharge's growth in transformer oil at 300 kV for the needle-plate electrode.



In Table 1 below, the values obtained during the simulation process, the values show the evolution of the streamer in the needle-plate system and the change from the 2nd to the 3rd mode according to the velocity of the streamer discharge through the transformer oil. Figure 6, represents the change in the shape of the streamer according to the periods shown in the one-dimensional diagram.

Figure 6. Evaluation of the streamer according to the periods shown, in a one-dimension diagram for the needle-plate electrode.

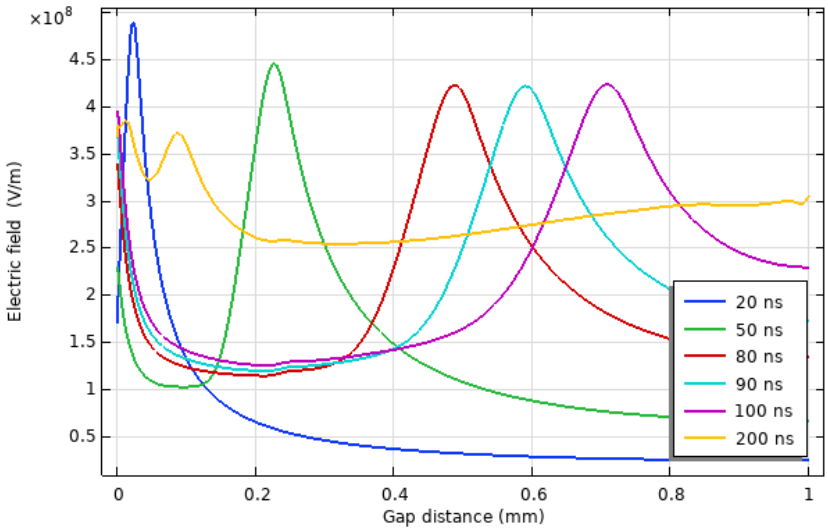


Table 2. The evolution of the streamer in the needle-plate system at a different time scale and the applied voltage was fixed at 300 kV.

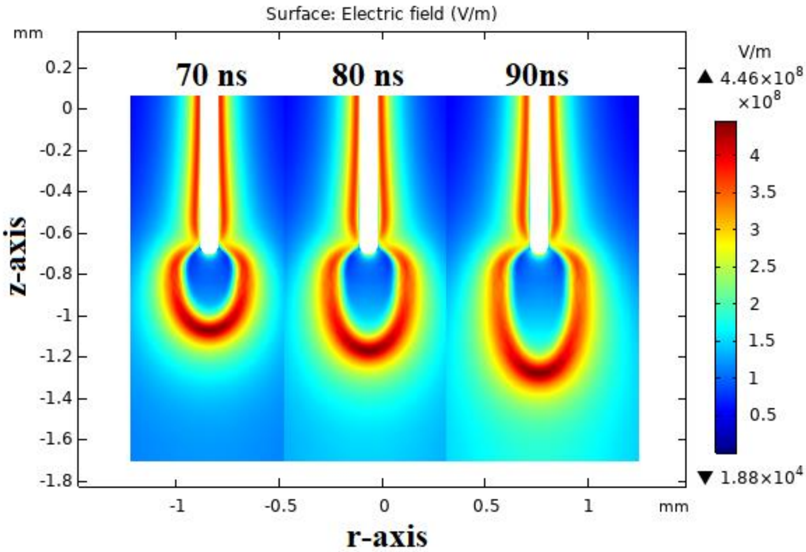
Time (ns)	Streamer length (mm)	Propagation velocity (km/s)	Modes	Streamer radius (mm)
50	0.027	5.5	2nd	0.25
60	0. 38	6.4	2nd	0.31
70	0.51	7.3	2nd	0.37
80	0.68	8.5	2nd	0.41
90	0.91	10.16	3rd	0.46
100	1	10	3rd	0.49
150	1	6.6	2nd	0.64
200	1	5	2nd	0.84

From the above table, we notice that the velocity of the streamer discharge increases gradually according to the increase of the applied impulse voltage until the transition occurs to the 3rd mode. The streamer remains in the third mode in an unstable state until it reaches the plate electrode, then the velocity decreases and returns to (5 km/s), due to the arrival of the streamer to the plate electrode and starting of electrical breakdown, which leads to loss of a large amount of the applied voltage, therefore, the decrease in velocity continues even if the time of the applied impulse voltage increases because of the continued occurrence of electrical breakdown.

3.2. Rod-plate electrode

In the rod-plate electrode, the streamer begins to form as soon as the time pulses are applied after connecting the anode with an applied voltage, as in the previous system with 300 kV. The rod was set as an anode with a top radius curvature of (40 µm), While the cathode electrode (the plate) was joined to the ground. The results indicate that the streamer discharge's radius and length gradually increase. The velocity of the streamer begins to increase and transits to the third mode, at an unstable state, to return to the more stable state of the second mode, after the streamer touches the plate electrode. Figure 6 shows the stages of streamer development in a rod-plate electrode at three steps (70, 80, and 90 ns), the stage in which a transition to 3rd mode occurs.

Figure 7. The evolution of a streamer discharge in transformer oil at 300 kV of applied voltage (Transition stage to the third mode) for the rod-plate electrode.



During this study, we noticed that the lowest voltage to achieve a transition to the third from the second mode was (265 kV) at the time (100 ns) for a rod-plate electrode. Table 2 the evolution of the streamer in the rod-plate system at a different time scale and the applied voltage was fixed at 300 kV. The electric field can be represented for some time phases in one dimension, the stages of the streamer are as shown in the figure below for the rod-plate system.

Figure 8. The evolution of the streamer stages for the second to the third mode, in one dimension At specific periods for the rod-plate system.

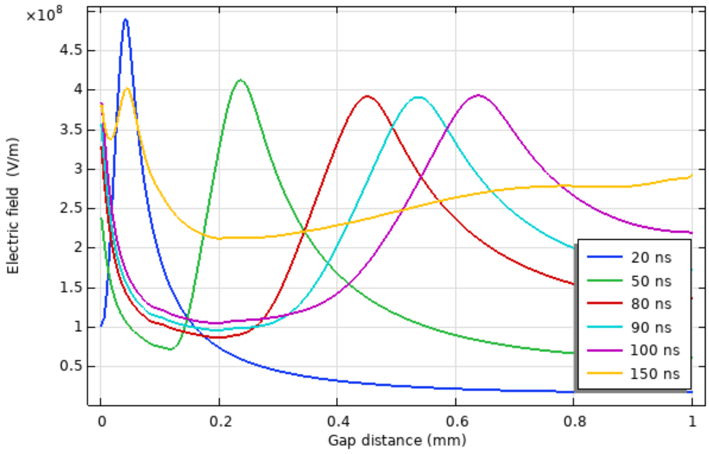


Table 3. the evolution of the streamer in the rod-plate system at a different time scale and the applied voltage was fixed at 300 kV.

Time (ns)	Streamer length (mm)	Propagation velocity (km/s)	Modes	Streamer radius (mm)
50	0.34	6.9	2nd	0.33
60	0. 46	7.7	2nd	0.40
70	0.59	8.4	2nd	0.46
80	0.76	9.5	2nd	0.52
90	1	11.11	3rd	0.57
100	1	10	3rd	0.60
150	1	6.6	2nd	0.72
200	1	5	2nd	0.83

From the above table for the rod-plate electrode, we can see that the values of the streamer's propagation velocity have somewhat risen from those in the needle-plate system. The streamer's radius was also slightly enlarged compared to that before. This is due, of course, to the different electrode shapes and this is what we are going to study.

3.3. Needle-sphere electrode

The third system that was studied is the needle-sphere electrode, where we noticed that the lowest voltage to achieve the change between the second and third modes of the streamer was (281 kV) at the time (100 ns). It was shown through simulation and results that this system needs a higher applied voltage than the previous two systems, and this is naturally because the spherical cathode electrode is confined to a lesser area, compared to the needle-plate or rod-plate electrode**.** Figure 9 represents the moment of transition of the streamer from 2nd to 3rd mode during the time of 100 ns, while Figure 10 represents the time evolution of the streamer and its transition to the third from the second mode at a time of (100 ns)at (300 kV) for the Needle-sphere electrode.

Figure 9. The streamer discharge at the 100 ns stage, which is the beginning of the transition to the third from the second mode in the needle-sphere electrode. The applied voltage is fixed at 300 kV.

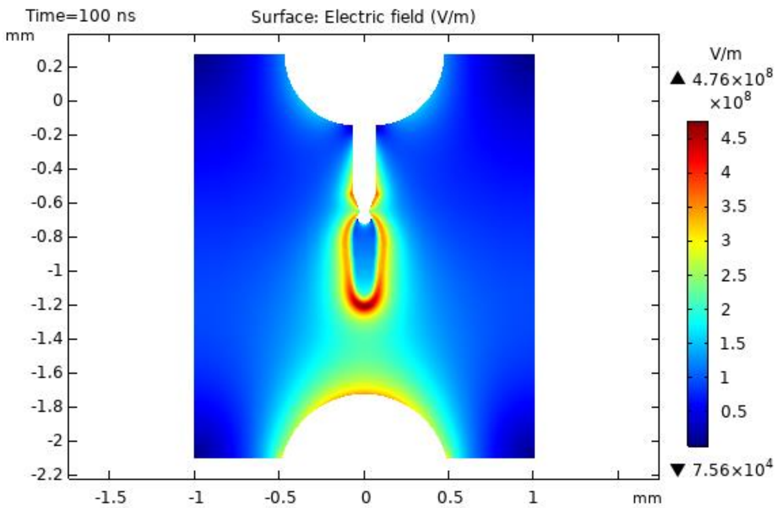
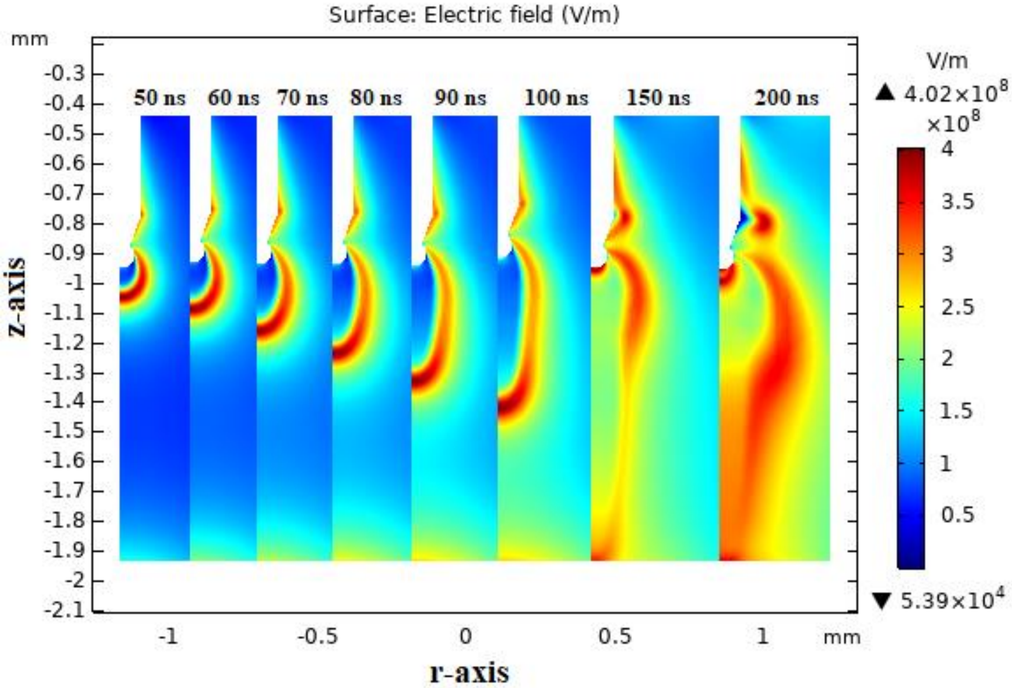


Figure 10. The evolution of a streamer discharge in transformer oil at 300 kV of applied voltage for the needle-sphere electrode.



The changes that occurred in some stages of the streamer transition to the third mode can be represented by a one-dimensional diagram as shown in Figure 11. From Figure 11 below, we noticed that the electric field grows and takes a curve, starting with a low value, then increasing gradually, then returning to descend and fading out according to the applied pulse voltage. This process continues until 100 ns, then after that, the streamer reaches the cathode electrode (sphere), then the breakdown process begins, which results in a large loss. In an applied voltage we can see from the diagram that the curves beyond 100 nanoseconds will not rise much due to the energy loss due to the occurrence of the breakdown process. Table 3 includes the values that we obtained during the application of the Needle-Sphere system, in which the process of the unstable transition to the third mode is observed, as shown in the table below. Figure 12 represents the change of radius of the three systems used during the study according to the periods used.

Figure 11. Some stages of the streamer transition to the third from the second mode can be represented by a one-dimensional diagram

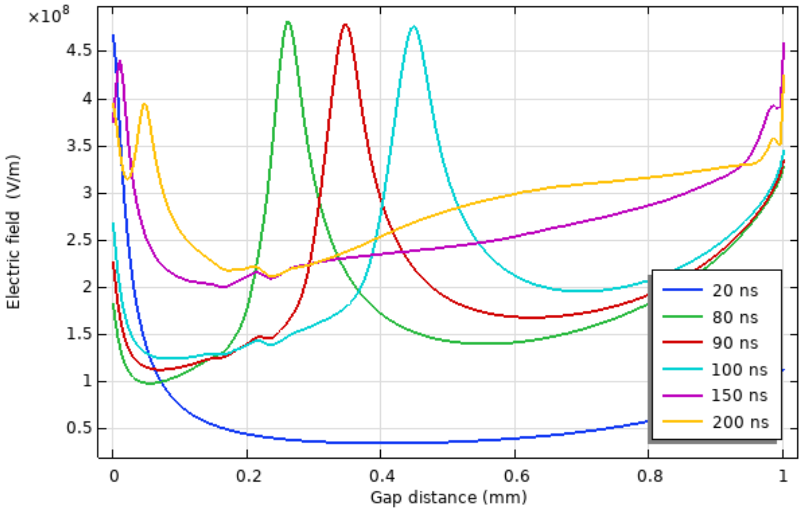
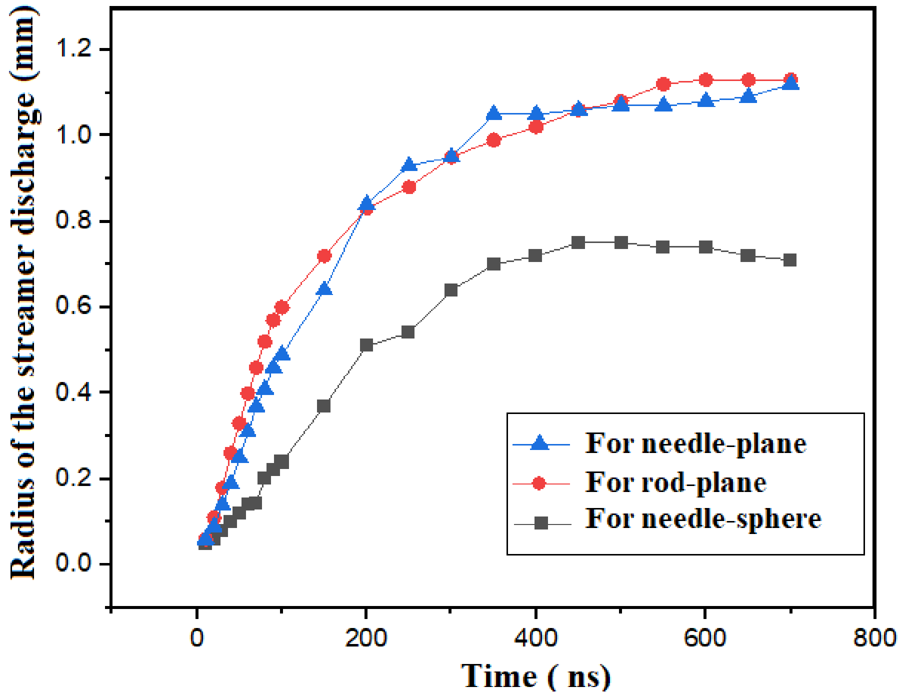


Table 4. the evolution of the streamer in the Needle-sphere system at a different time scale and the applied voltage was fixed at 300 kV.

Time (ns)	Streamer length (mm)	Propagation velocity (km/s)	Modes	Streamer radius (mm)
50	0.18	3.62	2nd	0.12
60	0. 25	4.25	2nd	0.14
70	0.33	4.8	2nd	0.145
80	0.43	5.46	2nd	0.2
90	0.59	6.58	2nd	0.22
100	1	10	3rd	0.24
150	1	6.6	2nd	0.37
200	1	5	2nd	0.51

Figure 12. The evolution of the radius of the streamer discharge, in one dimension at specific periods for the three configurations.



4.Conclusion

The simulation that it carried out on three systems, namely, the needle-plate, the rod-plate, and the needle-sphere electrodes, where the purpose of this work is to demonstrate how the design of the electrodes affects the creation and expansion of the streamers discharge. Through our study, we concluded that the shape and dimensions of the electrode clearly affect the length, velocity, and radius of the streamers discharge, and thus affect the transition to 3rd mode after crossing the 2nd mode, and this was evident from the tables of results and shapes that we obtained during our simulation. Through the results, it was found that the lowest applied voltage to permit the transition to the third from the second mode of needle-plate, rod-plate, and needle-sphere electrodes, were (269,265,281) kV, respectively. Despite the (1 mm) stability of the gap between the electrodes and the (40 µm) same curve of the anode tip throughout all configurations.

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