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Numerical Analysis for Streamer Discharge at the Discharge Transition from the Second to the Third Mode in Transformers Oil

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Abstract

This study is a numerical analysis of the transition process from the second to the third mode in transformer oil. In this study, it was determined how to change from the second to the third mode, which is thought to be a precursor to the process of electrical breakdown, which results in a significant loss of electrical energy and harm to electrical devices and equipment. The initiation time, length, rate of propagation velocity, and radius of the streamer discharge were determined. The transition from the second to the third mode during the electrical discharge process may lead to the occurrence of an electrical breakdown, which is one of the greatest challenges facing scientists and engineers who deal with the electrical power of transmission and generation devices. The model was designed by AutoCAD software, which included two electrodes: a needle, with a tip radius of (4μm), and a plate, with a gap of (1 mm) between them. The gap between the two electrodes was filled with transformer oil. The equations, which are Poisson's equation and the continuity equations for positive and negative ions and electrons, which are generated by applying an applied voltage (from 27 kV to within 278 kV), had been solved by a simulation process. All the schematics and drawings were extracted by the Comsol Multiphysics program.

Keywords: Keywords: Transformer oil, Comsol Multiphysics, streamer discharge, Electrical breakdown.

التحليل العددي لتفريغ التدفق عند انتقال التفريغ من النمط الثاني إلى النمط الثالث في زيت المحولات

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الخلاصة

هذه الدراسة هي تحليل عددي للتدفق الثاني وكيفية توليده ثم معرفة الية انتقاله الى النمط الثالث من تدفق التفريغ في زيت المحولات . حيث تم خلال هذه البحث معرفة طول وسرعة الانتشار ونصف القطر وتحديد نمط السرعة وكيفية الانتقال الى النمط الثالث الذي يعتبر ممهدا لعملية الانهيار الكهربائي والذي يؤدي الى ضياع كبير في الطاقة الكهربائية وتلف الاجهزة والمعدات الكهربائية ، حيث يعتبر الانتقال من نمط الى اخر خلال عملية التفريغ الكهربائي وبالتالي الى حدوث الانهيار الكهربائي تحديا كبيرا يواجه العلماء والمهندسين العاملين في مجال نقل الطاقة الكهربائية واجهزة التوليد.تم تصميم النموذج بواسطة برنامج Auto CAD والذي يتضمن

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قطبين هما الابرة وبقمة نصف قطر تحدبها 4 مايكرومتر ، والقطب الاخر هو صفيحة مستوية. ويفصل بينهما ثغرة مقدارها 1 ملم ومابين القطبين زيت المحولات . تم حل المعادلات وهي معالات بوازون ومعادلات الاستمرارية للايونات الموجبة والسالبة والالكترونات المتولدة خلال تسليط جهد متغير من 27 كيلوفولت الى حدود 278 كيلوفولت واستخراج المخططات والرسوم بواسطة برنامج Comsol multiphysics .

1. Introduction

Insulating fluids are used to impede the occurrence of discharge or electrical breakdown processes in transformers and electrical equipment. In addition, dielectric liquids are utilized as heat-reducing materials. For many decades, scientists and engineers have investigated the cause of an electrical breakdown and ways to postpone or even avoid its occurrence. Their efforts have largely been directed toward creating electrical streamers and studying how they are formed. Electric excitation generates streamers (plasma channels) in dielectric liquids [1, 2]. Streamers that develop within oil areas or gas have suffered high electric field stress equal to 1×10^8 (V/m) or greater. Studying streamer discharges and breakdown characteristics of dielectric liquids can be difficult due to the high electric field levels involved. After forming the streamer, based on continuous flow, it tends to extend and grow from starting point toward the ground point. An increase in the applied voltage may lead to the formation of an arc, which leads to an electrical breakdown. Researchers have experimentally discovered that the voltage excitation to the liquid has a significant impact on the propagation characteristics of streamers (For example, amplitude, polarity, wave types, length, rising time, fall time, etc.) [3]. Experimental data show that, in general, in transformer oil, positive streamers start at lower voltages and spread more quickly and widely than negative streamers. Four positive streamer propagation modes, known as the first, second, third, and fourth modes, have been identified for transformer oil excitations due to lightning impulse voltage. The magnitude of the excitation affects how quickly the four modes begin to exist. The first mode starts at the minimum voltage level, whereas the fourth mode begins at the highest. The second mode begins at breakdown voltage V_b, which indicates a 50% possibility of a breakdown [4], but the third mode often occurs at acceleration voltage V_a, as the streamer velocity rapidly increases. For streamers in the first, second, third, and fourth modes, the equivalent propagation velocities are 100 m/s, 1 km/s to 10 km/s, and 100 km/s, respectively [5]. As a result, the streamer's form and velocity change dramatically with increased applied voltage, becoming more dangerous and energetic. The first mode is frequently ignored in pre-breakdown research because it has a low likelihood of results. The researchers' ability to comprehend and formulate hypotheses about the fundamental mechanisms causing the formation of streamers and the various modes has improved as a result of the growth in empirical findings. Transformer oil, in general, is a complex composition of numerous aromatic, naphthenic, and paraffinic molecules; for example, the Nytro 10XN commercial transformer oil has a naphthenic base and a 7% aromatic composition [6]. The model is solved numerically with the finite element application COMSOL Multiphysics. Based on the results, it can be determined that Biller's qualitative model adequately explains the fundamental physics that gives way to many streamer modes in transformer oil [7].

Some studies dealt with the issue of numerical analysis of the streamer discharge and the mechanism of the transition from the 2nd to the 3rd mode. In addition to that, there are several other studies close to the study that we conducted.

Hwang et al. (2009) presented an electro-thermal hydrodynamic model that explained the mechanism and the development of different streamer modes in transformer oil. The main point of discussion was the distinction between the quick third mode and the slow second mode streamers discharge. The model showed, via the numerical techniques, that streamer modes develop in transformer oil as a result of the electric field-dependent molecular ionization of several types of hydrocarbon molecules (i.e., aromatic, naphthenic, and paraffinic) at rising electric field levels (or applied voltages). The simulation was run using a needle-sphere setup with Comsol multiphysics software to obtain all data. According to the results of the study, the two streamer modes started to function at different applied voltages because of the varying ionization energies of the molecular species. For instance, aromatic molecules, which have lower ionization energies, were ionized at lower applied voltages compared to naphthenic/paraffinic compounds, which usually have greater ionization energies and need a higher applied voltage to ionize [3].

Jadidian and Zahn (2011 investigated charge transport processes in series, two-region, and oil-pressboard composite dielectric systems with a step current source using migration-ohmic unipolar analysis. The governing partial differential equations were converted into a set of ordinary differential equations using the characteristic method, allowing analytical solutions for the electric field and voltage drop in the oil and press-board regions as well as the volume and interfacial surface charge densities. Steady-state and transient injection solutions with space charge constraints were given using this method. Certain COMSOL Multiphysics numerical results were constructed with some analytical solutions to boost confidence in the precision and correctness of the numerical solutions. They found that the numerical outcomes of their analysis closely matched the analytical answers with errors that were less than 0.1% [8].

Madshaven et al. (2017) used a needle-plane electrode to study the transition to fast mode streamers in dielectric liquids. They demonstrated how two basic principles might be used to explain several streamer propagation characteristics. Additionally, they concluded that when the electric field intensity at the head grew during propagation, the streamers for highly conducting channels changed from slow to rapid. On the other hand, a change from rapid to slow mode was seen when the electric field weakened, for weaker conducting channels. For streamers in tubes, the acceleration voltage should be near the breakdown voltage. Energy balances, which examine both the available and necessary energies, maybe one part of a better model, among others [9].

Liu et al. (2021) tested the second mode positive streamer in cyclohexane by considering optimized electron saturation velocity (ESVs). They found that the main cause for the stable propagation velocity of the second mode streamer charge-drift model can be changed by choosing various electron saturation velocities (ESVs) into account is determined to be the restriction of streamer propagation velocity by employing ESVs. In a simulation, they found that decreasing the ESV from 30 km/s to 2.5 km/s results in a considerable reduction in the positive streamer propagation velocity in cyclohexane from 4.15 km/s to 0.50 km/s. When the ESV in cyclohexane was considered to be 7.5 km s^{-1} in the simulation, the streamer propagation velocity rose from 1.59 km s^{-1} at 80 kV (below breakdown voltage) to 1.91 km s^{-1} at 100 kV (near acceleration voltage), nearly matching the experimental data [10].

2. MODELING AND SIMULATION

2.1 Governing principles

The equations in this model that govern the formation of streamers were derived using Gauss' Law-coupled drift-dominated charge continuity, Equations (2), (3), and (4) for positive ions (ρ_p), negative ions (ρ_n), and electron charge densities (ρ_e), respectively, which serve as the basis of the governing equations for streamers creation in this model. The three transmission continuity model, which is essential for the investigation of streamers, contains charge generation and capture mechanisms [11]. Equation (1), represents Poisson equation.

$$\nabla\cdot(\varepsilon\vec{E})=\rho_e+\rho_p+\rho_n \tag{1}$$

$$\frac{\partial\rho_p}{\partial t}+\nabla\cdot(\rho_p\mu_p\vec{E})=G_F(|\vec{E}|)+\frac{\rho_p\rho_e R_{pe}}{q}+\frac{\rho_p\rho_n R_{pn}}{q} \tag{2}$$

$$\frac{\partial\rho_n}{\partial t}-\nabla\cdot(\rho_n\mu_n\vec{E})=\frac{\rho_e}{\tau_a}-\frac{\rho_p\rho_n R_{pn}}{q} \tag{3}$$

$$\frac{\partial\rho_e}{\partial t}-\nabla\cdot(\rho_e\mu_e\vec{E})=-G_F(|\vec{E}|)-\frac{\rho_p\rho_e R_{pe}}{q}-\frac{\rho_e}{\tau_a} \tag{4}$$

Where: Ɛ is the permittivity of insulators (permittivity for transformer oil specified to 2.2), E is the electric field which is calculated from Poisson's equation (1), q denotes electron charge, and the term G (|E|), which relates to the electric field, is the ionization source term in a dielectric liquid. In dielectric fluid, R_{pe} and R_{pn} express the recombination rates of ions to electrons and ions to ions, respectively, μ_p and μ_e, are the mobilities of positive ions and electrons, respectively and μ_n is a negative ion. τ_a is the time of the electron attachment, which has a magnitude of 200 *ns* [4]. The terms $G_p(|\vec{E}|)$, $G_n(|\vec{E}|)$, and $G_e(|\vec{E}|)$ are the model generalized sources, which are used to describe the formation terms of positively charged ions, negatively charged ions, and electron charge, respectively.

By using the Zener model, a method for determining the charge rate production under the impact of an external electric field is created in this work, as in the following equation [12]**:**

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

The equation has the following components: n_0 is the density of molecules in the ionizable transformer oil; $\boldsymbol{a}$ is the spacing among molecules; h is the Planck constant; Δ is the electric energy required to emit the molecules; m*is the effective electron mass; $|\vec{\boldsymbol{E}}|$ is the electric field; and $\boldsymbol{q}$ is the electric charge t. The main physical parameters needed for this study's simulation model were gathered from the literature [13] [14] [15] [16] and are listed in Table

Table 1: some of the field ionization parameter values of streamer models.

Parameter	Symbol	Value
The density of molecules in ionizable transformer oil	n_0	1×10^{23} m^{-3} [6], [7], [17]
The amount of electric energy required to emit the molecules	Δ	$8.5-50\sqrt{1.9528\times10^{-12}\,\lvert\vec{E}\rvert}$ eV [18], [19]
Separation of Molecules	a	3.0×10^{-10} m [20]
Rate of ion-ion recombination	R_{pn}	1.64×10^{-17} m^{3}s^{-1}
Rate of ion-electron recombination	R_{pe}	1.64×10^{-17} m^{3}s^{-1}
Positive ion mobility	μ_p	1×10^{-9} m^{2}V^{-1}s^{-1}
Negative ion mobility	μ_n	1×10^{-9} m^{2}V^{-1}s^{-1}
Electron mobility	μ_e	1×10^{-4} m^{2}V^{-1}s^{-1}
Effective electron mass	m^*	$0.1\times m_e = 9.11\times10^{-32}$ kg [21]

2.2. Domain of computation

In this study, CAD tools were used for designing configurations included in the conceptual framework for COMSOL geometries. The Needle-plane electrode with a tip radius of 40 µm was designed according to IEC 60897 Standard [22]. A 1 mm gap between the plate and the needle tip was fixed. Because the streamer is mostly focused in the area around the axisymmetric, there are numerous locations throughout the discharge where the electric field gradient is exceptionally large. Therefore, for the numerical findings to be accurate and reliable, various meshing densities must be determined. As shown in Figure 1, the region utilized to generate the electric field is specified by $r \times z = 2 \times 2 mm^2$.

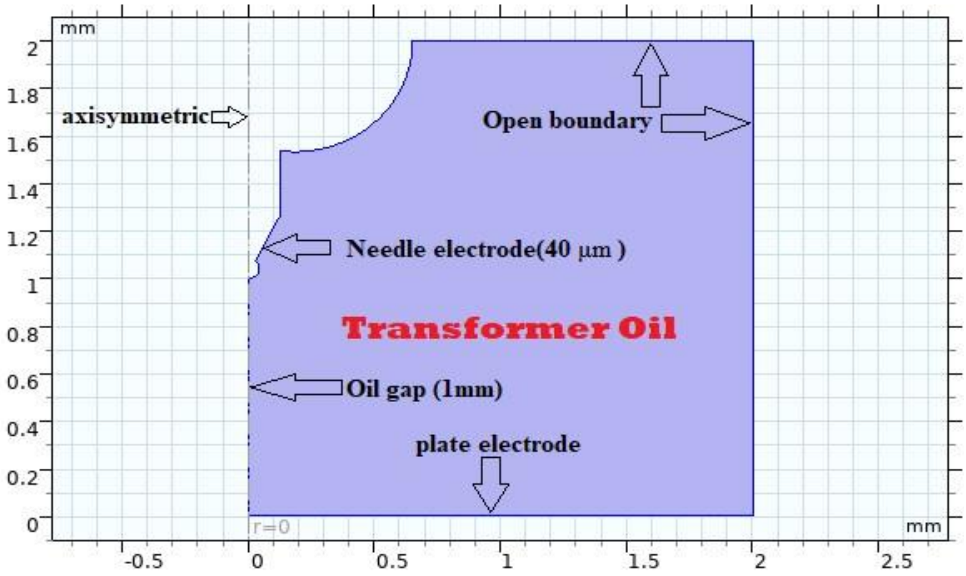


Figure 1: Region of COMSOL's simulation model analysis (2D axial symmetric graph)

2.3. Numerical technique and boundary conditions

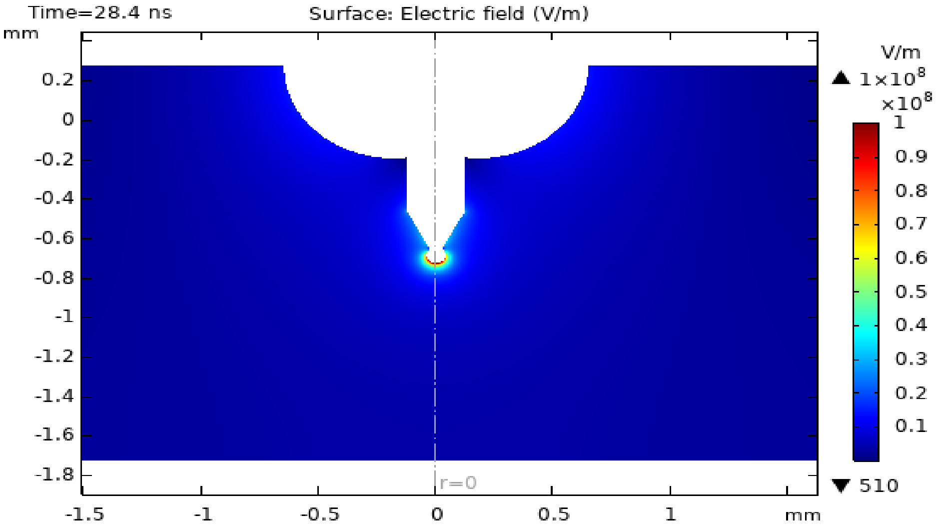
As shown in Equation (6), the impulse voltage is created by connecting the needle electrode to an electric potential of V_i and the plate electrode to the ground. The impulse voltage is made up of two exponentials with various time constants, τ_1 is the rising time and τ_2 the falling time, under IEC 600060-1. V_i was calculated according to the following equation [14], [22]:

$$V_i = KV_0\left(e^{-\frac{t}{\tau 1}} - e^{-\frac{t}{\tau 2}}\right) \tag{6}$$

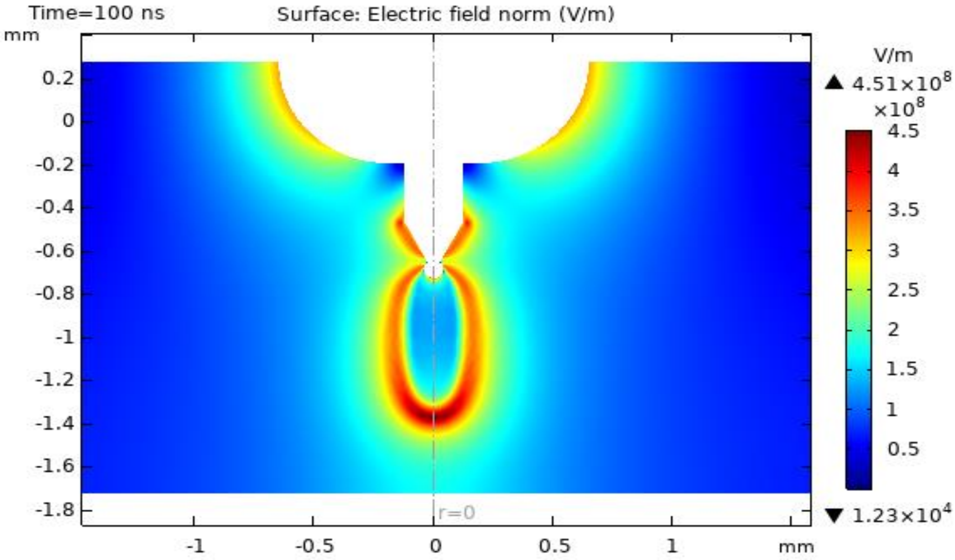
K denotes the compensation factor and V_0 is the applied voltage. The continuity Equations (2), (3), and (4), were calculated by the "Transport of Diluted Species" module of the commercial computer program COMSOL Multiphysics, while the "Electrostatics" subsystem was utilized to calculate Poisson's equation (1). In general, the highest value that is not always equal to one is formed when subtracting two exponential functions [11].

3.RESULTES AND DISCUSSION

This simulation was designed to demonstrate the initiation time, rate of propagation velocity, length, and radius of the streamer discharge at the second and third modes. Two electrodes formed the discharge, the ground cathode (plate) and the anode, a needle's tip with (40 µm) radius of curvature, the gap between the plate and the needle tip, fixed at (1 mm), was filled with transformer oil. It was found that the streamer initiated and spread throughout the solution zone between the two electrodes whenever the electric field was above a threshold value of 7.4 kV/mm [22]. The electric field must be larger than the necessary level (200 kV/mm) at the streamer's head as the second requirement [23], [24]. According to the electronic theory, the density of the liquid decreases as it is heated, giving electrons greater energy before they collide with another molecule. At the front of the streamer, a density of low-energy electrons starts to spread spherically under the influence of the resulting cloud of negative charge [25], [26]. A streamer grows and seems thick once it has crossed a gap. The rate of electron implication increases as the density of the oil decreases [27], [28], [7]. If the electrical field is high enough, electrons at the electrode may be released from the lattice and transported into the bulk. The required field strength varies with the electrode material but is typically in the range of 10^7–10^8 V/m [14]. According to the numerical analysis data, field ionization is the main factor for the initiation and propagation of the second and third mode positive streamers. Figure 2 (a) and (b) illustrate the initiation time and growth at the minimum applied voltage between the two electrodes for the second and third mode streamer discharge (28.6 kV for the second mode and 278kv for the third mode).



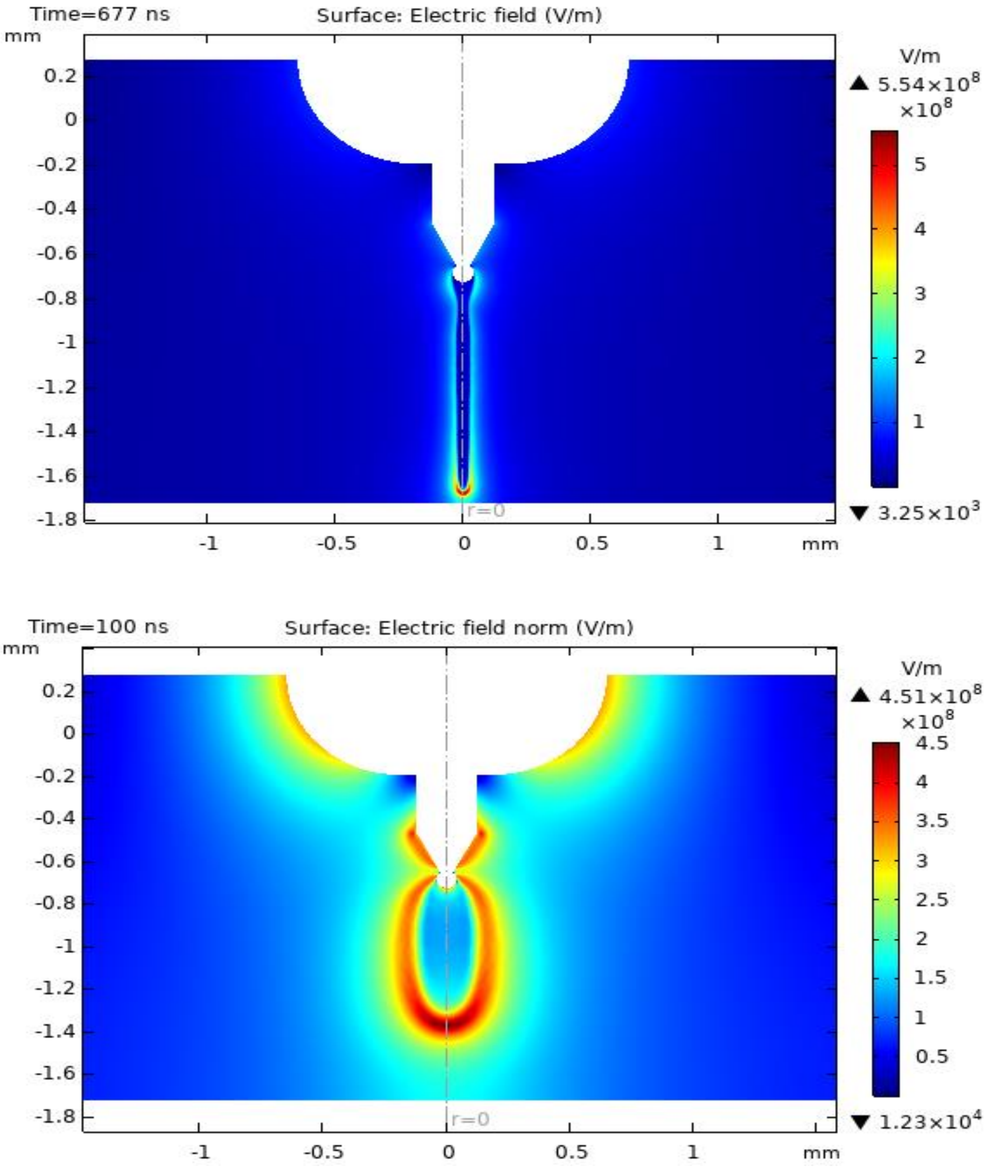
(a)



(b)

Figure 2: The initiation time of the streamer discharge for (a) second mode and (b) third mode streamer discharge.

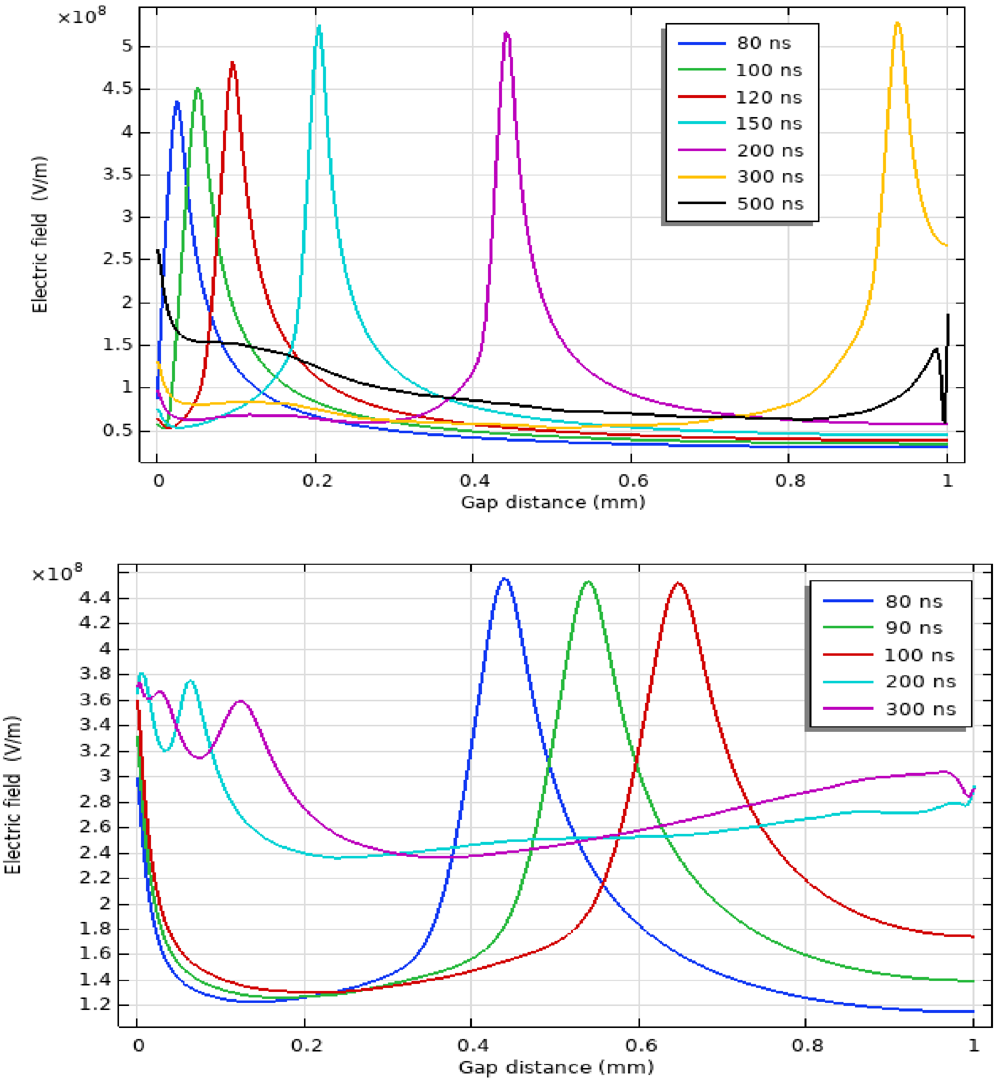
The streamer was formed at the needle's tip because the anode had the highest electric field. Figure 2 illustrates the overstressed oil between the electrodes on the plate and the needle tip, which exhibits significant time variation in the electric field distribution. It was also noticed that the minimum applied voltage to create the streamer was (28.6 kV), and the initiation time for the second mode was (28.4 ns) at this applied voltage. For the second mode, the applied voltage must increase to (100 kV) for the streamer to grow and cross the gap at (296 ns) to reach the plate. However, the voltage had to be increased to (278 kV) to reach and create the third mode. The initiation time of the third mode streamer discharge was (100 ns), where the minimum applied voltage to transit to the third mode was (278 kV) and the streamer needed (100 ns) to cross the gap and reach the plate, as shown in Figure 3. Figure 4 shows the electric field distribution at different times for second and third-mode streamer discharge at applied voltage 100 and 278 kV. It was also observed that with the rising input voltage, the electric field that formed the streamer gradually increased until the streamer reached its maximum value before starting to decline, either because there was not enough voltage to allow it to continue expanding or because the electric breakdown process occurred as the streamer reaches the ground plate.



(a)

(b)

Figure 3: Streamers crossing the gap at minimum values of applied voltage at different times for (a) second mode streamer discharge and (b) third mode streamer discharge.



(a)

(b)

Figure 4: Electric Field Distribution for (a) second-mode streamer discharge at 100 kV (b) Third mode streamer discharge at 278 kV

Table 2: Comparison of some characteristics of the streamer discharge

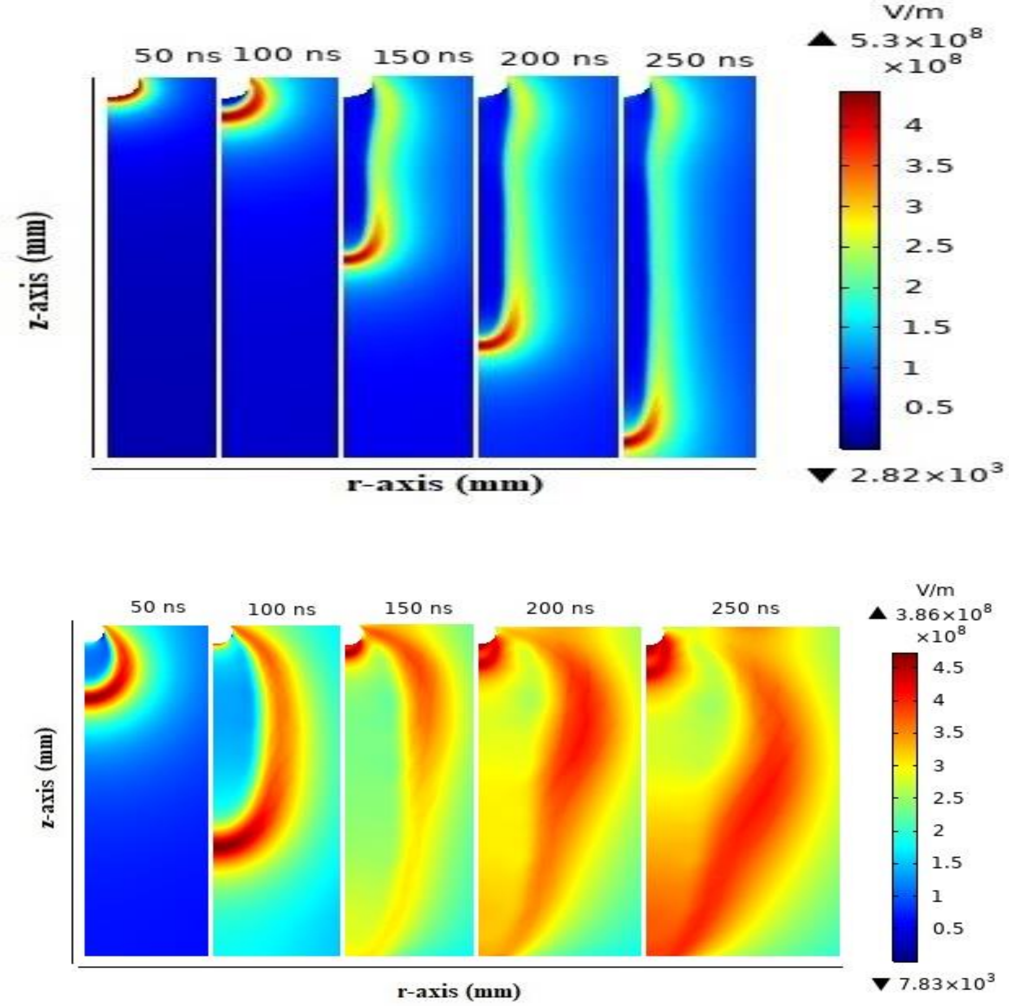
Applied voltage (kV)	Time (ns)	Streamer length (mm)	The rate of velocity (km/s)	Modes
27	30.5	0.029	0.95	1st
28.6	28.4	0.029	1.02	2nd
29	26.5	0.027	1.01	2nd
30	25.5	0.028	1.09	2nd
40	18.5	0.027	1.45	2nd
100	297	1	3.36	2nd
150	195	1	5.12	2nd
278	100	1	10	3rd

As the applied voltage was raised, it was noticed that the second and third modes changed from the first mode. The transition would occur from the first mode, which had a rate propagation velocity mostly lower than 1 km/s, to the second mode, and finally to the third mode, which had a velocity of at least 10 km/s. Table 3 shows how the streamer's radius changed throughout the transition.

Table 3: The radius of streamer discharge for different applied voltages

Applied voltage (kV)	Time (ns)	The radius of the streamer (mm)
27	31	0.04
28.6	28.4	0.05
29	28	0.047
30	27	0.0476
40	20	0.049
100	295	0.1
150	195	0.166
278	100	0.37

The electric field intensity for second and third-mode streamer discharges is shown in Figures 5 (a) and (b). The development of the streamer along the 1mm gap denotes that the ionization of the oil molecules has occurred as the tip electrode is exposed to a high voltage, so ionization of the oil molecules takes place, creating electrons and both positive and negative ions. Because the mobility of electrons is much higher than that of ions, they leave the area of ionization and travel in the direction of the ground electrode, leaving a large number of ions behind and creating a positive space charge. This result supports the experimental results that the third mode streamers have a higher degree of branching than their second mode equivalents.



(a)

(b)

Figure 5: (a) Growth of streams in transformer oil under (a)100 kV for the second (b) 278 kV for the third mode.

4. CONCLUSION

The model used in this study replicates the qualitative model of Biller [19]. The processes that occur, starting with the initiation time, propagation velocity, and transition from one mode to another, each of which depends on the applied voltage, which causes the electric field. In addition, the ionization energy of an insulating medium placed between the electrode is one of the major and influential factors for creating streamers; for example, the light density and low ionization energy of aromatic molecules enable the creation of the second mode streamer through it, while the third mode can be generated through naphthenic and paraffinic molecules because of their higher ionization energy and larger density than aromatic molecules.

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