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The transitional fast 3rd mode streamer*

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**Citation:** Hwang, J.G. et al. "Modeling streamers in transformer oil: The transitional fast 3rd mode streamer." Properties and Applications of Dielectric Materials, 2009. ICPADM 2009. IEEE 9th International Conference on the. 2009. 573-578. © 2009 IEEE

**As Published:** <http://dx.doi.org/10.1109/ICPADM.2009.5252362>

**Publisher:** Institute of Electrical and Electronics Engineers

**Persistent URL:** <http://hdl.handle.net/1721.1/54691>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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## MODELING STREAMERS IN TRANSFORMER OIL: THE TRANSITIONAL FAST 3<sup>rd</sup> MODE STREAMER

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**Abstract**—This paper presents an electro-thermal hydrodynamic model that explains the development of different streamer modes in transformer oil. The focus is on the difference between the slow 2<sup>nd</sup> and fast 3<sup>rd</sup> mode streamers discussed in the literature. Through the use of numerical methods the model demonstrates that streamer modes arise in transformer oil due to the electric field dependent molecular ionization of different families of hydrocarbon molecules (*i.e.*, aromatic, naphthenic, and paraffinic) at increasing electric field levels (or applied voltages). Ionization of the low number density aromatic molecules, that generally have lower ionization energies than naphthenic/paraffinic molecules, leads to the propagation of 2<sup>nd</sup> mode streamers with velocities on the order of 1 km/s. As the applied voltage is increased, the ionization of the main hydrocarbon molecules in transformer oil, high number density naphthenic/paraffinic molecules, dominates producing high electric field levels and space charge at the streamer tip. This ultimately leads to the propagation of the 3<sup>rd</sup> mode streamer with velocities on the order of 10 km/s.

### I. INTRODUCTION

Due to the major implications which an insulation failure in electric power apparatus can have, scientists and engineers have for many years studied the insulating properties of dielectric liquids, particularly transformer oils, with a view to understanding the mechanisms behind electrical breakdown in an effort to reduce their likelihood [1]. Much of their work has focused on the formation of electrical streamers. These are low density conductive structures that form in regions of oil that are over-stressed by electric fields on the order of  $1 \times 10^8$  V/m or greater. Once a streamer forms it tends to elongate, growing from the point of initiation towards a grounding point. Sustained over-excitation can result in a streamer short circuiting the oil gap between electrodes. When this happens an arc will form and electrical breakdown will occur.

Much of the research on streamers in dielectric liquids has been empirical in nature and has led to the formation of a large literature on the subject of which the references [1]–[8] are representative. Unfortunately, unlike the gaseous and solid states, the molecular structure and behavior of liquids is more complex and even in the purest liquids there exists trace amounts of impurities that make it difficult to isolate the mechanisms behind electrical breakdown [7], [8]. In particular, transformer oil is a mixture of many different aromatic, naphthenic, and paraffinic molecules with complex molecular structures. For example, the commercial transformer

oil Nytro 10XN is a naphthenic-based oil with approximately 7% aromatic content [9].

Researchers have experimentally observed that streamers have different propagation characteristics that are strongly dependent on the voltage excitation (*i.e.*, magnitude, polarity, wave shape, duration, rise time, fall time, etc.) to the liquid [1]–[6]. In the case of transformer oil, experimental evidence has shown that positive streamers emanating from the positive electrode tend to initiate at lower applied voltages and propagate faster and further than negative streamers [1], [2]. As a result, positive streamers constitute a greater risk to oil insulated high voltage electrical equipment than do negative streamers and are the focus of this work.

In transformer oil, four positive streamer propagation modes have been identified, called the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, and 4<sup>th</sup> modes, for lightning impulse voltage excitations in transformer oil. The onset of the four modes are dependent on the magnitude of the excitation with the 1<sup>st</sup> mode initiating at the lowest voltage magnitude and the 4<sup>th</sup> mode at the highest. The 2<sup>nd</sup> mode initiates at the breakdown voltage  $V_b$  which denotes 50% probability of breakdown, while the 3<sup>rd</sup> mode initiates at the acceleration voltage  $V_a$  where the streamer propagation velocity rises dramatically [6]. Therefore, with increased applied voltage the streamer velocity and shape changes dramatically becoming more energetic and dangerous. In prebreakdown studies, the 1<sup>st</sup> mode is often ignored as it has a low probability of leading to breakdown [10]. On the other hand, propagation velocities for 2<sup>nd</sup>, 3<sup>rd</sup>, and 4<sup>th</sup> mode streamers are on the order of 1 km/s, 10 km/s, and 100 km/s respectively [2]–[6]. The applied voltage range for the 3<sup>rd</sup> mode region, where the streamer transitions from the slow 2<sup>nd</sup> mode to the highly energetic 4<sup>th</sup> mode, is small compared to that of the 2<sup>nd</sup> mode. Therefore, the transitional 3<sup>rd</sup> mode streamer is dangerous, as it can quickly lead to the extremely fast 4<sup>th</sup> mode streamer with only a small increase in applied voltage.

The majority of streamer data in the literature is concerned with 1<sup>st</sup> and 2<sup>nd</sup> modes. Recently, with the advancement of measurement technologies the amount and quality of experimental results for the fast traveling 3<sup>rd</sup> mode, and to a lesser extent the 4<sup>th</sup> mode, has also increased significantly. This increase in empirical results has allowed researchers to better understand and hypothesize the underlying mechanisms that lead to streamer development and the different modes.

For example, Biller hypothesized that for non-homogeneous dielectric liquids like transformer oil the equivalent of  $2^{nd}$  mode streamers were linked to the ionization of the “easily ionizable” molecules, while the faster modes result from the ionization of the main “ordinary” molecules. In the context of transformer oil, the easily ionizable species are equivalent to aromatic molecules which have lower ionization energies [11], [12] and lower number density [9], [13] than the naphthenic and paraffinic molecules. The “ordinary” molecules are precisely the main naphthenic and paraffinic hydrocarbons that comprise the majority of transformer oil.

In our previous work, a model was presented that showed the electric field dependent molecular ionization of low number density and low ionization energy impurity molecules is the key mechanism for  $2^{nd}$  mode positive streamer development in transformer oil [14]. This paper further develops the mathematical model to elucidate the mechanisms and conditions that produce the  $3^{rd}$  mode streamer. The model is solved numerically using the finite element software package COMSOL Multiphysics [15]. The numerical results are compared to experimental results found in the literature and to our previous work on  $2^{nd}$  mode streamers [14]. The results show that the qualitative model by Biller [16] accurately describes the underlying physics that lead to different streamer modes in transformer oil.

This paper is organized such that the governing equations of the electro-thermal hydrodynamic model are presented in Section II. In Section III, a detailed description of the charge generation mechanism, electric field dependent molecular ionization, is given. The dependence of the propagation of  $2^{nd}$  or  $3^{rd}$  modes on the field ionization of different sets of molecules will be discussed in length. Section IV will give the results of the  $3^{rd}$  mode streamer model and compare them to the model results for the  $2^{nd}$  mode streamer. The paper concludes in Section V with the key results of the model and how it describes the different physics that pertain to  $2^{nd}$  and  $3^{rd}$  mode streamers.

## II. ELECTRO-THERMAL HYDRODYNAMIC MODEL

Electrical breakdown and pre-breakdown in dielectric liquids including transformer oil are characterized by observable events such as the formation of streamers and ultimately arcs. These structures form as a result of electrically dissipative processes, which take place in the liquid when it is highly electrically stressed. Therefore, the modeling of streamer formation in dielectric liquids must primarily focus on the electro-thermal dynamic processes taking place in the liquid.

The governing equations that contain the physics to model streamer development are based on the drift dominated charge continuity equations (2)-(4) for positive ion ( $\rho_p$ ), negative ion ( $\rho_n$ ), and electron ( $\rho_e$ ) charge densities which are coupled via Gauss’ Law (1) and include the thermal diffusion equation (5) to model temperature variations ( $T$ ) and gas formation in oil. The negative ion and electron charge densities are both negative quantities. The three carrier continuum model

is utilized to account for the charge generation and capture mechanisms, which are critical in the study of streamers.

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

$$\frac{\partial \rho_p}{\partial t} + \nabla \cdot (\rho_p \mu_p \vec{E}) = G_I + \frac{\rho_p \rho_e R_{pe}}{e} + \frac{\rho_p \rho_n R_{pn}}{e} \quad (2)$$

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

$$\frac{\partial \rho_e}{\partial t} + \nabla \cdot (-D_e \nabla \rho_e - \rho_e \mu_e \vec{E}) = -G_I - \frac{\rho_p \rho_e R_{pe}}{e} - \frac{\rho_e}{\tau_a} \quad (4)$$

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \frac{1}{\rho_l c_v} (k_T \nabla^2 T + \vec{E} \cdot \vec{J}) \quad (5)$$

Parameters  $\vec{v}$ ,  $\epsilon$ ,  $k_T$ ,  $c_v$ , and  $\rho_l$  are the oil’s velocity, permittivity ( $2.2\epsilon_0$ ), thermal conductivity ( $0.13 \text{ W/m}\cdot\text{K}$ ), specific heat ( $1.7 \times 10^3 \text{ J/kg}\cdot\text{K}$ ), and mass density ( $880 \text{ kg/m}^3$ ), respectively, and these values are representative for transformer oil. In the microsecond time scales of interest for streamer formation the oil’s velocity is negligible such that  $\vec{v} = 0$ . Also,  $e$  is the magnitude of electronic charge ( $1.602 \times 10^{-19} \text{ C}$ ) and  $\vec{E}$  is the local electric field.

In (1)-(5), the parameters  $\mu_p$ ,  $\mu_n$ , and  $\mu_e$  are the mobilities of the positive ions ( $1 \times 10^{-9} \text{ m}^2/\text{V}\cdot\text{s}$  [17]), negative ions ( $1 \times 10^{-9} \text{ m}^2/\text{V}\cdot\text{s}$  [17]), and electrons ( $1 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{s}$  [18], [19]) respectively, and  $D_e$  is the electron diffusion coefficient obtained from the Einstein equation at room temperature  $D_e = kT\mu_e/e = 2.58 \times 10^{-6} \text{ m}^2/\text{s}$ .

The electro-dynamics are coupled to the oil’s temperature through the  $\vec{E} \cdot \vec{J}$  dissipation term in (5), where  $\vec{J} = (\rho_p \mu_p - \rho_n \mu_n - \rho_e \mu_e) \vec{E} - D_e \nabla \rho_e$  is the total current density. This term reflects the electrical power dissipation or Joule heating that takes place in the oil as a result of the motion of free charge carriers under the influence of the local electric field.

$R_{pn}$  and  $R_{pe}$  are the ion-ion and ion-electron recombination coefficients obtained from the Langevin relationship  $R_{pn} = R_{pe} = e(\mu_p + \mu_n)/\epsilon = 1.65 \times 10^{-17} \text{ m}^3/\text{s}$  [14], [19]. The two rates are assumed equal because using the Langevin relationship for the ion-electron recombination rate leads to overestimation. The Langevin recombination relationship is a diffusion limited process and valid for situations where the electric field levels are low to moderate and the recombining species are of similar physical scale [19]. To compensate for the reduction in the recombination cross-section caused by high electric field levels, some authors have used the Langevin recombination term for ion-ion recombination to model ion/electron recombination [20]. This approach effectively compensates for the reduction in the recombination cross-section by reducing the apparent electron mobility.

In addition to recombination, electrons also combine with neutral molecules to form negative ions. This process is modeled as an electron attachment time constant,  $\tau_a = 200 \text{ ns}$  [20]. The term  $G_I$  is the model for the electric field dependent molecular ionization positive ion and electron charge generation mechanism to be discussed in Section III.

The boundary conditions applied to the streamer model of (1)-(5) are:

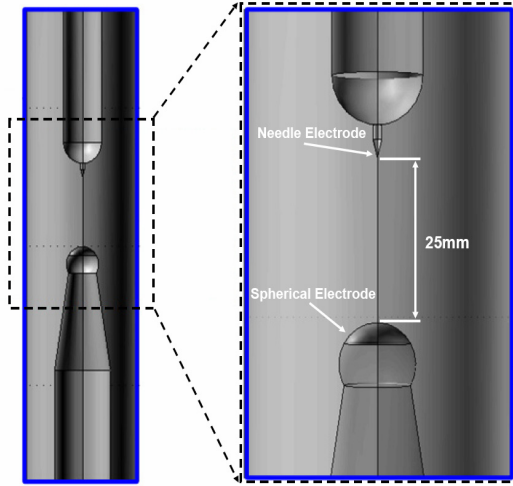


Fig. 1. Computer-aided design representation of the needle-sphere electrode geometry used for streamer simulation purposes as described by IEC 60897 standard [21].

- Gauss' Law (1): The sharp needle and large diameter sphere electrodes are set to a step voltage at  $t=0$  and 0 V, respectively. The symmetry z-axis and the top, bottom and side insulating walls have the Neumann boundary condition of zero normal electric field components (*i.e.*,  $\vec{n} \cdot \nabla V = 0$ ).
- Charge Transport Continuity Equations (2)-(4): The boundary conditions along the outer insulating boundaries are  $-\vec{n} \cdot \vec{J} = 0$ . In addition, the necessary boundary condition at the electrodes is  $\vec{n} \cdot \nabla \rho = 0$ .
- Thermal Equation (5): All boundaries are set to zero inward normal thermal diffusive flux (*i.e.*,  $\vec{n} \cdot \nabla T = 0$ ) making the approximation that the system is adiabatic on the timescales of interest.

The mathematical model described by the set of equations above is solved numerically using the finite element method software package COMSOL Multiphysics. The setup corresponds to the needle-sphere electrode geometry as shown in Fig. 1 and detailed in the IEC 60897 standard [21]. The axial distance between the needle electrode's tip and the spherical electrode is 25 mm. The radius of curvature of the needle electrode and spherical electrode are  $40 \mu\text{m}$  and  $6.35 \text{ mm}$ , respectively. The applied voltage to the needle electrode is a step voltage with a rise time of  $0.01 \mu\text{s}$ . The setup of the numerical model is in agreement with O'Sullivan *et al.* [14] and the electrothermal model (1)-(5) are solved in their two dimensional form with azimuthal symmetry.

### III. CHARGE GENERATION VIA ELECTRIC FIELD DEPENDENT MOLECULAR IONIZATION

Previously we showed that electric field dependent molecular ionization, also called field ionization, of low number density and low ionization energy impurity molecules is the key mechanism for  $2^{\text{nd}}$  mode positive streamer development in transformer oil [14]. By ionizing the low number density and low ionization energy impurity molecules into slow positive

ions and fast electrons, an area of net positive space charge quickly develops because the highly mobile electrons are swept away to the positive electrode from the ionization zone leaving behind the low mobility positive ions. The net homocharge modifies the electric field distribution in the oil such that the electric field at the positive electrode decreases while the electric field ahead of the positive charge in the oil increases. The new field distribution leads to ionization of more impurity molecules occurring further away from the positive electrode, which in turn causes further modification of the electric field distribution. The ultimate result of these electrodynamic processes is the development of an ionizing electric field wave, which is a moving dissipative source that raises the temperature to vaporize transformer oil and create a gas phase. This oil vaporization leads to the formation of the low mass density streamer channel in transformer oil.

The field ionization charge density rate source term is based upon the Zener model [22] and has the form

$$G_I(|\vec{E}|) = \frac{e^2 n_0 a |\vec{E}|}{h} \exp\left(-\frac{\pi^2 m^* a \Delta^2}{eh^2 |\vec{E}|}\right) \quad (6)$$

where  $h$  is Planck's constant,  $a$  is the molecular separation distance,  $m^*$  is the effective electron mass,  $n_0$  is the number density of ionizable species and  $\Delta$  is the liquid-phase ionization energy. Devins, Rzad, and Schwabe [8] qualitatively applied this model to dielectric liquids to explain streamer propagation. From their qualitative analysis they extrapolated that the rate of field ionization in a liquid is proportional to the liquid's mass density and inversely proportional to the ionization energy of the liquid molecule.

Billar theorized that fast  $3^{\text{rd}}$  mode streamers result from ionizing the main high number density liquid molecules, which are naphthenic and paraffinic molecules in transformer oils, generating more space charge [16]. Consequently, the large space charge produces a higher space charge electric field which continues the ionization of the same molecules further into the liquid. This results in an efficient streamer propagation due to a higher field ionization rate  $G_I$ . Also, researchers have hypothesized that the underlying mechanism that drives  $2^{\text{nd}}$  and  $3^{\text{rd}}$  mode streamers is comparable due to the similar streamer characteristics between the two modes [6]. Therefore, applying these assumptions to (6) would result in the following two constraints

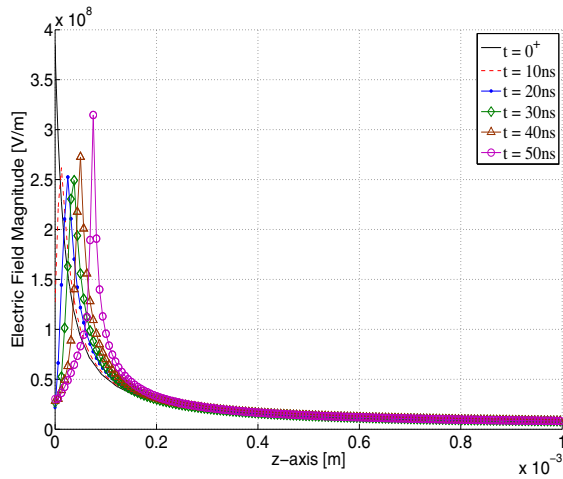
$$n_{0 \text{ aromatic}} \ll n_{0 \text{ naphthenic/paraffinic}} \quad (7)$$

$$\Delta_{\text{aromatic}} < \Delta_{\text{naphthenic/paraffinic}} \quad (8)$$

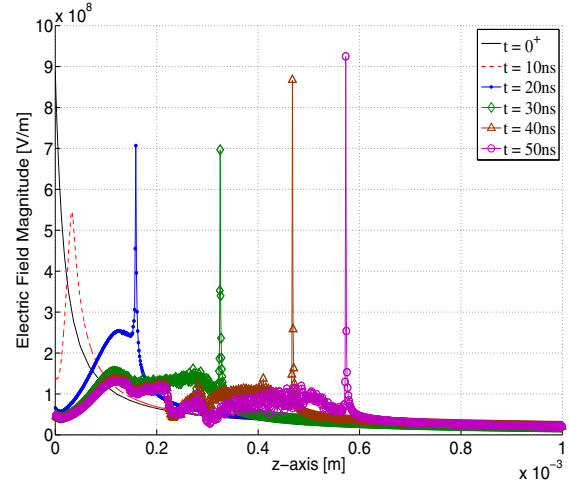
The major difficulty in trying to apply (6) to transformer oil is determining correct parameter values. Many commonly used dielectric liquids, such as transformer oil, are comprised of numerous individual molecular species, each with unique number density, ionization energy, and mass, that have very complex molecular structures. Also, values for molecular separation, effective electron mass, and ionization energy are not well known for molecules in the liquid-state. In these cases educated assumptions are made based upon known liquid-state

TABLE I  
CASE STUDIES: FIELD IONIZATION PARAMETER VALUES FOR 2<sup>nd</sup> AND 3<sup>rd</sup> MODE STREAMERS

Parameter	Symbol	Case 1: 2 <sup>nd</sup> Mode Values	Case 2: 3 <sup>rd</sup> Mode Values	Ref.
Number density	$n_0$	$1 \times 10^{23} \text{ m}^{-3}$	$1 \times 10^{26} \text{ m}^{-3}$	[9], [13], [16]
Ionization potential	$\Delta$	$1.18 \times 10^{-18} \text{ J}$ (7.40 eV)	$1.58 \times 10^{-18} \text{ J}$ (9.86 eV)	[11], [12]
Molecular separation	$a$	$3.0 \times 10^{-10} \text{ m}$		[20]
Effective electron mass	$m^*$	$0.1 \times m_e = 9.11 \times 10^{-32} \text{ kg}$		[23]
Applied voltage amplitude	$V$	130 kV	300 kV	



(a) Case 1: 2<sup>nd</sup> mode parameter values



(b) Case 2: 3<sup>rd</sup> mode parameter values

Fig. 2. Electric field temporal dynamics along the needle-sphere electrode axis at 10 ns intervals from  $t = 0$  to 50 ns given by the solution of the field ionization model of (1)-(5) for the field ionization parameter values summarized in Table I. Note, the  $t = 0^+$  plot is the Laplacian field distribution.

characteristics and the chemical composition of the dielectric liquid of interest.

For example, a typical hydrocarbon liquid has a molecular number density on the order of  $1 \times 10^{27} \text{ m}^{-3}$  to  $1 \times 10^{28} \text{ m}^{-3}$  [13], of which only a small percentage is ionized [16]. The molecular separation distance is strictly a solid-state concept and is difficult to find an analogous measure in liquids, however Qian *et al.* [20] state that the molecular separation of water is  $3.0 \times 10^{-10} \text{ m}$ . The effective electron mass in several nonpolar liquids has been found to range from  $0.1 \times m_e$  to  $m_e$ , where  $m_e = 9.11 \times 10^{-31} \text{ kg}$  is the free electron mass [23]. Lastly, the ionization energy of hydrocarbon liquids and gases primarily range from  $9.6 \times 10^{-19} \text{ J}$  to  $1.92 \times 10^{-18} \text{ J}$  (6 eV to 12 eV) [11], [12]. Consequently, in this work the field ionization parameter values and applied voltages used for 2<sup>nd</sup> and 3<sup>rd</sup> mode streamers are summarized in Table I. The values for the 2<sup>nd</sup> mode molecular species models low number density aromatic molecules (*e.g.*, pyrene) and the 3<sup>rd</sup> mode molecular species' values correspond to the high number density naphthenic/paraffinic molecules (*e.g.*, cyclohexane).

#### IV. RESULTS AND DISCUSSION

To test Biller's hypothesis, that the propagation of slow and fast streamers is related to the ionization of the different families of molecules, two test cases summarized in Table I were studied. Each set of parameter values were utilized in

the model (1)-(5) and solved numerically via COMSOL.

In Biller's hypothesis the specific charge generation mechanism involved in streamer development is not discussed [16]. The results of the numerical study reveal that field ionization is the key contributor to the initiation and propagation of 2<sup>nd</sup> and 3<sup>rd</sup> mode positive streamers. Fig. 2 shows that significant temporal dynamics in the electric field distribution occur in the highly stressed oil between the needle tip and spherical electrodes. The electric field distribution dynamics predicted by the field ionization model from  $t = 0^+$  to 50 ns (the  $t = 0^+$  electric field represents the Laplacian electric field) show that the peak of the electric field does not occur at the needle tip, as it does for the Laplacian field, but rather at a point in the oil gap between the two electrodes. This temporally dynamic electric field distribution represents an ionizing electric field wave that ionizes molecules into positive ions and electrons. The electrons, which are highly mobile when compared to the slow positive ions, are quickly swept back towards the needle anode leaving a net positive space charge peak that occurs at the same position as the electric field peak. The motion of free charge carriers, especially the mobile electrons, results in Joule heating which raises the temperature of the oil as the wave propagates. Therefore, the electric field wave leads to the formation of a moving dissipative source, which causes thermal dissipation in the oil.

In addition to examining temporal dynamics along the needle-sphere z-axis, it is interesting to examine how the

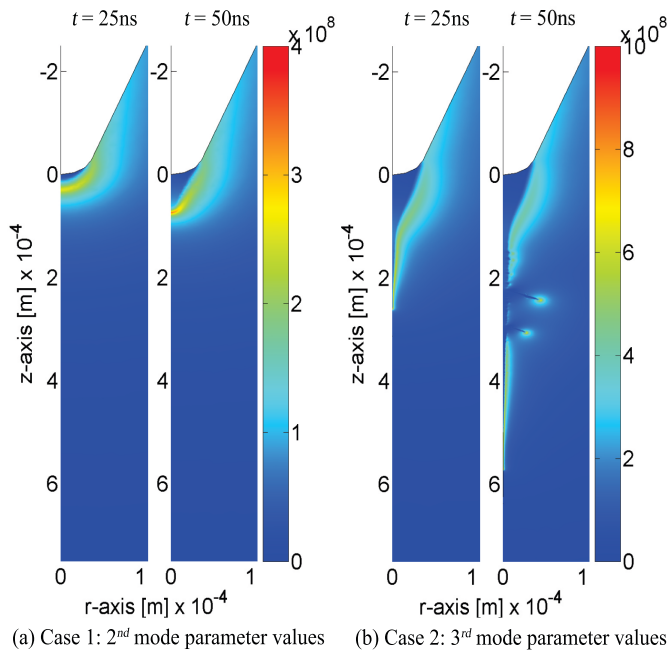
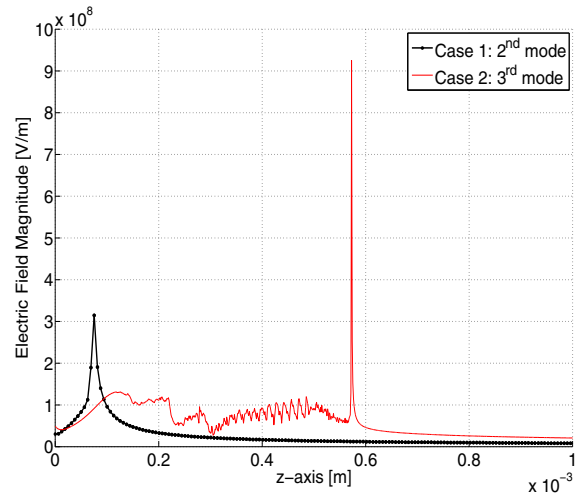


Fig. 3. Electric field magnitude surface distributions (as a function of  $r$  and  $z$  in the electrode geometry) at  $t = 25$  ns and  $50$  ns given by the solution to the field ionization model of (1)-(5) for both  $2^{nd}$  and  $3^{rd}$  mode field ionization parameter values summarized in Table I. Note, the different scales for the  $2^{nd}$  and  $3^{rd}$  mode color bars.

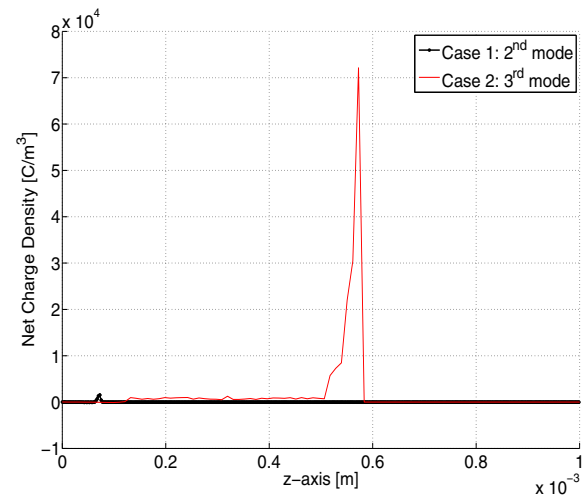
electric field's spatial distribution changes with time. In Fig. 3, the electric field's surface distribution at  $t = 25$  and  $50$  ns are plotted. As time progresses the streamer tip, where there is an enhancement of the electric field due to the positive space charge created in the ionization region, moves further into the oil for both the  $2^{nd}$  and  $3^{rd}$  mode cases; however, it is evident that the propagation velocity of the  $3^{rd}$  mode streamer is much faster than the  $2^{nd}$  mode streamer. The  $2^{nd}$  and  $3^{rd}$  mode propagation velocities are  $1.5$  km/s and  $11.5$  km/s, which correspond closely to the experimental data in the literature [3], [5], [6].

The spatial plots of Fig. 3 also give insight on the dimensions of the tip and body of the main streamer filament. The radius of the streamer channel for the  $2^{nd}$  and  $3^{rd}$  mode cases are approximately  $12.5 \mu\text{m}$  and  $2.0 \mu\text{m}$  respectively, which corresponds well to the dimensions of main streamer channels in transformer oil that have been observed experimentally [4]. Interestingly, the  $3^{rd}$  mode streamer at  $t = 50$  ns has protrusions from the main streamer body that are indicative of streamer branching. This agrees with the experimental observation that  $3^{rd}$  mode streamers have a higher branched structure than its  $2^{nd}$  mode counterparts [6].

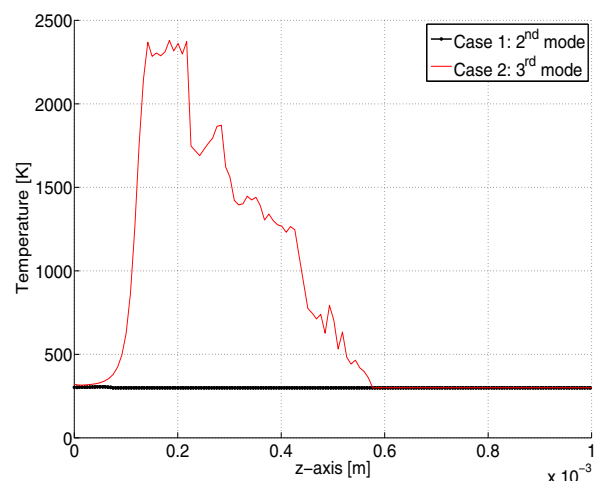
To facilitate a direct comparison of streamer propagation of the  $2^{nd}$  and  $3^{rd}$  mode cases, the electric field, net space charge density, and temperature distributions along the needle-sphere  $z$ -axis at  $t = 50$  ns are plotted in Fig. 4. The  $2^{nd}$  mode streamer initiates at  $130$  kV and propagates at  $1.5$  km/s. As the streamer travels further into the oil its' ionizing electric field wave can only ionize the low number density aromatic molecules into positive ions and electrons due to the low applied voltage. On the other hand, when a voltage of  $300$  kV



(a) Electric Field Distribution.



(b) Net Charge Density Distribution. Note, the net charge density distribution for the  $2^{nd}$  mode case is small compared to the  $3^{rd}$  mode case.



(c) Temperature Distribution. The oil temperature at time  $t = 0$  is  $300$  °K. Note, the temperature enhancement for the  $2^{nd}$  mode case is small at  $t = 50$  ns.

Fig. 4. Electric field, net charge density, and temperature distributions along the needle-sphere electrode axis at time  $t = 50$  ns given by the solution to the field ionization model of (1)-(5) for both  $2^{nd}$  and  $3^{rd}$  mode case studies using parameters summarized in Table I.

is applied to the needle electrode the  $3^{rd}$  mode streamer initiates and propagates at 11.5 km/s. This produces a streamer tip with a higher electric field enhancement, compared to the  $2^{nd}$  mode streamer (Fig. 4(a)), that readily ionizes high number density naphthenic/paraffinic molecules.

The ability to ionize low or high number density molecules is directly related to the amount of space charge created in the ionization region. Ionizing the higher number density molecules creates more space charge (Fig. 4(b)) leading to a larger electric field enhancement at the streamer tip. The larger field allows for a more efficient field ionization (*i.e.*, higher  $G_I(|\vec{E}|)$ ) and results in faster streamer propagation. The level of space charge in the ionization region, as predicted in Fig. 4(b), is close to the value of  $1 \times 10^{24} \text{ m}^{-3}$  found in the literature [24].

In the  $3^{rd}$  mode streamer case, due to the ionization of more molecules, there is a greater number of free charge carriers in the streamer body that contribute to Joule heating. Therefore, the level of dissipation is higher compared to the  $2^{nd}$  mode streamer case (Fig. 4(c)) and the oil is heated significantly such that vaporization occurs quickly leading to the formation of a low mass density region. The simulation results indicate a thermal rise greater than  $2000^\circ\text{C}$ , which is much greater than the boiling temperature of oil and on the order of results from the literature [24]. Taking into consideration the parameter estimation used for the model, this level of thermal enhancement strongly suggests that field ionization of the high number density naphthenic/paraffinic molecules is the source of  $3^{rd}$  mode streamers.

## V. CONCLUSION

This paper presents a model that shows that streamer propagation modes are a product of the ionization of different families of molecules, each with their specific number density and ionization energy, thereby confirming the qualitative model of Biller [16]. In transformer oil the propagation of the slow  $2^{nd}$  mode streamers are a result of the field ionization of low number density and low ionization energy aromatic molecules, while  $3^{rd}$  mode streamers propagate due to the field ionization of the main high number density and high ionization energy hydrocarbon molecules in the transformer oil (*i.e.*, naphthenic and paraffinic molecules). The two streamer modes initiate at different applied voltages due to the differing ionization energies of the molecular species. For example, aromatic molecules with lower ionization energies will ionize at lower applied voltages compared to naphthenic/paraffinic molecules that generally have higher ionization energies and therefore need a greater applied voltage to ionize.

## ACKNOWLEDGMENT

This work has been supported by ABB Corporate Research, Västerås, Sweden.

## REFERENCES

- [1] A. Beroual, M. Zahn, A. Badent, K. Kist, A. J. Schwabe, H. Yamashita, K. Yamazawa, M. Danikas, W. G. Chadband, and Y. Torshin, "Propagation and structure of streamers in liquid dielectrics," *IEEE Electr. Insul. Mag.*, Vol. 14, No. 2, pp. 6-17, March/April 1998.
- [2] R. E. Hebner, "Measurements of electrical breakdown in liquids," in *The Liquid State and its Electrical Properties*, E. E. Kundhardt, L. G. Christophorou, and L. H. Luessen, Eds., New York: Plenum Press, 1988, pp. 519-537.
- [3] D. Linhjell, L. Lundgaard, and G. Berg, "Streamer propagation under impulse voltage in long point-plane oil gaps," *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 1, No. 3, pp. 447-458, June 1994.
- [4] Y. V. Torshin, "On the existence of leader discharges in mineral oil," *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 2, No. 1, pp. 167-179, February 1995.
- [5] L. Lundgaard, D. Linhjell, G. Berg and S. Sigmond, "Propagation of positive and negative streamers in oil with and without pressboard interface," *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 5, No. 3, pp. 388-395, June 1998.
- [6] O. Lesaint and G. Massala, "Positive streamer propagation in large oil gaps: experimental characterization of propagation modes," *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 5, No. 3, pp. 360-370, June 1998.
- [7] Y. Nakao, T. Yamazaki, K. Miyagi, Y. Sakai, and H. Tagashira, "The effect of molecular structure on prebreakdown phenomena in dielectric liquids under nonuniform field," *Electrical Engineering in Japan*, Vol. 139, No. 2, pp. 1-8, 2002.
- [8] J. C. Devins, S. J. Rzd and R. J. Schwabe, "Breakdown and prebreakdown phenomena in liquids," *J. Appl. Phys.*, Vol. 52, No. 7, pp. 4531-4545, July 1981.
- [9] Nynas AB, Nynas Transformer Oil - Nytro 10XN (IEC 60296/03), 2008.
- [10] L. Costeanu and O. Lesaint, "On mechanisms involved in the propagation of subsonic positive streamers in cyclohexane," in *Proc. International Conference on Dielectric Liquids ICDL02*, Graz, Austria, July 2002, pp. 143-146.
- [11] M. Harada, Y. Ohga, I. Watanabe, and H. Watarai, "Ionization energies for solvated polycyclic aromatic hydrocarbons," *Chem. Phys. Lett.*, Vol. 303, pp. 489-492, 1999.
- [12] H. S. Smalø, P.-O. Åstrand, and S. Ingebrigtsen, "Calculation of ionization potentials and electron affinities for molecules relevant to streamer initiation and propagation," in *Proc. IEEE International Conference on Dielectric Liquids*, Poitiers, France, July 2008, pp. 280-283.
- [13] "Physical Constants of Organic Compounds", in *CRC Handbook of Chemistry and Physics, 89th Edition*, D. R. Lide, ed. Boca Raton: CRC Press/Taylor and Francis, 2009.
- [14] F. O'Sullivan, J. G. Hwang, M. Zahn, O. Hjortstam, L. Pettersson, R. Liu, and P. Biller, "A model for the initiation and propagation of positive streamers in transformer oil," in *Proc. IEEE International Symposium on Electrical Insulation ISEI08*, Vancouver, British Columbia, Canada, June 2008, pp. 210-214.
- [15] COMSOL AB, <http://www.comsol.com>.
- [16] P. Biller, "A simple qualitative model for the different types of streamers in dielectric liquids", in *Proc. International Conference on Conduction and Breakdown in Dielectric Liquids ICDL96*, Baden-Dättwil, Switzerland, July 1996, pp. 189-192.
- [17] U. Gäfvert, A. Jaksts, C. Törnkvist and L. Walfridsson, "Electrical field distribution in transformer oil," *IEEE Trans. Electr. Insul.*, Vol. 27, No. 3, pp. 647-660, June 1992.
- [18] A. O. Allen, *Drift Mobilities and Conduction Band Energies of Excess Electrons in Dielectric Liquids*. Washington: National Standards Reference Data Series - National Bureau of Standards, 1976.
- [19] J. G. Hwang, M. Zahn, F. O'Sullivan, L. A. A. Pettersson, O. Hjortstam, and R. Liu, "Electron scavenging by conductive nanoparticles in oil insulated power transformers," in *2009 Electrostatics Joint Conference*, Boston, Massachusetts, USA, June 2009, pp. 1-12.
- [20] J. Qian, R. P. Joshi, E. Schamiloglu, J. Gaudet, J. R. Woodworth, and J. Lehr, "Analysis of polarity effects in the electrical breakdown of liquids," *J. Phys. D: Appl. Phys.*, Vol. 39, pp. 359-369, 2006.
- [21] IEC Standard #60897, "Methods for the determination of the lightning impulse breakdown voltage of insulating liquids."
- [22] C. Zener, "A theory of the electrical breakdown of solid dielectrics," *Proc. Roy. Soc. A*, Vol. 145, No. 855, pp. 523-529, 1934.
- [23] R. A. Holroyd and W. F. Schmidt, "Transport of electrons in nonpolar fluids," *Annu. Rev. Phys. Chem.*, Vol. 40, pp. 439-468, 1989.
- [24] P. Bärmann, S. Kröll, and A. Sunesson, "Spectroscopic measurements of streamer filaments in electric breakdown in a dielectric liquid," *J. Phys. D: Appl. Phys.*, Vol. 29, pp. 1188-1196, 1996.