Modeling streamers in transformer oil: The transitional fast 3rd mode streamer

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MODELING STREAMERS IN TRANSFORMER OIL: THE TRANSITIONAL FAST 3rd MODE STREAMER

J. George Hwang1*, Markus Zahn1, Leif A. A. Pettersson2, Olof Hjortstam2, and Rongsheng Liu2
1 Laboratory for Electromagnetic and Electronic Systems, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 USA
2 ABB Corporate Research, Power Technologies, S-72178 Västerås, Sweden
*Email: ghwang@mit.edu

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 2nd and fast 3rd 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 2nd 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 3rd 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 1st, 2nd, 3rd, and 4th 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 1st mode initiating at the lowest voltage magnitude and the 4th mode at the highest. The 2nd mode initiates at the breakdown voltage $V_b$ which denotes 50% probability of breakdown, while the 3rd 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 1st mode is often ignored as it has a low probability of leading to breakdown [10]. On the other hand, propagation velocities for 2nd, 3rd, and 4th 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 3rd mode region, where the streamer transitions from the slow 2nd mode to the highly energetic 4th mode, is small compared to that of the 2nd mode. Therefore, the transitional 3rd mode streamer is dangerous, as it can quickly lead to the extremely fast 4th mode streamer with only a small increase in applied voltage.

The majority of streamer data in the literature is concerned with 1st and 2nd modes. Recently, with the advancement of measurement technologies the amount and quality of experimental results for the fast traveling 3rd mode, and to a lesser extent the 4th 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 2nd 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 2nd mode positive streamer development in transformer oil [14]. This paper further develops the mathematical model to elucidate the mechanisms and conditions that produce the 3rd 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 2nd 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 2nd or 3rd modes on the field ionization of different sets of molecules will be discussed in length. Section IV will give the results of the 3rd mode streamer model and compare them to the model results for the 2nd 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 2nd and 3rd 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.

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

\[
\frac{\partial \rho_p}{\partial t} + \nabla \cdot (\rho_p \vec{E}) = G_I + \frac{\rho_p \rho_e R_{pe}}{e} + \frac{\rho_p \rho_n R_{pn}}{e} \tag{2}
\]

\[
\frac{\partial \rho_n}{\partial t} - \nabla \cdot (\rho_n \vec{E}) = \frac{\rho_n}{\tau_a} - \frac{\rho_p \rho_n R_{pn}}{e} \tag{3}
\]

\[
\frac{\partial \rho_e}{\partial t} + \nabla \cdot (\vec{E}) = -G_I - \frac{\rho_p \rho_e R_{pe}}{e} - \frac{\rho_e}{\tau_a} \tag{4}
\]

\[
\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \frac{1}{\rho_c \rho_l} (k_T \nabla^2 T + \vec{E} \cdot \vec{J}) \tag{5}
\]

Parameters \( \vec{v}, \rho, k_T, c_v, \) and \( \rho_l \) are the oil’s velocity, permittivity (2.2\( \varepsilon_0 \)), thermal conductivity (0.13 W/m·K), specific heat (1.7\( \times 10^3 \) J/kg·K), and mass density (880 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\(^{-19} \) 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\(^{-9} \) m\(^2\)/V·s \([17]\)), negative ions (1 \( \times \) 10\(^{-9} \) m\(^2\)/V·s \([17]\)), and electrons (1 \( \times \) 10\(^{-4} \) m\(^2\)/V·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 electrodynamics 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

\[
R_{pn} = R_{pe} \epsilon (\mu_p + \mu_n) / e = 1.65 \times 10^{-17} \text{ m}^3/\text{s} \quad [14], [19].
\]

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:
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 homonuclear charge 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

\[
G_f(|\vec{E}|) = \frac{e^2 n_0 a |\vec{E}|}{\hbar} \exp\left( -\frac{\pi^2 m^* a \Delta^2}{e \hbar^2 |\vec{E}|} \right)
\]

where \(\hbar\) 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.

Biller 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 \(G_f\). 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

\[
n_{0\text{naphthenic/paraffinic}} \ll n_0
\]

\[
\Delta_{\text{naphthenic/paraffinic}} < \Delta_{\text{aromatic}}
\]

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 2nd AND 3rd MODE STREAMERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Case 1: 2nd Mode Values</th>
<th>Case 2: 3rd Mode Values</th>
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<td>Number density</td>
<td>$n_0$</td>
<td>$1 \times 10^{25}$ m$^{-3}$</td>
<td>$1 \times 10^{26}$ m$^{-3}$</td>
<td>[9], [13], [16]</td>
</tr>
<tr>
<td>Ionization potential</td>
<td>$\Delta$</td>
<td>$1.18 \times 10^{-18}$ J (7.40 eV)</td>
<td>$1.58 \times 10^{-18}$ J (9.86 eV)</td>
<td>[11], [12]</td>
</tr>
<tr>
<td>Molecular separation</td>
<td>$\alpha$</td>
<td>$3.0 \times 10^{-10}$ m</td>
<td></td>
<td>[20]</td>
</tr>
<tr>
<td>Effective electron mass</td>
<td>$m^*$</td>
<td>$0.1 \times m_e = 9.11 \times 10^{-32}$ kg</td>
<td></td>
<td>[23]</td>
</tr>
<tr>
<td>Applied voltage amplitude</td>
<td>$V$</td>
<td>130 kV</td>
<td>300 kV</td>
<td></td>
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Table I: Case Studies: Field Ionization Parameter Values for 2nd and 3rd Mode Streamers

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.

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 2nd and 3rd 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 toward 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 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 $1 \times 10^{27}$ m$^{-3}$ to $1 \times 10^{28}$ 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 $3.0 \times 10^{-10}$ m. The effective electron mass in several nonpolar liquids has been found to range from $0.1 \times m_e$ to $m_e$, where $m_e = 9.11 \times 10^{-31}$ kg is the free electron mass [23]. Lastly, the ionization energy of hydrocarbon liquids and gases primarily range from 6 eV to 12 eV [11], [12]. Consequently, in this work the field ionization parameter values and applied voltages used for 2nd and 3rd mode streamers are summarized in Table I. The values for the 2nd mode molecular species models low number density aromatic molecules (e.g., pyrene) and the 3rd mode molecular species’ values correspond to the high number density naphthenic/paraffinic molecules (e.g., cyclohexane).
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 2nd and 3rd mode field ionization parameter values summarized in Table I. Note, the different scales for the 2nd and 3rd mode color bars.

The 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 2nd and 3rd mode cases; however, it is evident that the propagation velocity of the 3rd mode streamer is much faster than the 2nd mode streamer. The 2nd and 3rd 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 2nd and 3rd mode cases are approximately 12.5 $\mu$m and 2.0 $\mu$m respectively, which corresponds well to the dimensions of main streamer channels in transformer oil that have been observed experimentally [4]. Interestingly, the 3rd 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 3rd mode streamers have a higher branched structure than its 2nd mode counterparts [6].

To facilitate a direct comparison of streamer propagation of the 2nd and 3rd 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 2nd 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

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 2nd and 3rd mode case studies using parameters summarized in Table I.
is applied to the needle electrode the 3rd mode streamer initiates and propagates at 11.5 km/s. This produces a streamer tip with a higher electric field enhancement, compared to the 2nd 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 $1 \times 10^{23}$ m$^{-3}$ found in the literature [24].

In the 3rd 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 2nd 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$^\circ$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 3rd 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 2nd mode streamers are a result of the field ionization of low number density and low ionization energy aromatic molecules, while 3rd 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.

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