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***RESEARCH ARTICLE***

# PREDICTION TOOL FOR OIL DIELECTRIC PERFORMANCE USING AN ELECTRICAL CIRCUIT APPROACH FOR FRESH SYNTHETIC, NATURAL ESTER, AND MINERAL OILS UNDER AC STRESS

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## *Abstract*

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Breakdown voltage and streamer velocity are crucial parameters in evaluating liquid dielectrics used in power transformers. The breakdown phenomenon is a complex physical process that requires a multidisciplinary approach. This paper presents a step-by-step modelling procedure for a single-arc discharge. A point-plane electrode configuration is employed, utilizing three distinct dielectric liquids. An AC voltage is applied, increasing at a rate of 1 kV/s until the breakdown voltage is reached, replicating the experimental setup. The input data include geometric parameters, such as the distance between electrodes and the radius of curvature of the point electrode, along with oil characteristics like relative permittivity ($\varepsilon_r$), dielectric dissipation factor ($tan\delta$), the electric field at the point electrode tip during streamer inception leading to breakdown, and the relative permittivity of gas within the bubble. The electric circuit-based model yields quantitative results that are consistent with experimental data. The low relative error values further validate the accuracy of the prediction tool.



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## Introduction:-

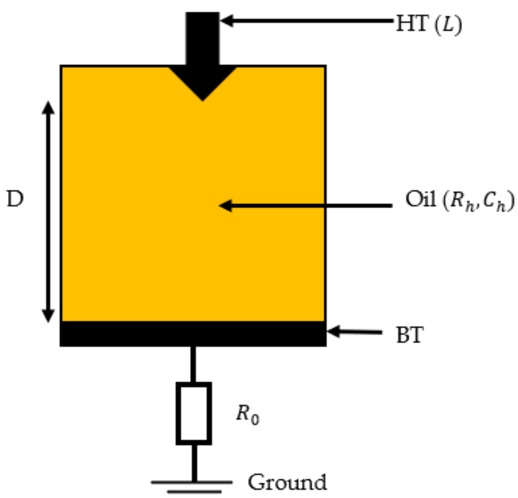
Power transformers are vital and strategic components of the electrical grid. One of the most critical vulnerabilities of these essential devices is their insulation system, which primarily consists of oil and paper. A major cause of insulation degradation is partial discharge (PD) [1]. PD is a key factor in determining the lifespan of liquid insulation and is widely studied to monitor the dielectric health of power transformers [2][3]. S. Chandrasekar et al. (2014) analyzed the characteristics of partial discharges in natural esters used as dielectric fluids in electric power equipment [4]. UrairatFuangsoongnern et al. (2014) proposed a measurement technique to identify and locate PD occurrences in the insulation of both oil-immersed and dry-type distribution transformers [5]. More recently, Wojciech Sikorski et al. (2023) presented a low-cost, portable online PD monitoring system based on acoustic emission (AE) techniques [2].

The primary goal of experimental studies and modeling is to detect faults early, enabling timely maintenance and preventing potential breakdowns. Interest in modeling is increasing, particularly with the advancement of computational tools. The growing computational power of modern computers has encouraged engineers and researchers to develop tools that predict the performance of dielectrics in power transformers. Modeling offers the advantage of saving time and money by enabling the analysis of individual parameters and their effects on the overall system. Tools based on the finite element method, such as Ansys, COMSOL Multiphysics, and the MATLAB Simulink platform, are commonly used for such simulations. For example, Pragati Sharma et al. (2015) used MATLAB Simulink to simulate PD activity caused by the presence of small voids inside solid insulation materials of high-voltage power equipment [6]. T. Aka-Ngnui et al. (2001) modeled streamer branches propagating in liquid dielectrics using an equivalent electrical network, physical laws, and energy considerations [7]. Issouf F. et al. (1998) proposed self-consistent models of streamer growth using an equivalent electrical network, with the only inputdata being electrode geometry and the applied voltage waveform [8].

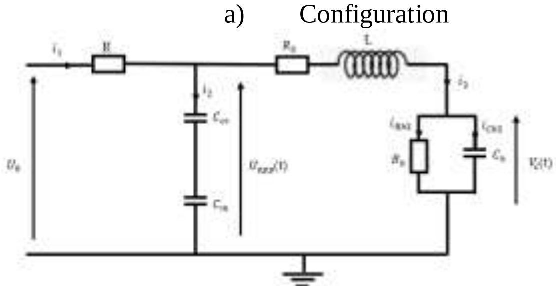
This paper utilizes an equivalent electrical network and point-plane configuration to simulate the inception and propagation of mono-arc discharges in fresh mineral oil (MO), natural ester (NE), and synthetic ester (SE). The model inputs include the permittivity of the oil, the dissipation factor, and the electric field at the tip of the electrode during discharge inception, which leads to breakdown. In the experimental setup, an alternating voltage (AC) was applied to the needle electrode with an increase rate of 1 kV/s. Experimental and simulation results are compared, and the relative error is computed.

**Experimental setup, model configuration and electric equivalent circuit, state equation**

The experimental setup is detailed in previous work [9]. The experimental results, focusing on the characteristics of streamers in fresh synthetic ester, natural ester, and mineral oils, are compared with numerical results. As in the experimental setup, AC voltage stress is applied in the numerical analysis. Figures 1(a) and 1(b) illustrate the configuration and the equivalent electrical circuit.




a) Configuration




b) Equivalent circuit

**Figure 1:-** a) Configuration and b) electric circuit.

| | | |
|---|---|---|
| $U_0$ | : | Voltage at the output of the transformer; |
| $U_{app}$ (t) | : | Voltage at the HT electrode ; |
| $C_{cc}$ et$C_m$ | : | Capacitive divider; |
| $C_h$ | : | Capacity of the liquid ; |
| $R_h$ | : | Resistance of the oil ; |

| | | |
|---|---|---|
| $R_0$ | : | Resistance for measuring the leakage current; |
| $i_3$ | : | Leakage current ; |
| $i_2$ | : | Current through the capacitive bridge; |
| $i_1$ | : | Current delivered by the transformer; |
| $v_c(t)$ | : | Voltage drop in the dielectric oil; |
| L | : | Inductance of the conductor and the high voltage tip. |

$$\begin{cases}\dot{X} = AX + BU \\ Y = CX + DU\end{cases} \qquad (1)$$

**Streamers inception**

The presence of bubbles in liquid dielectrics is inevitable [10], as their formation results from various mechanisms, including electrical, mechanical, electromechanical, and thermal processes. It can be assumed that an air bubble forms near the tip of the electrode when the initiation conditions are met. However, in this study, it is assumed that an air bubble with a radius of 7 nanometers is present in the oil, formed at the tip of the electrode. Additionally, the bubble's lifetime, $\Delta \mathbf{t_b}$, is considered long enough for the initiation conditions to be satisfied. The bubble is assumed to be sufficiently close to the tip, and the electric field at the electrode's tip is equivalent to the field in the vicinity of the bubble, as illustrated in Figure 2.

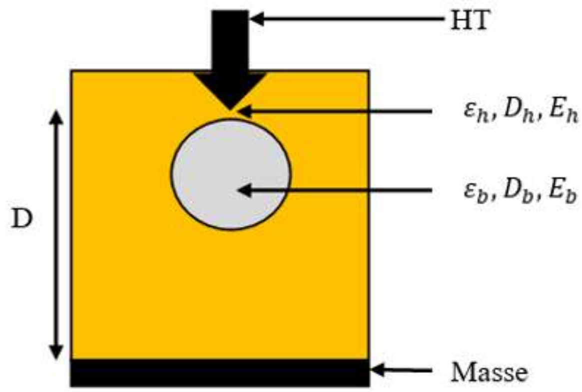



**Figure 2:-** Compute electric field into the bubble.

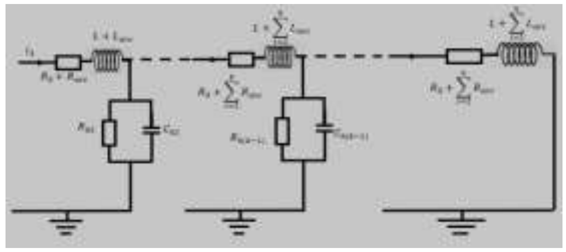
| | | |
|---|---|---|
| $\varepsilon_h$ | : | Relative permittivity of the oil ; |
| $D_h$ | : | Electric displacement in the oil; |
| $E_h$ | : | Electric field in the oil; |
| $\varepsilon_b$ | : | Relative permittivity of the bubble ; |
| $D_b$ | : | Electric displacement in the bubble; |
| $E_b$ | : | Electric field in the bubble. |

The continuity of the normal component of the electricfieldallows us to calculate the field in the bubble by the following relation:

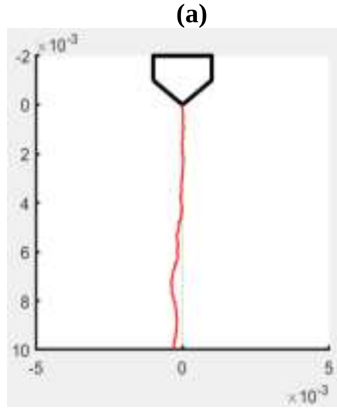
$$E_b = \frac{\varepsilon_h}{\varepsilon_b} E_h \qquad (2)$$

**Streamers propagation**

In the initiation phase, the streamers begin to form and make an initial jump equal to the diameter of the bubble created by evaporation. The arc impedance and the voltage drop between the streamer head and the tip electrode are then calculated. The voltage at the streamer head is determined, as well as the leakage current from the previous partial discharge (PD). The power and energy of the arc are also computed. Knowing β, the fraction of energy useful for streamer propagation, the calculation of the velocity and length of the next bounce is performed. Once all the conditions are met such as the total propagation time not being exceeded, the inter-electrode gap remaining unshorten, and the field at the streamer head being sufficient the streamers continue to propagate. This process repeats until one or more of the propagation conditions are no longer satisfied. At each step, the oil impedance and arc values are recalculated. The arc is treated as an extension of the tip electrode, so the arc impedance is in series with $\mathbf{R_0}$ and L. The partial discharge propagates almost continuously. Figure 3 presents the electric equivalent circuit for the propagation of streamers.



**(a)**



**(b)**

**Figure 3:-** (a) Electric equivalent circuit of streamers propagation (b) example of trajectory of discharge

**Description Of The Model**

**Computing the oil impedance**

The liquid dielectric is modeled by a parallel $R_h$ and $C_h$ circuit. For the calculation of $C_h$, it is assumed that the domain between the tip and the plane electrode is formed by two concentric half-spheres and a spherical approximation is adopted.

$$C_h = 2 * \pi * \varepsilon_0 * \varepsilon_h * \frac{(d_b + r_p)(d_b + r_p + D)}{D} \quad (3)$$

$d_b$ : Diameter of the bubble;

$r_p$ : Radius of curvature of the tip;

D : Inter-electrode distance;

$\varepsilon_h$ : Relative permittivity of the oil;

$\varepsilon_0$ : Vacuum permittivity.

To calculate $R_h$ , it is best to go by the dissipation factor

$$\tan\delta = \frac{1}{R_h * C_h * \omega} \quad (4)$$

So $$R_h = \frac{1}{\tan\delta * C_h * \omega} \quad (5)$$

The oil can be represented by an equivalent impedance

$$Z_h = \frac{R_h}{1 + jR_h * C_h * \omega} \quad (6)$$

**Leakage current**

The leakagecurrent$I_f$ is the current flowing through the measuring resistor $R_0$. The input variables of the state equation system are the voltage $U_{app}(t)$ and $V_c(t)$ and as output variables $i_3(t)$. Then solving the equations of state gives the leakage current $I_f = i_3$ and the voltage across the liquid dielectric $V_c(t)$. Another way to calculate the leakage current $I_f$ is to determine the voltage $V_c$ across the liquid dielectric. It is found that:

$$I_f = \frac{U_{app} - V_c}{Z_{eq}} \quad (7)$$

With

$Z_{eq} = R_0 + jL\omega + Z_{arc}$. (8)

$U_{app}$ : Applied voltage at HV electrode;

$Z_{arc}$ : Impedance of the arc composed of $R_{arc}$ (the resistance of the arc) and $L_{arc}$ (the inductance of the arc) connected in series;

L : Inductance of the HV conductor.

**Length of the bound**

The streamer propagates by bound or quasi-continuous. In the initiation model the calculation of the energy at the tip isdoneusingfollowing relation:

$W = U_{app} * I_f * \Delta t$ (9)

Initially $I_f = I_{ref}$ avec $I_{ref} = 10^{-9}$ A and whenever the calculated leakage current $I_f$ is lower than $I_{ref}$ set $I_f = I_{ref}$. In the model, a time step of $\Delta t = 4 * 10^{-6}$s was fix and constant.

The relations used to calculate the radius of the bubble formed if the energy W is greater than the latent heat of vaporization of the oil [11].

$$R_m = kth\left(\frac{W}{P_\infty}\right)^{1/3} \quad (10)$$

$$kth = \left(\frac{3RT_b}{4\pi}\Delta U_{int}\right)^{1/3} \quad (11)$$

In the model resolution $kth = 0.25$ because for hydrocarbons the constantkth is between 0.2 and 0.3. The bond length is estimated at $\Delta x_i = 2 * R_m$ and the bubble disappears when the streamer passes through it.

The length of the streamer leap depends on several parameters, the main one being energy. The puissance at the streamer head is calculated using relation 12.

$P_i = U_{app} * I_f$ (12)

The expression of the energy is:

$W_i = P_i * \Delta t$ (13)

Total energy $W_i$ can be distributed in various forms (kinetic energy, evaporation energy, etc.). Kinetic energy $W_c$ is transferred to the streamer channel, which extends from $\Delta x_i$. The expression for kinetic energy is :

$W_c = \frac{1}{2}mv^2$ (14)

Recall that there is always a gas phase in front of the streamer channel. The discharge channel is cylindrical with a volume of $V = \pi * r_i^2\Delta x_i$ and density $\rho = \frac{m}{V}$. It shows that the air mass that can be contained by the future canal is: $m = \rho\pi r_i^2\Delta x_i$. The new expression for kinetic energy is:

$W_c = \frac{1}{2}\rho\pi r_i^2\Delta x_i v_i^2 = \beta\Delta W_i$ (15)

With β between 0 and 1.

β is the fraction of energy the arc uses to propagate. To simplify the model, it is assumed that the radius of the streamer channel is identical to the radius of curvature of the tip electrode. $r_i = r_p$ : streamer radius and $v_i$ the propagation velocity of streamers during the bond.

Assuming the bubble is filled with a perfect gas, the law of perfect gases gives: $PV = \frac{m}{M}RT$

with $P = \frac{m}{V}\frac{RT}{M}$ then $P = \rho\frac{RT}{M}$ and $\rho = \frac{PM}{RT}$as long as the streamer channel is not in its explosion phase $P = cte$. $k = PM$ is a constant. R the constant of perfect gases and $\rho = \frac{k}{T(K)*R}$ the streamer's propagation velocity can be written as follows:

$v_i^2 = \frac{2*\beta*\Delta W_i}{\rho*\pi*r_p^2\Delta x_i}$ (16)

by replacing ρ by its value then:

$v_i^2 = \frac{2*T(K)*R*\beta}{k*\pi*r_p^2}\frac{\Delta W_i}{\Delta x_i}$. (17)

Posing $\Delta x_i = v_i * \Delta t$and replacing $\Delta x_i$by its value in the bond velocity expression, it follows that:

$v_i^3 = \frac{2*\beta*T(K)}{k*\pi*r_p^2}\frac{\Delta W_i}{\Delta t}$. (18)

If $T(K) = T_0$ the temperature at the streamer head, the expression for velocity becomes:

$$v_i = \left(\frac{2*R*\beta*T_0}{k*\pi*{r_p}^2}\frac{\Delta W_i}{\Delta t}\right)^{1/3} \quad (19)$$

Or $v_i = \left(\frac{2*R*\beta*T_0}{k*\pi*{r_p}^2}P_i\right)^{1/3}$ with $P_i = \frac{\Delta W_i}{\Delta t}$

$\Delta t$ : the duration of the bond is known and $\beta = 0.15$ because it is between 0,1 and 0,2. Since the streamer's propagation velocity is known, the expression for the bond length is

$$\Delta x_i = v_i * \Delta t \quad (20)$$

**Arc impedance**

The arc impedance is composed of a resistance $R_{arc}$ and an inductance $L_{arc}$ connected in series. Arc resistance is calculated using the relationship below:

$$R_{arc} = \frac{\Delta x_i}{\sigma \pi r_0^2} \quad (21)$$

With σ the conductivity$\sigma=5\Omega^{-1}.m^{-1}$ and $r_0 = 5\mu m$ according to Issouf et al [12] and $\Delta x_i$ the length of the bond. To calculate inductance $L_{arc}$ the relationship used in the model Issouf et al [12] is applied :

$$L_{arc} = \frac{(\Delta x_i * \mu_0)}{\left(2*pi*\left(0.25+\log\left(\frac{Dfar}{r_p}\right)\right)\right)} \quad (22)$$

With Dfar : the distance from the channel at which the magnetic induction field due to the current is considered to be zero [13] ;

$\mu_0$ : is the magnetic permeability of vacuum and is equal to $\mu_0 = 4 * pi * 10^{-7} Tm/A$.

The remaining inter-electrode gap to be crossed by the arc is given by:

$$L_{axial} = D - \Sigma\Delta x_i. \quad (23)$$

This is a condition for stopping the simulation if $L_{axial}$ becomes negative.The stopping length and average propagation speed are presented in the following section.

**Electric field at the streamer'shead**

One condition for propagation is to have a field at the streamer head greater than the minimum ionization field $E_i$. The expression for the electric field at the streamer head is given by the relation below:

$$E_{head} = \frac{2*U_{app}}{r_p \ln\left(4*\left(\frac{D-L_{axial}}{r_p}\right)\right)} \quad (24)$$

**Stoppinglength and averagevelocity**

Aftereach simulation, the stoppinglengthisdetermined by the followingrelationship:

$$L_f = \sum \Delta x_i. \quad (23)$$

Knowing the stoppinglength enables us to calculate the average streamer propagation velocityduring the simulation.

$$v_{moy} = \frac{L_f}{\sum \Delta t} \quad (24)$$

With$\sum \Delta t$ the total propagation time.

## Results and Discussion:-

In the first series of simulations, the inter-electrode distance is set to $D = 10$ mm,, and the radius of curvature is set to $R_p = 10{,}744\mu m$. The program receives the following input data: the relative permittivity ($\varepsilon_r$), the dielectric dissipation factor (tanδ), and the electric field at the head of the tip electrode at the inception of the streamers that led to breakdown, based on the experimental data for the dielectric being considered. The model input data, excluding D and $R_p$are presented in Table 1. For fresh oil, a low value of relative permittivity is desirable to minimize capacitance, while still maintaining acceptable chemical and heat transfer properties. Regarding the dielectric dissipation factor, mineral oil (MO) exhibits better quality compared to ester oils, as its dielectric strength, obtained experimentally, is higher. The results presented in Table 2 show Ui, the streamer inception voltage leading to breakdown. Ui will be referred to as the breakdown voltage, as it is nearly identical to the actual breakdown voltage. The average propagation velocity of the streamers is also presented.

**Table 1:-** Data of the input model [14].

| Data | | | |
|---|---|---|---|
| **Oil** | $\varepsilon_r$ | $\tan\delta$ | $E_l$(kV/mm) |
| **MO** | 2,2 | 0,001 | 768,6 |
| **NE** | 3,44 | 0,02 | 644,6 |
| **SE** | 3,1 | 0,02 | 632,8 |

Each dielectric is characterized by its permittivity and dielectric dissipation factor. Experiments have shown that the breakdown voltage characteristics depend on various experimental conditions, such as electrode geometry, the shape and duration of the applied voltage, the type and condition of the oil, and other factors. In the simulation, the dissipation factor is used as a measure of the oil's quality.

**Table 2:-** Comparison between experimental and simulation results.

| | Experimentalresults | | Simulation results | |
|---|---|---|---|---|
| Oil | **Ui(kV)** | **Velovity (km/s)** | **Ui (kV)** | **Velovity (km/s)** |
| MO | $33{,}9 \pm 0{,}6$ | $1{,}7 \pm 0{,}7$ | $33{,}6 \pm 0{,}4$ | $2{,}1 \pm 0{,}01$ |
| NE | $28{,}5 \pm 0{,}8$ | $1{,}5 \pm 0{,}6$ | $28{,}1 \pm 0{,}5$ | $1{,}6 \pm 0{,}01$ |
| SE | $28 \pm 1{,}4$ | $1{,}7 \pm 0{,}7$ | $27{,}7 \pm 0{,}4$ | $1{,}7 \pm 0{,}01$ |

Both experimental and simulation results yield streamer propagation velocities characteristic of the second mode. The relative error between the experimental breakdown voltages and those obtained from the simulations is calculated using the following relationship :

$$\varepsilon_{rel}\,x(\%) = 100 * \left(\frac{x_{estimated} - x_{measured}}{x_{estimated}}\right) \quad (25)$$

Table 3 presents the relative error. The simulation results in the case of SE are close to that of experimental one.

**Table 3:-** Relative error

| **Oil** | **Relative errorUi(%)** |
|---|---|
| **MO** | 1,13 |
| **NE** | 1,39 |
| **SE** | 0,81 |

Experimental results are compared with simulation results for two values of the radius of curvature, $R_p = 46\mu m$ and $R_p = 0{,}94\mu m$, with a fixed gap $D = 10$ mm. The relative error is found to be low when the radius of curvature is small. Table 4 presents the experimental and simulation results. Overall, the low relative error between the experimental and simulation results validates the simulation model.

**Table 4:-** Experimental and simulation results.

| **Rp=5,46µm** | **Oil** | **ExperimentalresultsUi(kV)** | **Simulation results Ui(kV)** | **Relative errorUi(%)** |
|---|---|---|---|---|
| | **MO** | $32 \pm 0{,}6$ | $31{,}6 \pm 0{,}4$ | 1,43 |
| | **NE** | $28{,}3 \pm 1{,}1$ | $28{,}2 \pm 0{,}1$ | 0,52 |
| | **SE** | $27{,}3 \pm 1{,}69$ | $26{,}9 \pm 0{,}5$ | 1,47 |
| **Rp=0,94 µm** | **Oil** | **ExperimentalresultsUi(kV)** | **Simulation results Ui(kV)** | **Relative errorUi(%)** |
| | **MO** | $34{,}6 \pm 0{,}4$ | $34{,}2 \pm 0{,}4$ | 1,22 |
| | **NE** | $27{,}3 \pm 1{,}4$ | $27{,}1 \pm 0{,}6$ | 0,63 |
| | **SE** | $27{,}9 \pm 1$ | $27{,}6 \pm 0{,}4$ | 0,93 |

## Conclusion:-

This study demonstrates the effectiveness of an electric circuit-based modeling tool for predicting the behavior of various dielectric liquids under electrical stress in power transformers. Breakdown voltage and partial discharge propagation speed were analyzed. A point-plane configuration with three pointed electrodes of varying radii of curvature was used while maintaining a fixed inter-electrode distance of 10 mm. The equivalent electrical circuit successfully estimates the breakdown voltage and propagation velocity of the single-arc discharge. Although the trajectory of the discharge is influenced by its random nature and the lack of experimental imagery, comparisons between the model and experimental trajectories were not made. The comparison primarily focuses on breakdown voltages, a critical parameter for evaluating the condition of dielectric liquids. The model shows strong correlation with experimental data, and the low relative error confirms the accuracy of this prediction tool. This makes it a valuable resource for optimizing the selection and management of liquid insulators in power transformers.

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