Modeling of Degradation Mechanism at the Oil-Pressboard Interface due to Surface Discharge

Presented by:
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INTRODUCTION

- **Surface discharge** is a type of partial discharge at the interface of oil-impregnated cellulose-based pressboard within power transformer.

- It is classified as a **serious fault condition** as it can occur under normal operating conditions. It can continue from minutes to months or even years, until the creeping conductive path or also known as tracking becomes an essential part of a powerful arc.

- The **tracking** appears in the form of **white and carbonised marks** on the pressboard surface from the discharge source towards the earth electrode.

- Generally, the formation of these degradation marks is believed due to **drying out** and **carbonization processes** during surface discharges at the oil-pressboard interface.
INTRODUCTION

**Figure 1:** Flashover failure along barrier board

**Figure 2:** Pressboard surface with white and carbonised marks due to surface discharge experiment
SIMULATION MODEL GEOMETRY

Figure 3. Model geometry for surface discharge simulation using the 2-D axial symmetry plane.
SIMULATION MODEL GEOMETRY

• There are **three media** which are:
  (a) bulk oil region
  (b) transition region
  (c) bulk oil/pressboard region.

• Transition region

  The **porous part** of the pressboard so that the streamer can be modelled to propagate through it.

• Bulk oil/pressboard region

  Assumed as a **perfect insulator**, i.e. this region is assigned zero conductivity \((\sigma = 0)\).

**Figure 4.** Physical model of the oil-pressboard interface [1].

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

• Charge transport continuity equation:

\[
\frac{\partial N_i}{\partial t} + \nabla \cdot \vec{F_i} = G_i - R_i
\]

✓ \( N_i \) is the density of each charge carrier (mol·m\(^{-3}\)), i.e. positive ion, \( N_p \) or negative ion, \( N_n \) or electron, \( N_e \)

✓ \( \vec{F_i} \) is the total flux density vector (mol·m\(^{-2}\)·s\(^{-1}\)) due to the movement of each charge carrier.

✓ \( G_i \) is the generation rate of the charge carriers.

✓ \( R_i \) is the recombination rate of the charge carriers.
GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- The **surface discharge streamer** is assumed to be dominated by **conduction currents**.

- The **total flux** only considers the **electro-migration of each charge carrier** due to the influence of the electric field and neglects any charge carrier movements due to diffusion process and fluid convection.

- The **total flux density vector** for each charge carrier:

  \[ \vec{F}_i = \pm N_i \mu_i \vec{E} \]

  - \( \vec{E} \) is the electric field vector (V·m\(^{-1}\))
  - \( \mu_i \) is the mobility (m\(^2\)·s\(^{-1}\)·V\(^{-1}\)) for each charge carrier.
  - The ‘\( \pm \)’ sign accounts for the direction of charge migration:
    - ‘+’ sign for positive ion
    - ‘−’ sign for negative polarity charge carriers (negative ion and electron).
GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Charge generation**: field dependent molecular ionisation (Zener Model [2]).

\[ G_i(|\vec{E}|) = \frac{qN_0a|\vec{E}|}{h} \exp\left( -\frac{\pi^2m^*a\Delta^2}{qh^2|\vec{E}|} \right) \]

- \( G_i(|\vec{E}|) \) is the charge generation rate (mol·m\(^{-3}\)·s\(^{-1}\)) for positive ion and electron
- \( q \) is the elementary charge (1.6022×10\(^{-19}\) C),
- \( N_0 \) is the density of the ionisable species (mol·m\(^{-3}\))
- \( a \) is the molecular separation distance (m),
- \( h \) is the Planck’s constant (6.626×10\(^{-34}\) J·s)
- \( m^* \) is the effective electron mass (kg)
- \( \Delta \) is the molecular ionisation energy (J).

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- Charge generation follows this relationship:

\[ G_i(|\vec{E}|) = G_p(|\vec{E}|) = G_e(|\vec{E}|) \]

- \( G_p(|\vec{E}|) \) and \( G_e(|\vec{E}|) \) are the generation rates \((\text{mol}\cdot\text{m}^{-3}\cdot\text{s}^{-1})\) for positive ions and electrons correspondingly.

A free electron and a positive ion are extracted from a neutral molecule.
GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Charge Recombination**:
  - Between +ve and −ve ions, $R_{pn}$
    \[ R_{pn} = N_p N_n K_{rpn} \]
  - Between +ve ions and electron, $R_{pe}$
    \[ R_{pe} = N_p N_e K_{rpe} \]
  - Electron attachment with neutral molecules, $EA$ to form negative ions and reduce the number of electrons.
    \[ EA = \frac{N_e}{\tau_a} \]

- $\tau_a$ is the time constant (s) for the electron attachment.
- $K_{rpn}$ and $K_{rpe}$ are the recombination coefficients (m³⋅s⁻¹⋅mol⁻¹) between positive and negative ions and between positive ions and electrons respectively determined using *Langevin’s equation*. 
GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- Langevin’s equation:

\[ K_{rpn} = \frac{q}{\varepsilon_0 \varepsilon_r (\mu_p + \mu_n) N_A} \]

- \( \mu_p \) and \( \mu_n \) are the mobility \( (\text{m}^2\cdot\text{s}^{-1}\cdot\text{V}^{-1}) \) for positive and negative ions
GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

• Poisson’s equation:

\[ \nabla \cdot (-\varepsilon_0 \varepsilon_r \vec{E}) = (N_p - N_n - N_e) q N_A \]

- \( \varepsilon_0 \) and \( \varepsilon_r \) are the permittivity of free space (8.854 \times 10^{-12} \text{ F} \cdot \text{m}^{-1})

- relative permittivity of the material respectively, \( N_p \), \( N_n \) and \( N_e \) are the density of positive ions, negative ions and electrons (mol·m⁻³) respectively.

- \( N_A \) is the Avogadro’s number (6.023 \times 10^{23} \text{ mol}^{-1})
GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Heat transfer** equation:

\[
\frac{\partial T}{\partial t} = \frac{1}{\rho C_P} \left( k_T \nabla^2 T + \vec{E} \cdot \left( \sum |\vec{F}_i| \right) q N_A \right)
\]

- \( \rho \) is the mass density (kg·m\(^{-3}\))
- \( C_P \) is the specific heat capacity (J·kg\(^{-1}\)·K\(^{-1}\))
- \( k_T \) is the thermal conductivity (W·m\(^{-1}\)·K\(^{-1}\)) of the material
- \( T \) is the temperature (K)

The heat conduction as a result of thermal diffusivity.

The heat source from the electrical power dissipation as a result of conduction current heating from the movement of charge carriers during the partial discharge under the influence of local electric field.
GOVERNING EQUATIONS IN BULK OIL/PRESSBOARD REGION

- With the assumption that the bulk oil/pressboard region is a perfect insulator,
  - The charge transport equation is not applicable in the modelling of this region.

\[ \nabla \cdot (\varepsilon_0 \varepsilon_r \vec{E}) = 0 \]

\[ \frac{\partial T}{\partial t} = \frac{1}{\rho C_p} (k_T \nabla^2 T) \]
BOUNDARY CONDITIONS

Figure 5. Boundary numbers for the model geometry
## BOUNDARY CONDITIONS

**Table 1:** Boundary conditions for the model

<table>
<thead>
<tr>
<th>Governing Equation</th>
<th>Charge Transport</th>
<th>Poisson’s</th>
<th>Heat Conduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary 1</td>
<td>Axial symmetry $r = 0$</td>
<td>Axial symmetry $r = 0$</td>
<td>Axial symmetry $r = 0$</td>
</tr>
<tr>
<td>Boundary 2</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boundary 3</td>
<td>$\hat{n} \cdot (-D_i \nabla N_i) = 0$</td>
<td>$V = V_{app}$</td>
<td></td>
</tr>
<tr>
<td>Boundary 4</td>
<td>$\hat{n} \cdot \overrightarrow{F_i} = 0$</td>
<td>$\hat{n} \cdot \overrightarrow{D} = 0$</td>
<td>$-\hat{n} \cdot (-k_T \nabla T) = 0$</td>
</tr>
<tr>
<td>Boundary 5</td>
<td>$\hat{n} \cdot (\overrightarrow{F_1} - \overrightarrow{F_2}) = 0$</td>
<td>$\hat{n} \cdot (\overrightarrow{D_1} - \overrightarrow{D_2}) = 0$</td>
<td>$\hat{n} \cdot (\overrightarrow{Q_1} - \overrightarrow{Q_2}) = 0$</td>
</tr>
<tr>
<td>Boundary 6</td>
<td>$\hat{n} \cdot (\overrightarrow{F_1} - \overrightarrow{F_2}) = F_0$</td>
<td>$\hat{n} \cdot (\overrightarrow{D_1} - \overrightarrow{D_2}) = N_s q N_A$</td>
<td>$\hat{n} \cdot (\overrightarrow{Q_1} - \overrightarrow{Q_2}) = Q_s$</td>
</tr>
<tr>
<td>Boundary 7</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boundary 8</td>
<td>$\hat{n} \cdot \overrightarrow{F_i} = 0$</td>
<td>$\hat{n} \cdot \overrightarrow{D} = 0$</td>
<td>$-\hat{n} \cdot (-k_T \nabla T) = 0$</td>
</tr>
<tr>
<td>Boundary 9</td>
<td>$\hat{n} \cdot (-D_i \nabla N_i) = 0$</td>
<td>$V = 0$</td>
<td></td>
</tr>
</tbody>
</table>
RESULTS AND ANALYSIS

• The hottest spot at a particular time appears at the tip of streamer along the pressboard surface:

  About 12.3 μm apart from the needle tip.

• The results indicate that streamer branch on the pressboard surface causes significant temperature increase at a spot that is vicinity of needle tip.

**Figure 6.** Temperature distribution along boundary 5
RESULTS AND ANALYSIS

• Temperature increased beyond 500 K - temperature level that may cause carbonisation of cellulose through dehydration and pyrolysis processes is less than 500 K [5].

• Hence, concentration of high temperature over a long period of surface discharges, would enhance the carbonisation of cellulose pressboard particularly at the vicinity of needle tip.

Figure 7. Variation of temperature at the hottest spot.

RESULTS AND ANALYSIS

- The significant growth of energy dissipation (Figure 8) causes the temperature to increase substantially (Figure 7).
- The moment when the energy increases steadily, the temperature starts to decrease gradually.
- This gradual decrease is caused by the thermal dispersion in the system.

Figure 8. Cumulative energy density
CONCLUSION

• The results support the hypotheses about the localised nature observed in the experiment of surface discharge at the oil-pressboard interface.

• These include the development of white marks on the pressboard surface and the formation of carbonised marks that predominantly appear on the pressboard surface at the vicinity of needle tip.

• The simulation results have associated both degradation marks on pressboard surface with high energy of long periods of partial discharge event that leads to thermal degradation at the oil-pressboard interface.
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THANK YOU