Model created in COMSOL Multiphysics 6.4

AC Breakdown Voltage of Parallel Electrodes in Air

Introduction

This simulation model focuses on electrical breakdown in air at atmospheric pressure, where streamer breakdown is the dominant mechanism. Unlike glow discharges, streamer discharges are unstable and marked by a rapid rise in discharge current due to electron impact ionization (see Fig. 7.1 in Ref. 1).

The model computes the AC breakdown voltage between parallel electrodes in air using a charge transport formulation. While implemented in one dimension for simplicity, the approach can be generalized to other gases and extended to higher dimensions.

Model Definition

The Electric Discharge interface is used to compute the discharge current. The built-in charge transport model is used:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (\mathbf{w}_i n_i - D_i \nabla n_i) = R_i$$

where

$i = \mathrm{e, p, n}$

$z_{\mathrm{e, p, n}} = -1, +1, -1$

$\mathbf{w}_i = z_i \mu_i \mathbf{E}$

$R_{\mathrm{e}} = \alpha|\mathbf{w}_{\mathrm{e}}|n_{\mathrm{e}} - \eta|\mathbf{w}_{\mathrm{e}}|n_{\mathrm{e}} - \beta_{\mathrm{ep}} n_{\mathrm{e}} n_{\mathrm{p}}$

$R_{\mathrm{p}} = \alpha|\mathbf{w}_{\mathrm{e}}|n_{\mathrm{e}} - \beta_{\mathrm{ep}} n_{\mathrm{e}} n_{\mathrm{p}} - \beta_{\mathrm{pn}} n_{\mathrm{p}} n_{\mathrm{n}}$

$R_{\mathrm{n}} = \eta|\mathbf{w}_{\mathrm{e}}|n_{\mathrm{e}} - \beta_{\mathrm{pn}} n_{\mathrm{p}} n_{\mathrm{n}}$

where

- e, p, n denote electrons, positive ions, and negative ions
- n_i is the number density of the charge carrier (SI unit: $1/\mathrm{m}^3$)
- $\mathbf{E}$ is the electric field (SI unit: V/m)
- z_i denotes the carrier charge (SI unit: 1)
- μ_i denotes the carrier mobility (SI unit: $\mathrm{m}^2/(\mathrm{V{\cdot}s})$)
- $\mathbf{w}_i$ is the drift velocity in the electric field (SI unit: m/s)
- D_i is the diffusion coefficient (SI unit: m^2/s)
- R_i is the reaction rate (SI unit: $1/(\mathrm{m}^3{\cdot}\mathrm{s})$)
- α is the ionization coefficient (SI unit: 1/m)
- η is the attachment coefficient (SI unit: 1/m)
- β_{ep} is the electron–ion recombination coefficient (SI unit: m^3/s)
- β_{pn} is the ion–ion recombination coefficient (SI unit: m^3/s)

The above transport equations are fully coupled with Poisson's equation through the electric field and the space charge:

$$\nabla \cdot (\varepsilon_r \varepsilon_0 \mathbf{E}) = \rho$$

$$\rho = e \sum_i z_i n_i$$

where e is the elementary charge.

Breakdown is detected as a sharp current rise triggered by electron avalanches. To capture this process, the model conducts a transient study with an AC voltage whose amplitude is gradually increased after several cycles. The simulation stops once the conductive discharge current surpasses a specified threshold.

Results and Discussion

Figure 1 shows the discharge current and applied voltage as a function of AC periods for three frequencies. The results indicate that the breakdown voltage are largely independent of frequency and remains close to the DC value, provided the frequency does not enter the RF range.

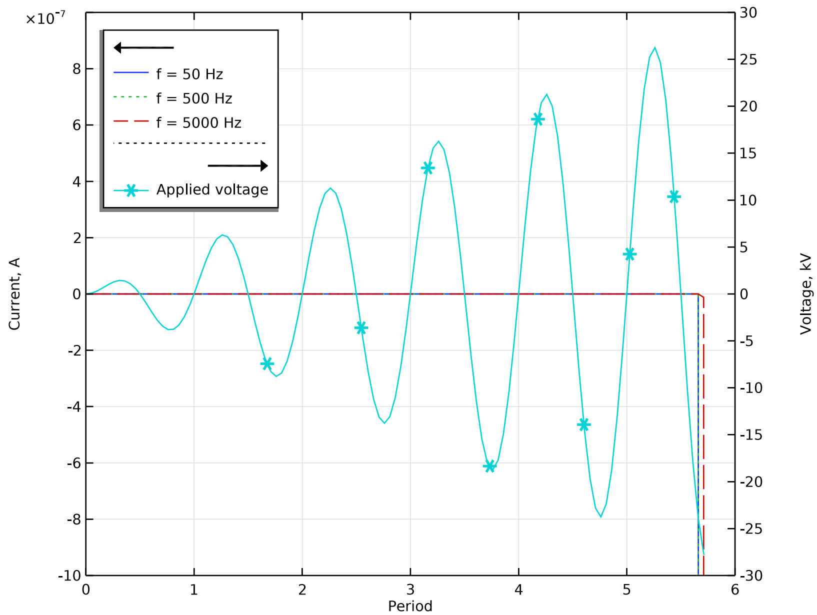

Figure 1: The discharge current as a function of AC periods for three frequencies.

Reference

1. Y.P. Raizer, *Gas Discharges Physics*, Springer, 1997.

Application Library path: `Electric_Discharge_Module/Electrical_Breakdown/breakdown_voltage_ac`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **1D**.

2 In the **Select Physics** tree, select **Electric Discharge** > **Electric Discharge (edis)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Time Dependent with Initialization**.

6 Click **Done**.

GEOMETRY 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **cm**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
V0	50[kV]	50000 V	Maximum voltage
d	1[cm]	0.01 m	Gap length

Name	Expression	Value	Description
f	50[Hz]	50 Hz	Frequency
t	1/f/100	2E-4 s	Time
Vapp	V0*(t*f/10)*sin(2*pi*f*t)	3.1395 V	Applied voltage

GEOMETRY 1

Interval 1 (i1)

1. In the **Model Builder** window, expand the **Component 1 (comp1)** > **Geometry 1** node.
2. Right-click **Geometry 1** and choose **Interval**.
3. In the **Settings** window for **Interval**, locate the **Interval** section.
4. In the table, enter the following settings:

Coordinates (cm)
0
d

5. Click **Build All Objects**.

ADD MATERIAL FROM LIBRARY

In the **Home** toolbar, click **Windows** and choose **Add Material from Library**.

ADD MATERIAL

1. Go to the **Add Material** window.
2. In the tree, select **Electric Discharge** > **Gases** > **Air** > **Air [Morrow and Lowke, 1997]**.
3. Click the **Add to Component** button in the window toolbar.

ELECTRIC DISCHARGE (EDIS)

Electrode 1

1. In the **Physics** toolbar, click **Attributes** and choose **Electrode**.
2. Select Boundary 1 only.

Gas 1

In the **Model Builder** window, click **Gas 1**.

Electrode 2

1. In the **Physics** toolbar, click **Attributes** and choose **Electrode**.

2 Select Boundary 2 only.

3 In the **Settings** window for **Electrode**, locate the **Terminal** section.

4 In the V_0 text field, type `Vapp`.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the list, choose **User-controlled mesh**.

Distribution 1

1 In the **Model Builder** window, right-click **Edge 1** and choose **Distribution**.

2 In the **Settings** window for **Distribution**, locate the **Distribution** section.

3 From the **Distribution type** list, choose **Predefined**.

4 In the **Number of elements** text field, type `200`.

5 In the **Element ratio** text field, type `5`.

6 Select the **Symmetric distribution** checkbox.

7 Click **Build All**.

STUDY 1

Step 2: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 2: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `range(1/f/100,1/f/20,10/f)`.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
f (Frequency)	50 500 5000	Hz

Next, keep track of the conduction current. Note that the displacement current is not of interest for evaluating AC breakdown.

DEFINITIONS

Global Variable Probe 1 (var1)

1 In the **Definitions** toolbar, click **Probes** and choose **Global Variable Probe**.

2 In the **Settings** window for **Global Variable Probe**, type `Ic` in the **Variable name** text field.

3 Locate the **Expression** section. In the **Expression** text field, type `comp1.edis.gas1.ece2.Ic`.

STUDY 1

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

Add a stop condition to terminate the simulation once a streamer breakdown takes place.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

3 In the **Model Builder** window, expand the **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1** node.

4 Right-click **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1** and choose **Stop Condition**.

5 In the **Settings** window for **Stop Condition**, locate the **Stop Expressions** section.

6 Click **Add**.

7 In the table, enter the following settings:

Stop expression	Stop if	Active	Description
`abs(comp1.Ic)>1e-5[A]`	True (>=1)	√	`Stop expression 1`

8 Locate the **Output at Stop** section. From the **Add solution** list, choose **Step after stop**.

9 In the **Model Builder** window, click **Study 1**.

10 In the **Settings** window for **Study**, locate the **Study Settings** section.

11 Clear the **Generate default plots** checkbox.

12 In the **Study** toolbar, click **Compute**.

RESULTS

Discharge Current

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Discharge Current` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol3)**.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** checkbox. In the associated text field, type `Period`.

7 Select the **Two y-axes** checkbox.

8 Select the **y-axis label** checkbox. In the associated text field, type `Current, A`.

9 Select the **Secondary y-axis label** checkbox. In the associated text field, type `Voltage, kV`.

Global 1

1 Right-click **Discharge Current** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`Ic`	`A`	`Global Variable Probe 1`

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type `t*f`.

6 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Cycle**.

7 Click to expand the **Legends** section. Find the **Include** subsection. Clear the **Solution** checkbox.

8 Clear the **Description** checkbox.

9 Find the **Prefix and suffix** subsection. In the **Prefix** text field, type `f = eval(f,Hz,4) Hz`.

10 In the **Discharge Current** toolbar, click **Plot**.

Global 2

1 In the **Model Builder** window, right-click **Discharge Current** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`Vapp`	`V`	`Applied voltage`

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `t*f`.

7 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`Vapp`	`kV`	`Applied voltage`

8 Locate the **y-Axis** section. Select the **Plot on secondary y-axis** checkbox.

9 Locate the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

10 From the **Positioning** list, choose **Interpolated**.

Discharge Current

1 In the **Model Builder** window, click **Discharge Current**.

2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.

3 Select the **Manual axis limits** checkbox.

4 In the **x minimum** text field, type `0`.

5 In the **x maximum** text field, type `6`.

6 In the **y minimum** text field, type `-1e-6`.

7 In the **y maximum** text field, type `1e-6`.

8 In the **Secondary y minimum** text field, type `-30`.

9 In the **Secondary y maximum** text field, type `30`.

10 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

11 In the **Discharge Current** toolbar, click **Plot**.