Model created in COMSOL Multiphysics 6.4

Current-Voltage Characteristics of a Wire-to-Wire Corona Discharge

Introduction

Computing current-voltage (I-V) characteristics is crucial for understanding the behavior of corona discharges, particularly in applications involving high-voltage electrical systems. The I-V curve of a corona discharge often resembles that of a forward-biased diode, where the discharge current remains minimal until a certain threshold voltage is reached, beyond which the current increases significantly. In this specific case, the threshold is at 5 kV, beyond which a sharp rise in current is observed, indicative of the onset of a strong corona discharge.

This numerical model leverages a continuation solver to efficiently compute the I-V characteristics of a corona discharge generated by a wire-to-wire configuration. The continuation solver allows for stable and accurate tracing of the solution path across varying voltage levels, making it an effective tool for modeling such nonlinear electrical phenomena. The model is designed with flexibility in mind, offering a robust framework that can be easily adapted to study other discharge configurations and types, facilitating a wide range of applications in high-voltage engineering and plasma physics.

Model Definition

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

$$
\begin{aligned}
&\frac{\partial n_i}{\partial t} + \nabla \cdot (\mathbf{w}_i n_i - D_i \nabla n_i) = R_i \\
&\text{where} \\
&i = \mathrm{e, p, n} \\
&z_{\mathrm{e,\,p,\,n}} = -1, +1, -1 \\
&\mathbf{w}_i = z_i \mu_i \mathbf{E} \\
&R_\mathrm{e} = \alpha|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \eta|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \beta_\mathrm{ep} n_\mathrm{e} n_\mathrm{p} \\
&R_\mathrm{p} = \alpha|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \beta_\mathrm{ep} n_\mathrm{e} n_\mathrm{p} - \beta_\mathrm{pn} n_\mathrm{p} n_\mathrm{n} \\
&R_\mathrm{n} = \eta|\mathbf{w}_\mathrm{e}|n_\mathrm{e} - \beta_\mathrm{pn} n_\mathrm{p} n_\mathrm{n}
\end{aligned}
$$

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.

To compute the lumped properties of the corona discharge, this model neglects photoionization within the domain and the effects of secondary electron emission at the cathode. Importantly, the model does not rely on any ad-hoc assumptions to simplify the ionization layer, ensuring it remains self-consistent and applicable to a wide range of discharge configurations.

Results and Discussion

Figure 1 shows current-voltage (I-V) characteristics. As can be seen, the discharge current increases significantly after 5 kV. Figure 2 plots the spatial distribution of space charge density under an applied voltage of 10 kV. As depicted, the majority of the space charge, predominantly composed of positive ions, is concentrated to the left of the first wire. This phenomenon occurs because the generation of positive charges between the two wires enhances the electric field near the left edge of the first wire, leading to increased charge generation in that region. This behavior results from the interplay between the Laplace field and the space charge effect. When the applied voltage is increased to 15 kV, the primary space charge distribution shifts to the region between the wires. Further increasing the voltage leads to convergence difficulties in the model, indicating the onset of streamer discharge breakdown. Under these conditions, the maximum electron density can surpass 10^8 cm^{-3}, which serves as a basis for evaluating the breakdown voltage.

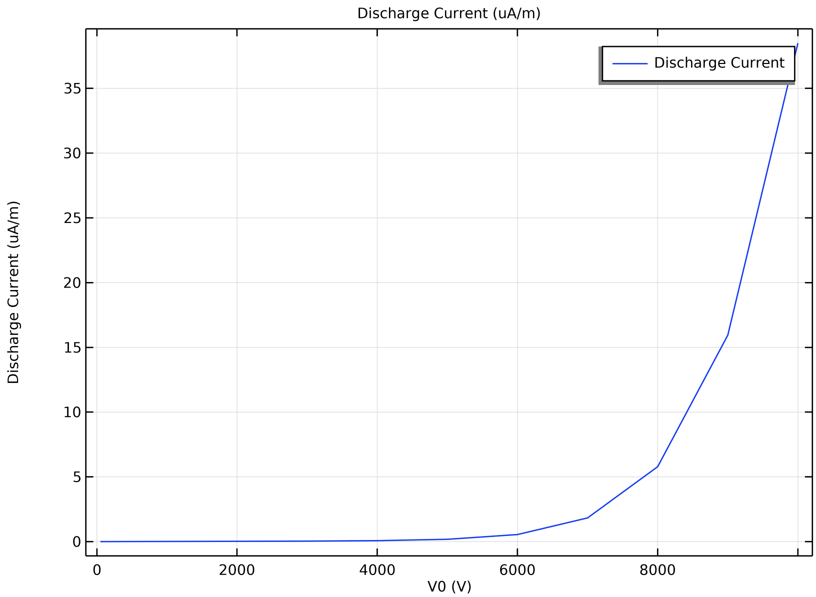


Figure 1: The current-voltage characteristics of the wire-to-wire corona discharge.

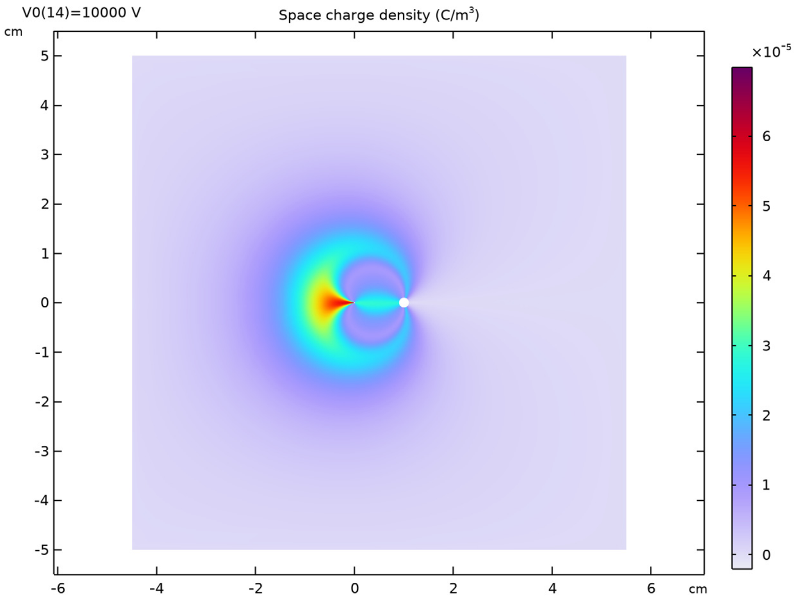


Figure 2: The distribution of space charge density when the application voltage is 10 kV.

Application Library path: `Electric_Discharge_Module/Corona_Discharges/corona_discharge_iv_curve`

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 **2D**.

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 > Stationary with Initialization**.

6 Click **Done**.

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	10[kV]	10000 V	Applied voltage
d	10[cm]	0.1 m	Out-of-plane thickness

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**.

Circle 1 (c1)

1 In the **Geometry** toolbar, click **Circle**.

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type 0.01.

Circle 2 (c2)

1 In the **Geometry** toolbar, click **Circle**.

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type 0.1.

4 Click **Build All Objects**.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.

6 Locate the **Position** section. In the **x** text field, type 1.

Rectangle 1 (r1)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type 3.

4 In the **Height** text field, type 3.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

6 In the **x** text field, type 0.5.

Rectangle 2 (r2)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type 10.

4 In the **Height** text field, type 10.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

6 In the **x** text field, type 0.5.

Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the objects **r1** and **r2** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the objects **c1** and **c2** only.

6 Click **Build All Objects**.

ELECTRIC DISCHARGE (EDIS)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electric Discharge (edis)**.

2 In the **Settings** window for **Electric Discharge**, locate the **Physical Model** section.

3 In the d_z text field, type d.

Gas 1

In the **Model Builder** window, under **Component 1 (comp1)** > **Electric Discharge (edis)** click **Gas 1**.

Electrode 1

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

2 Select Boundaries 9–12 only.

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

4 In the V_0 text field, type V0.

5 Locate the **Charge Transport** section. From the **Boundary condition for positive ions** list, choose **Number density**.

Gas 1

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

Electrode 2

1 In the **Physics** toolbar, click **Attributes** and choose **Electrode**.
2 Select Boundaries 13–16 only.
3 In the **Settings** window for **Electrode**, locate the **Charge Transport** section.
4 From the **Boundary condition for electrons** list, choose **Number density**.
5 From the **Boundary condition for negative ions** list, choose **Number density**.

ADD MATERIAL

1 In the **Materials** toolbar, click **Add Material** to open the **Add Material** window.
2 Go to the **Add Material** window.
3 In the tree, select **Electric Discharge** > **Gases** > **Air** > **Air [Kang et al. 2003]**.
4 Right-click and choose **Add to Component 1 (comp1)**.
5 In the **Materials** toolbar, click **Add Material** to close the **Add Material** window.

MESH 1

1 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.
2 From the list, choose **User-controlled mesh**.

Distribution 1

1 In the **Model Builder** window, right-click **Free Triangular 1** and choose **Distribution**.
2 Click the **Select Box** button in the **Graphics** toolbar.
3 Select Boundaries 9–12 only.
4 In the **Settings** window for **Distribution**, locate the **Distribution** section.
5 In the **Number of elements** text field, type 8.

Size 1

1 Right-click **Free Triangular 1** and choose **Size**.
2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3 From the **Geometric entity level** list, choose **Domain**.
4 Select Domain 2 only.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** checkbox. In the associated text field, type `0.04`.

Size 2

1 Right-click **Free Triangular 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 Select Domain 1 only.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** checkbox. In the associated text field, type `0.2`.

Boundary Layers 1

In the **Mesh** toolbar, click **Boundary Layers**.

Boundary Layer Properties

1 Click the **Select Box** button in the **Graphics** toolbar.

2 In the **Model Builder** window, click **Boundary Layer Properties**.

3 Select Boundaries 9–16 only.

4 In the **Settings** window for **Boundary Layer Properties**, click **Build All**.

STUDY 1

Step 1: Electrostatics Initialization

1 In the **Model Builder** window, under **Study 1** click **Step 1: Electrostatics Initialization**.

2 In the **Settings** window for **Electrostatics Initialization**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** checkbox.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V0 (Applied voltage)	50	V

Step 2: Stationary

1 In the **Model Builder** window, click **Step 2: Stationary**.

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** checkbox.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
V0 (Applied voltage)	`50 100 200 500 range(1000,1000,10000)`	V

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

RESULTS

Space Charge Density

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

2 Clear the **Plot dataset edges** checkbox.

3 In the **Label** text field, type `Space Charge Density`.

Surface 1

1 In the **Model Builder** window, expand the **Space Charge Density** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.

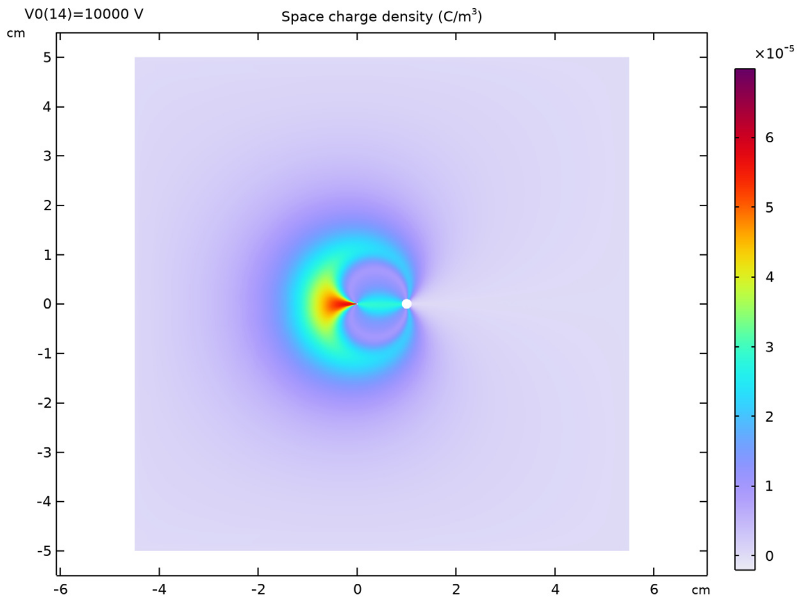
3 From the **Color table** list, choose **Prism**.

Space Charge Density

1 In the **Model Builder** window, click **Space Charge Density**.

2 In the **Space Charge Density** toolbar, click **Plot**.

3 Click the **Zoom Extents** button in the **Graphics** toolbar.



IV Curve

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

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

Global 1

1 Right-click **IV Curve** 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
`edis.I0_0/d`	`uA/m`	`Discharge Current`

4 In the **IV Curve** toolbar, click **Plot**.