1. Streamer criterion

Introduction

This chapter deals with V12.2 new features regarding the new electric applications tool called « Streamer criterion ».

Contents

This chapter contains the following topics :

1.1. Dielectric breakdown and Streamer: physical principle

Dielectric breakdown

A dielectric breakdown can occur in a dielectric gas when the applied potential difference is higher than the breakdown voltage. It is illustrated by the apparition of an electric arc in the dielectric area which can destroy definitively the device.
Several applications are concerned, for example: Gas Insulated Switchgears, Air insulated switchgears, cables in ambient air, bushings, capacitors banks, etc.

The complete simulation of every physical processes yielding to an electrical discharge development is highly complex (Boltzmann equations, drift-diffusion models…), and not applicable yet to determine the breakdown voltage value in real industrial devices, due to their complexity and calculation time.

The streamer criterion do not intend to be a complete simulation of the breakdown process in gases, it is only a criteria that is applied on the field obtained by an electrostatic simulation (i.e. the background field, before any discharge phenomena occurrence)*.
This criterion gives an estimation of the threshold voltage that can trigger the electronic avalanche process leading to an electrical breakdown in the gas. This voltage is called "Streamer inception voltage".

*Reference : A. Pedersen, T. Christen, A. Blaszczyk, H. Boehme, 2009, "Streamer inception and propagation models for designing air insulated power devices", Proceedings IEE Conference on electrical insulation and dielectric phenomena

Streamer

The streamer is a phenomenon that occurs just before the full breakdown. Ionized and conductive canals appear and spread in the dielectric gas. Initially, a first electron is accelerated by the electric field, and enters in collision with the surrounding gas molecules and atoms, with enough energy to ionize them. New electrons are generated, and then they are accelerated again by the field, creating also new ionized canals. This can be seen as a chain reaction: the electronic avalanche process.

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Streamer criterion : mathematical model

The principle of the streamer criterion is based on the integration of the effective ionization coefficient (alpha_eff) of the considered gas, along the most probable path for the breakdown, between the two electrical contacts. These contacts are energized at different electrical potentials (typically one contact is energized at high voltage, the other one is earthed).

The effective ionization coefficient αeff is defined by a mathematical formula obtained by fitting experimental curves (in general, polynomial function). Therefore, the curves are valid only in the experience conditions and in a defined field range chosen for the fitting. In the literature, several mathematical formula exist for a same gas. User has to choose the formula adapted to his device.

The criterion is given by the formula:

$$\int_{x} \alpha_{eff}\, dx = K ,$$

Where:
αeff it the effective ionization coefficient of the gas
x is the coordinate on the critical path
K is the ionization content. A common value of K is 18.

Streamer criterion : Path importance

The most probable path definition has a huge influence on the criterion application, and must be determined with care.

Generally, the path starts from high field area on one of the contacts, and is following field line from this point. Alternative most probable paths exist also.

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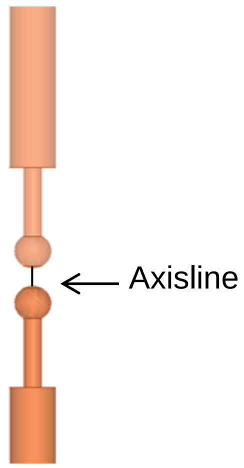
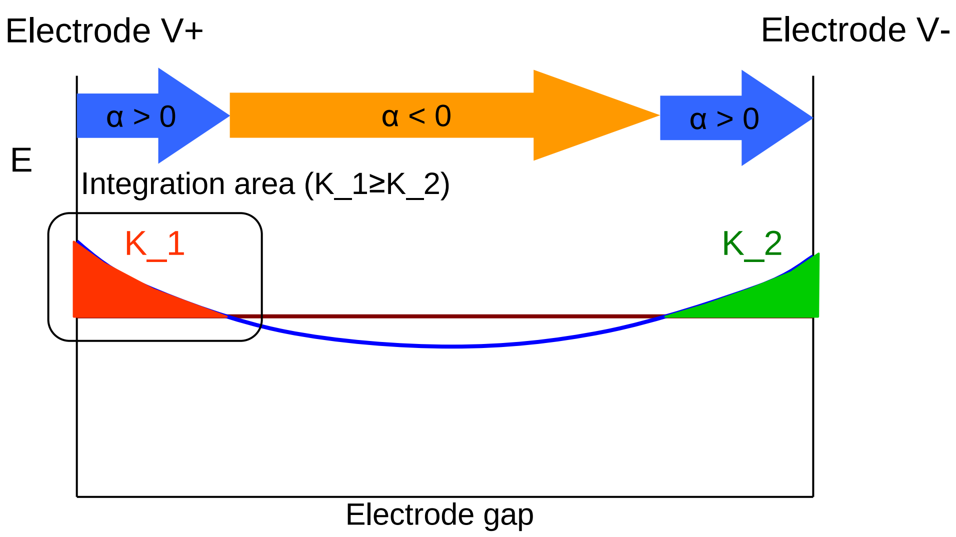
Streamer criterion : Electric field distribution

There are two configurations for the integral computation depending on electric field distribution in the dielectric media:

- Homogenous electric field: The computation of K is done by integrating α_{eff} on all the path
- Inhomogeneous electric field descreasing below a threshold value corresponding to α_{eff} equal to zero (2.6kV/mm for the air): The computation of K is done by integrating α_{eff} until α_{eff} is equal to 0. In some cases, the integration value of the positive α_{eff} near the high potential conductor is lower than the integration of the positive α_{eff} near the low potential conductor. In that case, the second integral is considered and the Streamer has a higher probability to start from the lower potential conductor.

<u>Inhomogeneous electric field case:</u>





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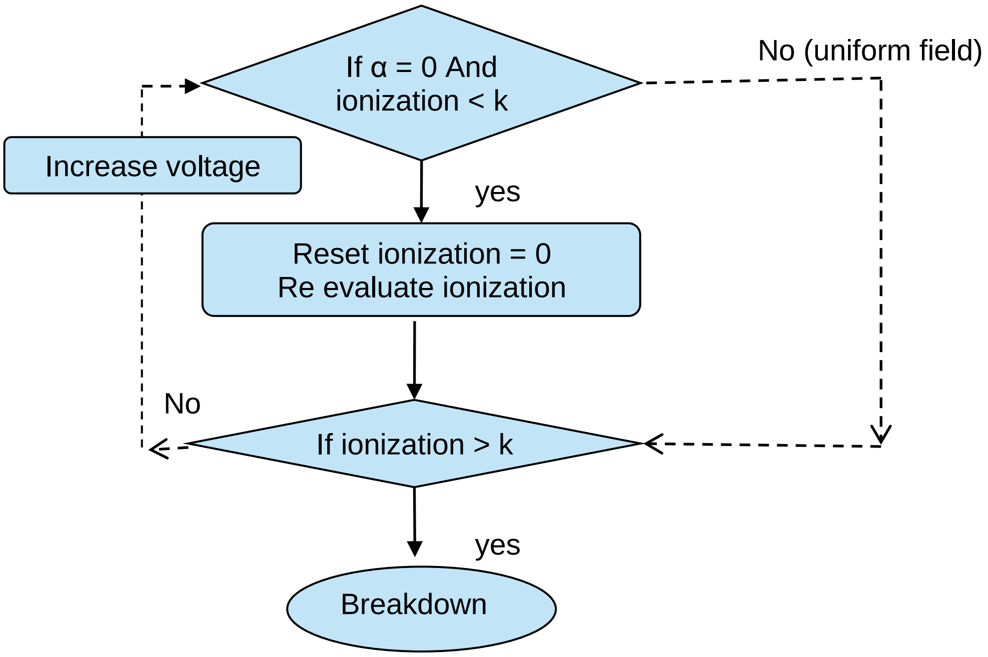
Streamer criterion : Dichotomy

As the law between the electric field and the electric potential is linear, a dichotomy is applied on the electric field until K is equal to the threshold. It allows finding the Streamer inception voltage on the considered path.



Streamer criterion : limits

The streamer criteria gives only an estimation of the voltage needed to initiate the electronic avalanche process in gases (Streamer inception voltage). It can be used to estimate the breakdown voltage in DC or AC (almost static) cases, but the results are not fully guaranteed: discharges physical processes not fully simulated, different ionization curves available from different authors valid in certain physical conditions, some details not included in the simulation as for example roughness of the contacts, and the path definition has a very high influence on the results.
It is also well known that the streamer criteria is not directly applicable for impulse voltage tests (typically Lightning impulse tests), where a correction must be applied on the results, based on the user experience.

Users of this new Flux feature are invited to use the criteria results as an indicative tool, useful to optimize dielectric geometries, but keeping in mind that the obtained results must be compared with real experimental data for the final validation.

References

For more information on physical aspects, especially for the mathematical models used in Flux (Air and SF6), please read the following references :
W.S. Zaengl and K. Petcharaks, “Application of Streamer breakdown criterion for inhomogeneous fields in dry air and SF6”, Swiss Federal Institute of Technology (Zürich)

1.2. « Streamer criterion » tool in Flux

Introduction

This section deals with the computing tool "Streamer criterion". It describes the computing method, the using method, and some best practices.

Content

This section contains the following topics:

- General principle and using conditions
- Gas model
- Global and local computation
- Computing method
- Mesh advices
- Postprocessing results
- Using advices and remarks

1.2.1. General principle and using conditions of the tool

General

As said before, in Flux, the dielectric breakdown study is based on Streamers inception criterion.
This criterion does not give precise information about arc path and breakdown voltage.
The aim is rather to identify the Streamer starting area and a "Streamer inception voltage".

Concerned dielectric medium

The "Streamer criterion" tool allows studying Streamers **in gas medium**. In fact, the gas has a lower breakdown voltage than liquids and solids.

Access in Flux

The tool is available in Flux **electrostatic application** (2D plane, 2D axisymmetric and 3D), in postprocessing context.
It is available through the menu "Computation".

General principle

Each gas has a coefficient called α_{eff} defined by a Streamer mathematical model depending on electric field and pressure. This model is determined by fitting an experimental curve. Consequently, a model will be optimal for some configurations (of electric field, geometry, pressure, temperature, etc.) but can not be universal.

<u>Air formula used in Flux:</u>
$\alpha_{eff} = P * (1.605 * Er^2 - 6.951 * Er + 7.2371)$
With :
$Er = Mod(E) / P$
Er: reduced electric field, E: electric field in kV/mm, P: pressure in bar

K is computed by integrating α_{eff} on a path (Streamer path), and its value is compared to the threshold value. If the value is higher than the threshold, then the Streamer has a high probability to start.

As the law between the electric field and the electric potential is linear, a dichotomy is applied on the electric field until K is equal to the threshold. It allows finding the Streamer inception voltage on the considered path.

Streamer path

Streamers paths are not predictable by modelization.
The paths used in the modeling are:
- Previously identified with experiments
- Or approximated by physical quantities evolution laws. In Flux, the electric field lines are considered.

1.2.2. Gas models

Introduction

In the "Streamer criterion" tool two predefined gas models exist:
- Air model
- SF6 gas model

The proposed models are simple models and they are not optimal for complex cases.
However, the user can use his models which are suited to the studied devices, thanks to the Flux user model.

User defined model

The user model proposes a formula which corresponds by default to the air predefined model.

It contains two fields to complete:
- The expression of the reduced electric field Er (scalar):

With $Er = Mod(E)/P$; Mod(E) is the electric field module (the value written by default defines it in kV/mm) and P is the pressure in bar (by default equal to 1 bar). It is important to enter Er in the desired unit in this field, because it is the unit which will be used in the formula following it, and K is depending on this formula. For example :
  - To choose V/m/bar : define Er = Mod(E)/1
  - To choose kV/mm/bar : define Er = Mod(E)/1E6/1
  - To choose kV/cm/torr : define Er = (Mod(E)/1E6)*750.062

- The formula of α_{eff} (scalar):

By default : $P*(1.605*Er^2 - 6.951*Er + 7.2371)*Valid(Er,2.0,)$
With P=1 bar by default
The formula must depend on "Er" (defined above).
The expression $*Valid(Er,2.0,)$ allows considering α_{eff} as equal to zero for all Er values under 2kV/mm/bar (for the air). In fact, positive α_{eff} for those low E values should not be taken into account in the integration (for negative α_{eff} values, it is automatically set to zero).

Air model

The air model formula is presented in the previous bloc.
User has only to enter the pressure value.

SF6 Model

The SF6 model formula is:
- For Er<12.36kV/mm/bar :

$\alpha_{eff} = 27.9*P*(Er - 8.9246)$
- For Er>12.36kV/mm/bar :

$\alpha_{eff} = 22.3595*P*(Er - 8.0579)$

As for the air, user has only the pressure to enter.

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New model

If user would like to enter a new formula, for the air or SF6 or other gas, a free online tool is available. From the gas chemical composition, it is possible to extract the curve α_{eff} =f(E). Then, user can fit the data curve with a mathematical formula (on Excel).
The steps to identify a new mathematical model are presented in the table below:

Step	Action
1	Open the following tool link: http://fr.lxcat.net/data/set_databases.php
2	Choose one / several databases and click on "next". For example: click on " – " to remove all, then select "Phelps database"
3	Select the gas chemical components
4	Confirm the database choice by clicking on "next"
5	Define the following data: • E/N range in Td *(at 1.013 bar and 293.15K, to convert E from kV/mm to Td, divide by 2.45e-2)* • Gas temperature • The exported points number • The normalized fraction of each gas chemical component
6	Click on "Run calculations"
7	Click on "Swarm parameters in text file"
8	• Copy the txt file content from "SWARM PARAMETERS" to "PROCESSES AND REACTION RATES" • Paste in an Excel file and "convert" the data to separate the columns
9	• Create a new column for E in kV/mm *(at 1.013 bar and 293.15K, convert E/N from Td to kV/mm by multiplying by 2.45e-2)* • Create a new column for the α_{eff} coefficient. The formula to obtain it is: $\alpha_{eff} = (alpha / N - eta / N) * N / 1000$ With N=2.44e25
10	Plot α_{eff} depending on E in kV/mm
11	Fit the previous curve with a mathematical model (polynomial,…)

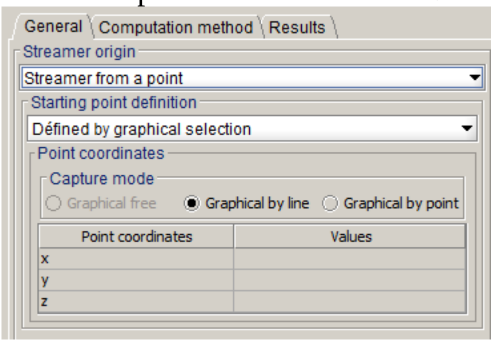
Reference : http://nl.lxcat.net/contributors/
The databases (Phelps mentioned here) and the online tool are indicated only as a reference to find its own ionization formula. Using the results and those values postprocessing is the responsibility of the user.

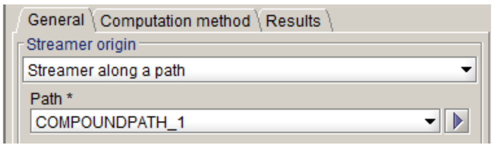
1.2.3. Global and local computation

Local computation

The local computation involves computing the Streamer inception voltage on a path going from a point of the high potential conductor, to arrive at a point of the low potential conductor.
Two path types exist:
- Defined by the electric field line going from the selected starting point
- Defined by a spatial path

Local computation choice in Flux:



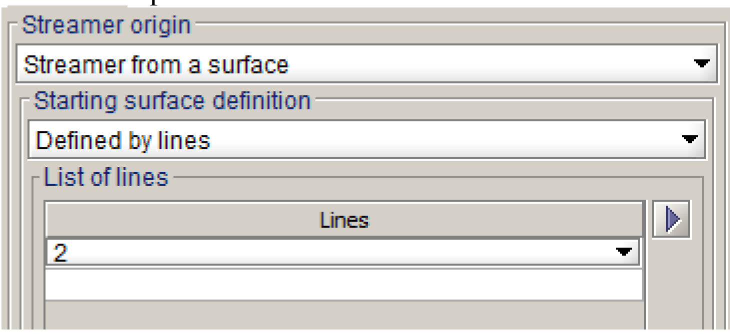


Global computation

For the global computation, user chooses a starting surface and the results give the path having the highest probability to breakdown (path with the highest K value), with the associated Streamer inception voltage value.

In 2D, a starting surface can be defined by :
- Lines
- Linear regions
- Face regions boundaries

Global computation choice in Flux:



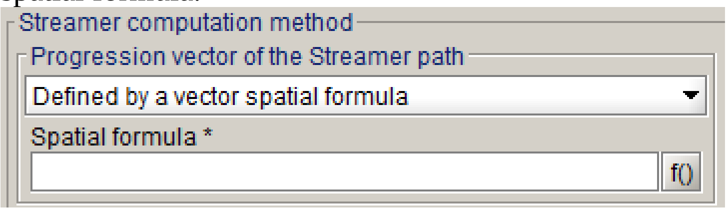
1.2.4. Computing method

Introduction

This section concerns the tool's second tab called "computation method".

Progression vector of the Streamer path

As said previously, the Streamer paths are approximated by physical quantities evolution laws: in Flux, the electric field lines are considered by default.
It is also possible to choose another progression vector, defined by a vector spatial formula.



Streamer path discretization

The path discretization is important to obtain a precise integration result. Three discretization methods exist, each one defines a specific discretization step. Then, the Euler-Cauchy method is applied to divide this discretization step n times (n is the "Number of Euler-Cauchy substeps" chosen by user).

The three discretization methods are presented below:

- Fixed : the discretization path is defined by a fixed value
- Adaptive with mesh size elements: the discretization path follows the corresponding mesh element size. This method is advised because it has the best ratio "results precision / computation time".
- Adaptive by angle minimization: it corresponds to an improvement of the previous method. The initial discretization step is chosen in the same way as the previous method, and it is subdivided until the angle between two consecutive electric field arrows becomes lower than 1°. This method can be more precise than the others in some cases (if the electric field lines are curved), but the computation time can increase.

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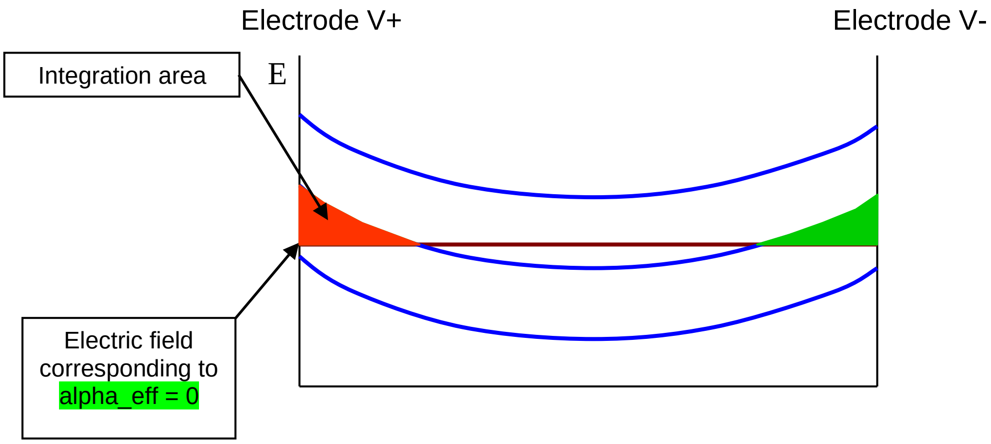
Integration mode

Actually, a Streamer won't go necessarily from the high potential conductor. Given that Flux imposes a path starting from the high potential conductor, this option can remedy this problem.

It has an impact when the electric field E is not homogeneous along the path. In fact, if E decreases until α_{eff} becomes negative, there are two possibilities for the integral computing:

- "Integrate starting only from the conductor" means that α_{eff} will be systematically integrated on the orange part of the figure (and never on the green part)
- "Integrate from the both sides of the path" means that the maximum between α_{eff} integral (K) value on the orange and the green part will be taken into account. The integration giving the maximum value indicates the Streamer starting side. A graphical arrow will indicate the Streamer propagation direction.



Computation mode

This option allows to choose :

- A parallelized computation
- A sequential computation
- An automatic computation: it corresponds to the parallelized computation in most of the time, except some cases which can not use the parallelized computation because of code limitation (the sequential computation is used).

Dichotomy

The dichotomy parameters are defined by:

- The maximum number of iterations
- The relative accuracy on K

1.2.5. Mesh advices

Introduction

The mesh quality has a considerable impact on the results.
In fact, it has an effect on:

- The electric field results quality
- The integration discretization quoted in the previous section. In fact, the discretization path selected by default is based on the mesh elements size.

But, a very fine mesh will involve relatively long computation time.

Depending on the studied devices geometries, the optimal mesh won't be the same.
This section presents some mesh advices for simple cases.

General approach

Given that the computation is based on the mesh elements size, it is essential to discretize enough the Streamers area (it is not possible to post process a computation done in an area with two or three mesh layers).

In a general way, it is advised to assign local mesh information (meshpoint, meshlines, etc.) on the geometric entities of the studied area.
In fact, in most of cases, the aided mesh or the adaptive solving will not discretize enough this area.

So the advised approach is to:

- Mesh (with aided mesh activated by default)
- Modify the aided mesh options (deviation, relaxation) and mesh
- Assign local mesh information on the studied area and mesh
- Important : **it is strongly advised to generate second order elements**. It changes entirely the results quality and it is not much longer to compute.

3D devices

Concerning the 3D devices, in some cases, the computation can be long with a mesh suited for Streamer computation. It is especially the case when the conductors have complex geometry shapes.
The advices are to:

- Choose a potential difference applied in the project which is not much higher/lower than the Streamer inception voltage (for more information, see the Using advices and remarks part)
- Use symmetries or periodicities when it is possible

1.2.6. Postprocessing results

General

After a computation using the "Streamer criterion" tool, it is possible to postprocess different results:

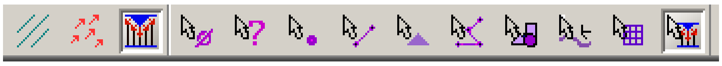
- Graphic
- Streamer results
- Complete results

Graphic

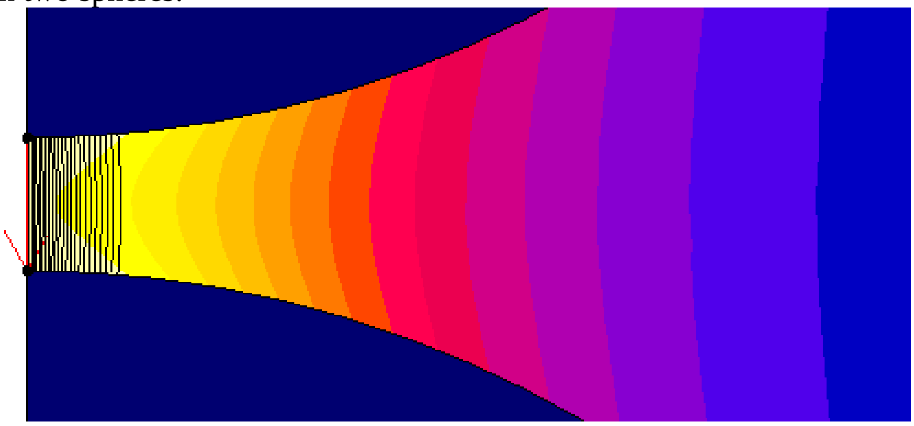
At the end of a computation, are displayed:

- The Streamer having the highest probability to start (maximum K) represented by a red arrow with the direction of ionization canal propagation
- The Streamers which can breakdown in black (having K higher than the threshold for the project potential difference)*

The following checked icons correspond to Streamers selection and display icons:



Here is the Streamers display in the graphic, for a global computation between two spheres:



*if the option "Streamers display mode" of the "results" tab is not changed

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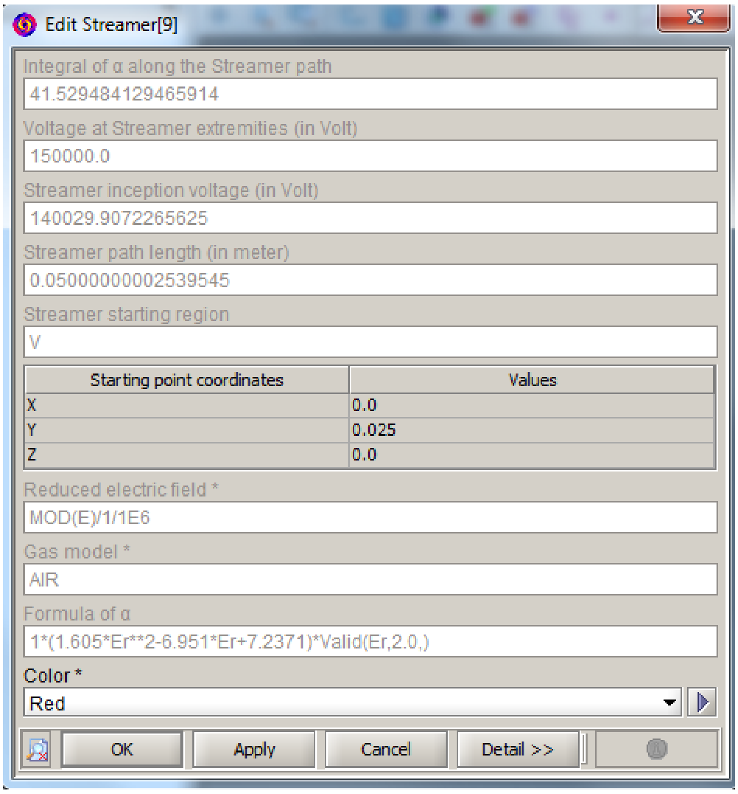
Streamer results

By editing the Streamer having the highest probability to start, the following results appear:



Remark: it is possible to launch a new “Streamer criterion” computation of one or several Streamers displayed on the graphic, by clicking directly on the command “compute Streamer inception voltage ” of the Streamers contextual menu.

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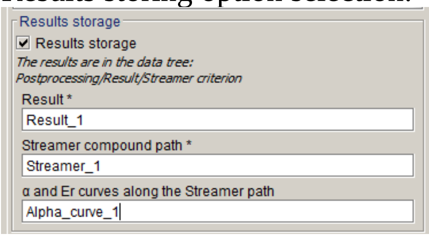
Complete results

User has the possibility to store Flux results.
For that, the “results storage” option must be checked in the “results” tab (see the image below).

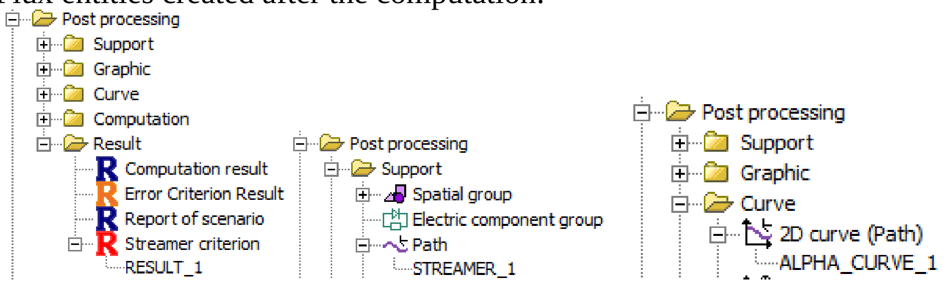
It allows storing:

- The results of the Streamer having the highest breakdown probability (same results as those displayed by graphical Streamer edition)
- The spatial path associated to the Streamer having the highest probability to start
- The curves:
  - Reduced field depending on the position on the Streamer path
  - α_{eff} depending on the position on the Streamer path for the project potential difference
  - α_{eff} depending on the position on the Streamer path for the Streamer inception voltage (the integral of this curve must be equal to 18 with an error until K precision)

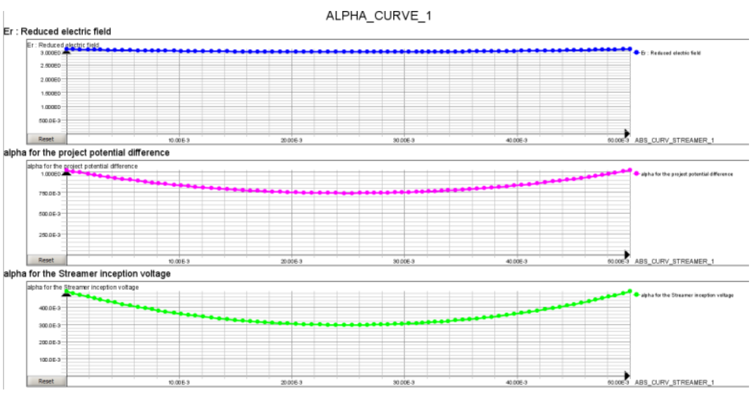
Results storing option selection:



Flux entities created after the computation:



Curves displayed in Flux:



1.2.7. Using advices and remarks

Additional advices and remarks

Here are some additional advices and warnings for the project preparation:

- Important: to obtain good results with a fast computation, it is important to apply a potential difference close to the Streamer inception voltage.

In fact, a very low project potential difference will give only negative α_{eff} (which are not considered in the integral). On the contrary, a very high project potential difference involves the integration of high α_{eff} values in the center of the Streamer path, whereas the method is valid for Streamer departure areas.

- Using symmetries and periodicities is advised to reduce computation time, except if the high breakdown probability Streamer is on the symmetry or periodicity axis: the computation can be refused if the electric field arrow direction goes on the other side of the axis (it is possible in finite elements computation)
- If there are Streamers far from the device, it is advised to increase infinite box size. In fact, a Streamer arriving on the infinite box is not taken into account.
- It is possible to make a Streamer computation between conductors of line region type in 2D (surface region in 3D) except if they are not on a surface region border (volume region in 3D)
- Remark: the predefined Streamer formula for the air and SF6 were found for a temperature around 20°C