Corona effect prediction methodologies for grounded sphere-sphere configurations

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Introduction

The corona effect is an electrical phenomenon known to be ubiquitous in any high voltage system whose insulation is a gas. Nowadays, there is a renewed interest due to high voltage implementations such as DC substations on offshore wind farms and long-distance transmission lines. These implementations are subjected to various environmental and operative conditions.

The corona effect is undesirable due to electrical losses, audible noise and electromagnetic interference. Therefore, when designing high voltage equipment, it is good to have an idea of the possibility of occurrence because it can degenerate into the formation of an electric arc.

The corona effect has a statistical character [1], and in practice, many factors influence its prediction, which is why it is difficult to avoid it in the usual operation of equipment. However, it is beneficial to have a design criterion that under controlled conditions indicates the occurrence of the corona effect or breakdown [2].

The corona prediction criteria are tested in canonical configurations because this offers several advantages, such as:

- The curvatures of the objects are easy to reproduce by other laboratories.
- The electric field can be calculated by analytical methods (not easily) or is known in the area of interest.
- The control of parameters, such as electrode, is straight forward to carry out experimentally.
- The distinction of the occurrence of the phenomenon is also easy to identify.

The most typical configurations of study are point-plane, concentric cylinders and sphere-sphere. For the present work, the geometry has been modified in such a way that we can observe the behaviour of different corona prediction criteria in slightly non-uniform cases, including a new interface introduced in COMSOL 5.5, the Electric Breakdown Detection Interface (EBDI) and the criterion developed by Pedersen [3]

In this work, Pedersen's method has been applied to predict the corona inception or breakdown voltage for several grounded sphere-sphere and grounded ellipsoid-ellipsoid configurations. Then, by using the Electric Breakdown Detection Interface (EBDI), we have calculated the voltage at which the Breakdown Indicator informs about the formation of streamers, taking as a reference to the value previously found. We will compare both results to determine the degree of agreement between both methods.

Corona Prediction Criteria for Electrical Configurations

For the prediction of corona effect (or breakdown), various criteria have been developed over time, as presented in the review papers of Donohoe [4] and Warne et al. [5]. In these criteria, some property of corona discharge is analysed, e.g., the transition between non-sustained to sustained discharge, or the transition between discharge mechanisms such as Townsend [6] or streamer [7].

Additionally, to properly define the criterion, a possible discharge path has to be known, as well as the reduced ionization coefficient across it. The ionization coefficient is related to the production of new free electrical charges in the gas due to the collisions of energetic electrons with neutral molecules (avalanche effect) per unit length [8].

This reduced ionization coefficient, α, depends on the number of molecules in the gas per unit volume called number density (that was "reduced" mean). Therefore, the breakdown phenomenon is dependent on thermodynamic conditions.

Dutton et al. [9] found a relationship with the reduced applied electric field and measured them experimentally, E/N. COMSOL includes these results in the model options.

In the case of gases with an electronegative molecule, like air, instead, we use the effective ionization coefficient, $\bar{\alpha}$, which also includes the effect that some electrons attach to the oxygen. This was not recognized when described, and even measured, the ionization coefficient [10] previously.

As a first approach to understanding whether such criteria are viable, canonical configurations are used first, such as sphere - grounded sphere, because the non-uniformity of the electric field can be described through the radius or by its separation.

In the present work, the criteria under study has been implemented in the sphere-grounded sphere configuration of the Application ID 74081. Then, in the same positions as the spheres, $(0,0,0)$ and $(a+d,0,0)$, an ellipsoid - grounded ellipsoid have been simulated. Their major axis coincided with the minimum discharge path, as can be seen in Figure 1.

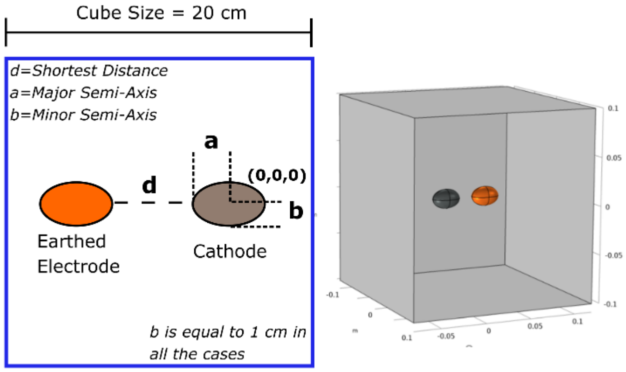

Figure 1. Geometry and position of the electrodes in the model

Table 1 shows the geometric dimensions considered to carry out the simulations. The parameters considered are equal if they are spheres or ellipsoids. In the case of the auxiliary parameter h, it is calculated to achieve the desired shortest distance as shown in (1).

$$h = 0{,}5 \times d + a \tag{1}$$

Table 1: Definition of geometrical parameters for each case

Case	Radius/ Major Semi-Axis (cm) a	Shortest Distance (cm) d	Auxiliary Variable (cm) h
1	1.00	0.625	1.3125
2	1.00	1.0	1.5000
3	1.00	2.5	2.2500
4	1.00	5.0	3.5000
5	1.25	0.625	1.5625
6	1.25	1.0	1.7500
7	1.25	2.5	2.5000
8	1.25	5.0	3.7500
9	1.50	0.625	1.8125
10	1.50	1.0	2.0000
11	1.50	2.5	2.7500
12	1.50	5.0	4.0000
13	1.70	0.625	2.0125
14	1.70	1.0	2.2000
15	1.70	2.5	2.9500
16	1.70	5.0	4.2000

Corona Prediction Criteria by using COMSOL Modules

The COMSOL Modules used for the present study are the Plasma Module that contains the Electric Breakdown Detection Interface (EBDI), as well as the Electrostatic Module. One of the elements is grounded, while the other is at a negative voltage (cathode). Unless the author specifies, the solver configurations in all the cases are the same as Application ID 74081.

One of the EBDI functions is the resolution for each particle that starts from the cathode of the integral according to (2).

$$\int_0^D N \cdot \alpha \cdot ds = K \tag{2}$$

where N is the number density, α is the reduced Townsend growth coefficient, and the term K defines what type of mechanism is most likely to be present under these conditions, described in COMSOL Manual as introduced in (3).

$$\begin{cases} K < \ln\left(1 + \dfrac{1}{\gamma_i}\right) & \text{No Discharge} \\ K > \ln\left(1 + \dfrac{1}{\gamma_i}\right) & \text{Sustained Discharge} \\ K > 17.7 + \ln(d/1\ \text{cm}) & \text{Streamer} \end{cases} \tag{3}$$

For this work, the term K is replaced by a function $G(x,p)$, since the method we verify corresponds to Pedersen's method [3]. The function is related to other variables, but these are the most prominent. The function can be calculated in a non-uniform electric field by (4).

$$N \cdot \alpha_x \cdot \exp\{\int_0^D N \cdot \alpha \cdot ds\} = G(x,p) \tag{4}$$

In this case α_x is the reduced Townsend growth coefficient in the avalanche head, at standard conditions. At standard conditions (i.e. pressure at 1 atm and temperature at 20 ° C), the number density is thus defined. By itself (4) does not indicate the corona inception or breakdown (when the streamer distance is equal to the gap) happen. Hence, the same function is calculated, but in the case of a uniform field by using (5):

$$N \cdot \alpha \cdot \exp\{N \cdot \alpha \cdot s) = G(x,p) \tag{5}$$

If at some point along the trajectory (4) and (5) are equal, then the streamer could travel to the position of coincidence and let us conclude that corona inception happens (or breakdown), as shown in Figure 2.

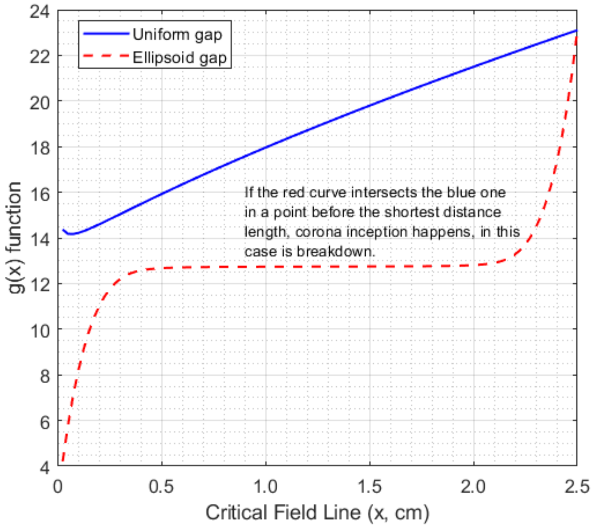

Figure 2. Application of Pedersen's method on Case 15 with ellipsoids

The values of α in (4) and (5) are different. Equation (4) is calculated with the electric field at point x in the configuration, whilst (5) calculations are made with a uniform electric field between two ideal parallel plates whose voltage is that of the electrode y whose separation is that of point x.

In all cases, be it the EBDI or Pedersen's method, it is necessary to know the electric field in the medium due to the electrodes. Using the COMSOL Electrostatics Module we can calculate the electrostatic field on each configuration. The relationship between the reduced Townsend growth coefficient, α, and the reduced electric field (E/N) is given by the relationship found by Dutton [9].

The general procedure for the verification of both methods is shown in Figure 3.

In the Electrostatic type study, the selected mesh type is *Finer* and *Physics-Controlled*. This feature is essential because the electric field along the critical line depends on the quality of the mesh. In Pedersen's method, the critical line was defined a priori because in this configuration it is known, as the shortest straight line between the two spheres (or ellipses). Using the *Line Plot* include in COMSOL electric field values along this path have been evaluated for the present work. The resolution configuration of the function *Line Plot* has a resolution *Extra Fine*, to improve the calculations.

With the voltage value obtained with the previous method, EBDI has been used. Under these conditions, we have observed for the maximum simulation time (0.015 s) which is the maximum value obtained and in which location of the *Breakdown Indicator*.

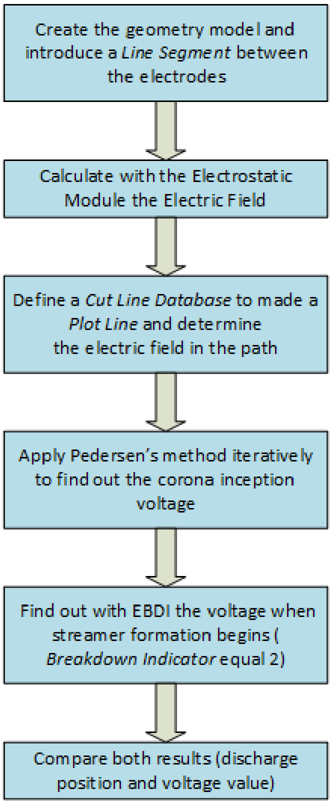

Figure 3. Steps made in COMSOL to compare the criteria

Results

Table 2 shows the results for the grounded sphere-sphere case. In none of the cases was obtained previous corona inception before breakdown. The values in black (left) correspond to those obtained using the Pedersen's method while the values in red (right) correspond to those obtained using EBDI.

Table 2: Breakdown voltage in kV for each case with spheres

	Radius (cm) **a**			
Gap (cm) **d**	1.00	1.25	1.50	1.70
1.0	-29.1/-30.8	-30.0/-30.9	-30.1/-30.9	-30.3/-30.9
2.5	-56.2/-55.2	-60.1/-59.1	-62.2/-61.5	-62.7/-63.9
5.0	-77.3/-71.3	-90/-80.6	-94.6/-87.8	-98.0/-92.1

Figure 4 shows the behaviour of the results obtained. The correspondence between both methods decreases as the separation between the spheres increases.

Table 3 shows the results obtained for the ellipse-grounded ellipse different cases. As in the sphere-earthed sphere configuration, no corona inception has been obtained before breakdown. The nomenclature used in Table 3 is the same as in Table 2.

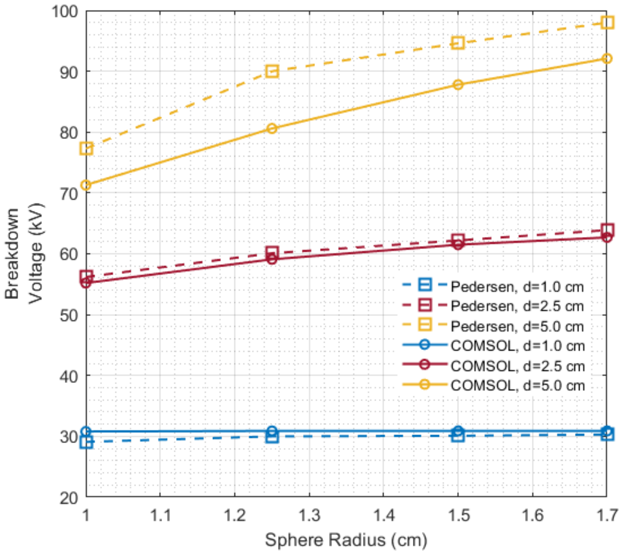

Figure 4. Breakdown voltage applying each method (Pedersen's and EBDI) on sphere configurations

Table 3: Breakdown voltage in kV for each case with ellipsoids

	Semi-major axis (cm) **a**		
Gap (cm) **d**	1.25	1.50	1.70
1.0	-29.0/-31.5	-28.6/-29.9	-28.2/-30.3
2.5	-53.6/-53.6	-51.5/-51.7	-50.0/-49.8
5.0	-73.5/-68.8	-70.0/-68.9	-68.4/-69.3

As in the previous configuration, the results are presented graphically in Figure 5. It is observed that the difference depending on the separation of the electrodes is less noticeable, although it remains wider in the case of greater separation.

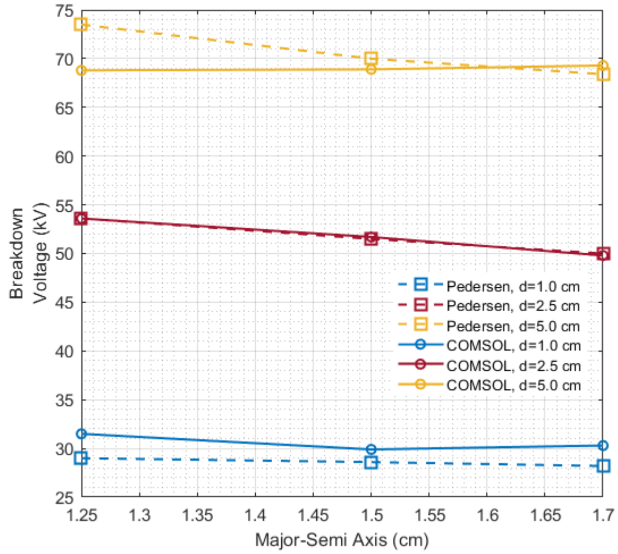

Figure 4. Breakdown voltage applying each method (Pedersen's and EBDI) on ellipsoid configurations

The location of the critical point in both configurations and all cases has been correctly predicted using EBDI. In Figure 5, the critical area (the red zone with a streamer condition) is observed on one of the ellipsoid-grounded ellipsoid cases. Although the discharge point still includes a fairly large area, it is reasonable to choose the midpoint of it for the study, as has been done with the Pedersen's method assumption.

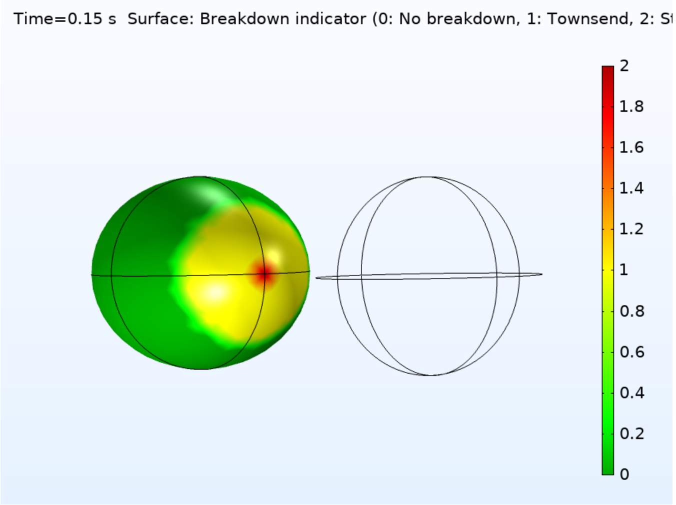

Figure 5. EBDI applied on ellipsoid (cathode) in Case 15. The voltage applied was -49.8 kV

Conclusions

In the present paper, two methods for the prediction of corona effect have been compared. The data required to use both methods is within the available tools in COMSOL 5.5.

One of the possible ways to apply the methods jointly are, first, use Pedersen’s method as an initial estimator of the voltage at which the corona inception is observed, and consequently fine-tune the results by using EBDI considering the streamer inception.

EBDI covers another aspect of the effect that is Townsend’s mechanism. We consider that this aspect is relevant in the inception of other corona modes, but are out of the scope of this study.

Both methods suffer from the inability to distinguish between inception and extinction voltage. That is important because the corona test standards set to measure the extinction voltage and if we assume that the methods predict the voltage inception, this introduce a difficulty in the validation process.

Also, there is a difference between the two methods under study when the separation between electrodes grows. A possible explanation is the higher sensitivity to non-uniformity of one of the methods. Therefore, it is necessary to find a way to describe this non-uniformity first. Without experimental data we can’t conclude which of the two is more precise.

According to the results in both configurations, sphere-grounded sphere and ellipsoid-grounded ellipsoid, the radius of curvature only begins to be critical on the corona inception when the separation is greater. Meanwhile, if the distance is small, this dependency is null.

The relationship between the corona inception and the separation of electrodes is clear. Inception voltage occurrence decreases when the distance grows for the same voltage value. Therefore, we conclude that a geometric factor to characterize the non-uniformity of the electric field related to the configuration geometry must include both variables. The form that these variables intertwine will be include in future studies.

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