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Influence of Corona layer on Corona Computation in Wire to Plane System

***Abstract**. The majority of models used for predicting corona dismiss the thickness of the ionization layer (avalanche) near the active electrode in which the total space charge is null. To justify the need to take or not the corona layer into account, computations are carried on with and without the corona layer for positive and negative corona discharges. Electric field and current density distributions are computed for a wire-to-plane geometry with and without corona layer. Poisson's equation is solved using the finite element method and the current continuity equation which updates the space charge density is solved using the simplified method of characteristics, which neglects ion diffusion. Numerical results were compared with experimental one for both polarities of corona.*

***Streszczenie.** Większość modeli wykorzystywanych do przewidywania zjawiska korony pomija grubość warstwy jonizacji (lawiny) w pobliżu aktywnego elektrodu, w której całkowity ładunek przestrzenny jest równy zeru. Aby uzasadnić potrzebę uwzględnienia warstwy korony lub jej braku, przeprowadzane są obliczenia z uwzględnieniem i bez uwzględnienia warstwy korony dla wyładowań korony dodatniej i ujemnej. Rozkłady pola elektrycznego i gęstości prądu obliczane są dla geometrii drut-płaskownia z uwzględnieniem i bez uwzględnienia warstwy korony. Równanie Poissona jest rozwiązywane za pomocą metody elementów skończonych, a równanie ciągłości prądu, które aktualizuje gęstość ładunku przestrzennego, jest rozwiązywane za pomocą uproszczonej metody cech, która pomija dyfuzję jonów. Wyniki numeryczne porównano z wynikami eksperymentalnymi dla obu polaryzacji korony. (**Wpływ warstwy koronowej na obliczenia koronowe w układzie drut-płaszczyzna**)*

Keywords: positive and negative corona discharge, ionization layer, numerical modelling, electric field and current density.
Słowa kluczowe: wyładowanie korony dodatnie i ujemne, warstwa jonizacji, modelowanie numeryczne, pole elektryczne

Introduction

Corona discharges investigations have been focused especially in high voltage D.C (HVDC) transmission lines. Indeed, corona discharges cause various biological effects, produce audible noise, create radio and TV interference, result in power losses, and lead to the deterioration of insulation systems [1-4].These consequences must be avoided by an exact conductor radii calculation which can't be achieved without knowledge of the physical characteristics of the insulation, the influence of the external parameters (rain, pollution...), the physical air parameters (humidity, temperature, pressure) and also of the network.

Contrary to HVDC transmission lines, coronas are of a considerable technical importance in modern industrial processes. Electrostatic precipitators, cyclone separators and granular bed filters are examples which operate upon the charged ions produced by a coronating electrode. These devices often use negative coronas for their operation. However, we must remind that investigations made for the positive polarity are more than for the negative polarity, this is because, for the same external insulation, negative polarity lead usually to a higher gradient breakdown and give so less importance for dielectric computation of network.

Finite element analysis of unipolar space charge fields, of both positive and negative polarities, has been carried out over the past thirty years and many papers have been published on the subject. In all the works done, the ionisation region is disregarded and has been taken into account in 2002 by Yala et al [5]. They include the critical electric field of minimum ionisation loop convergence on the borderline of the ionisation region in addition to the potential and the space charge loops.

The numerical method they used was derived from positive polarity experiments by Abdel Salam and Al Hamouz (2-4). Oussalah et al. [9,10] improved the numerical computation by taking the ionization area into consideration. The new model reduces the number of algorithm loops to two or three (a loop for the potential convergence and another loop for the space charge convergence) by introducing the potential corresponding to the critical electric field of the minimum ionization (CEFMI) directly on the finite element formulation as a Dirichlet condition on the edge of the ionization region.

Corona in wire to plane configuration

For a wire to plane geometry (see Figure.1), when an enough high potential is applied to the active electrode, corona discharge can be observed. This discharge comprises a thin region named ionization region close to the most highly curved part of the electrode in which the electric field is sufficiently high to breakdown the air molecules and to produce both free electrons and charged ions of both positive and negative signs.

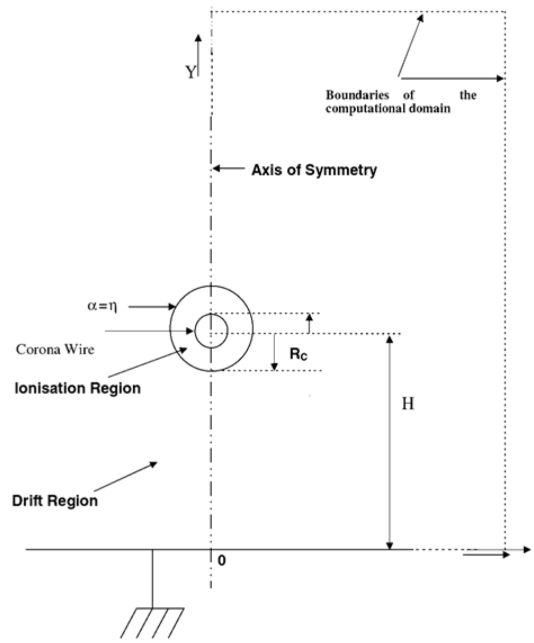


Fig.1. DC corona structure

Away from the corona, the ions with the same polarity as the electrode drift into the gas and form a space charge region; we are so in the drift region. These ions are carried by the electrostatic strength through the field lines. On the borderline between the ionisation region and the drift region, the electric field is called critical electric field of the minimum ionisation (CEFMI) in which $\alpha=\eta$(ionisation coefficient α is equal to the attachment coefficient η). When the electrode has a negative potential then corona is described as negative corona. In this case, the electronic avalanche progresses from the conductor to outside. When the electrode has a positive potential the corona is described as positive corona. The electronic avalanche in this case takes form in the neighbor space and progresses toward the conductor. The ionization process spread around the conductor further than the avalanche of negative polarity.

Space charges created by DC corona fill the entire interelectrode space. Analytical calculation of electric fields with space charges for such configuration is extremely difficult because of the non linear nature of space charge generation by corona. But they are possible for simple configurations such as concentric spheres and coaxial cylinders.

Onset field

The electric field value in which corona appears is called corona onset field, it is given by Peek's law:

(1) $$E_{sPeek} = 31.m.\delta.\left(\frac{1+0.308}{\sqrt{\delta R}}\right)$$

where: R – is the electrode radius, m – is the surface irregularity (roughness) factor (1 for smooth conductors).

An improved model which generalized the Peek's law has been developed recently [11,12], it takes account of the physical air parameters. The onset field is given by:

(2) $$E_i(2R,\delta,H_a) = E_c(\delta,H_a)\left[1+\left(A_0/2R\right)\left(\left(2\,\mathrm{Re}^{(a_0/2R)}+z_0\right)\Big/\delta\right)f(H_a)\right]$$

and

(3) $$E_C(\delta,H_a) = E_C\left(1,0\right).\delta(1+\alpha_H\sqrt{H_a})$$

where: H_a – is the absolute humidity, δ – is the relative air density (δ=1 for P=1013 kPa and T=20°C) and E_C –is the critical electric field of the minimum ionisation, $E_C(1,0)$ is given for normal air conditions (δ=1 and H_a=0) A_0=0.1088, a_0=3.10-7m, z_0=17.10-6m and the humidity function $f(H_a)$=1 for H_a=0, α_H=16.0310-3 (g/m3)-1/2, $E_C(1,0)$ =2.468106 (V/m), δ=293P/(1013(273+T)).

Using the onset potential V_S found by drawing the current–voltage V=f(I) characteristic [9,10], E_i can be calculated as follows

(4) $$E_i = \mathrm{V}_s\Big/\left(R.\ln\left(\left(2H+R\right)/R\right)\right)$$

The corona radius R_C can be found by using the relationship:

(5) $$R_C = E_i.\left(R/E_C\right)$$

The voltage in the ionisation region is expressed as follows:

(6) $$U_C = E_C.R_C.ln\left(R_C/R\right)$$

The potential V_C at the border of the ionisation region is given by:

(7) $$V_C = V_{app} - U_C$$

where: V_{app} – is the applied potential

Mathematical model

The governing electrostatic equations outside corona sheath are Poisson's equation:

(8) $$\nabla^2\phi = \mp\rho/\varepsilon_0$$

and the steady state conservation of current equation is:

(9) $$\nabla\vec{J} = 0$$

Current density is related to electric field by:

(10) $$\vec{J} = \pm\rho.\mu.\vec{E}$$

and

(11) $$\vec{E} = -\nabla\phi$$

where: ϕ – is the electric potential (V), ρ – is the ionic space charge density (C/m3) and is always positive. The sign in (8) is negative if the active electrode is subjected to a positive potential and positive in the reverse case, $\vec{E}$ – is electric field (V/m), $\vec{J}$ – is the vector of current density (A/m2). The sign in (8) is positive if the applied potential is positive and negative in the reverse case, μ – is the positive or negative ion mobility according to the polarity of the active electrode (m2/V.s), ε_0 – is the air permittivity $\left(\varepsilon_0 = 8.85.10^{-12}\left(F/m\right)\right)$.

The equations (8), (9) and (10) are the Poisson, current continuity and current density equations, respectively. An exact solution to these is impracticable as a result of their nonlinear nature.

Analysis model

The iterative FEM (finite element method) was used to solve the ionized field problem in wire-to-plane geometry. The wire radius is R (and diameter d), height H=50mm with respect to the ground plane (see Figure.1). The wire is subjected to positive and negative potential.

The geometry wire-to-plane is considered of infinite length, thus the problem can be reduced to 2D. As it is an open geometry, so artificial boundaries are built to restrict the domain of study (0.2m according to X axis and 0.4m according to the Y axis). Computations are carried on with and without the ionization region.

When it is taken into account, the Dirichlet boundary conditions set for the numerical resolve are so:

- The wire is subjected to the applied potential ($\phi_w=V_{app}$);
- The plane is at zero potential ($\phi_p=0$);
- The potential at the border of the ionization region is ($\phi_C=V_C$);

The flow chart of the algorithm [9,10] is shown in figure.2 for the case when the ionization layer is taken into account. The first mesh is created in the absence of space charge and, therefore, the electric field is Laplacian. To map the field lines, electric image method is used and the equipotential contours are built. Each quadrangle produced by the intersection of field lines and equipotential contours is divided into two triangles. Such generated grid is shown in figure 3.

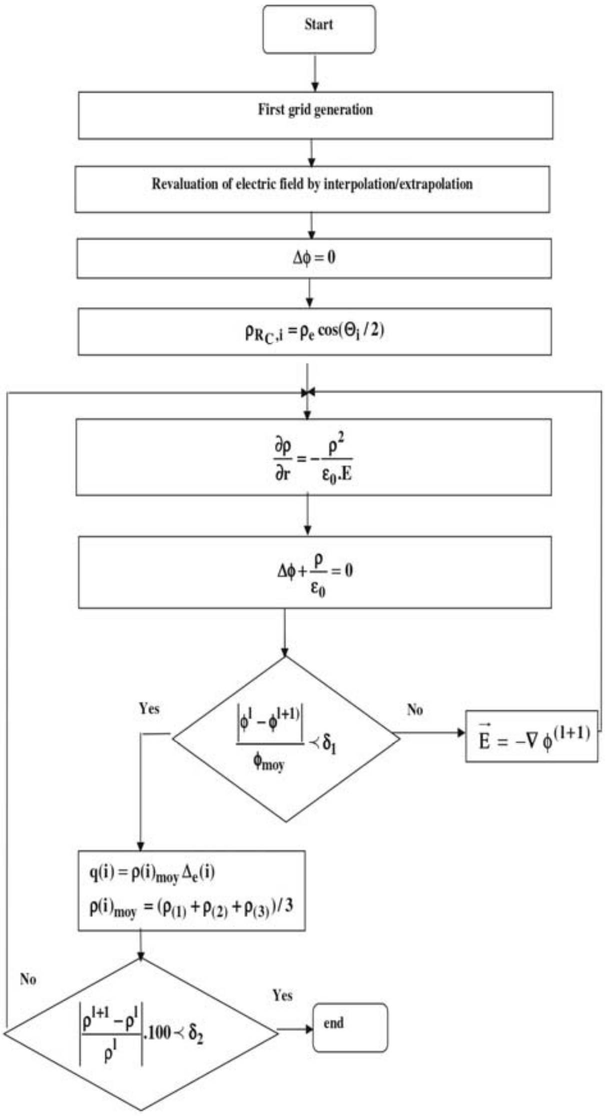


Fig. 2. Flow chart for numerical computations

The evaluation of the space charge density is obtained using the simplified method of characteristics which neglects ion diffusion. The Poisson's equation is then solved using the finite element method and the electric field distribution is estimated using the interpolation/extrapolation method. Once convergence of the potential is reached, space charge is calculated in the center of mesh triangles and used to reconstruct a new orthogonal grid. More new meshes are built until the difference value between the space charge densities of two consecutive grids is less than a pre- specified value.
When the ionization layer is dismissed, the algorithm is the same, the difference is that space charge density is estimated starting from the periphery of the conductor.

Results and discussion

The method is tested through application to wire-to-plane geometry, for which experimental results have been reported [12]. Computation is then extended to other corona wire radii. We have computed for two wire radii of 0.2 mm and 0.4 mm. In these conditions: P=1013 mbar, T=20 °C, H_a=13 g/m3. Wires are subjected to positive and negative applied voltages. Computations are carried while including and while dismissing the ionisation region. The numerical program including the ionisation layer was modified to dismiss it. Experiment results are taken from [9,10].

Figures 4 and 5 show the electric field and current density distributions at the plane for R=0.4 mm and V_{app}=±25 kV for both polarities with and without including ionization region. Figures 6 and 7 show the electric field and current density distributions at the plane for R=0.2 mm and V_{app}=±18 kV for both polarities too.

By changing the conductor radii the onset field values are affected and consequently the corona onset charge
When the conductor radius is larger, corona onset field is higher. Space charge starts increasing when the conductor starts emitting charges of both polarities (positive and negative).

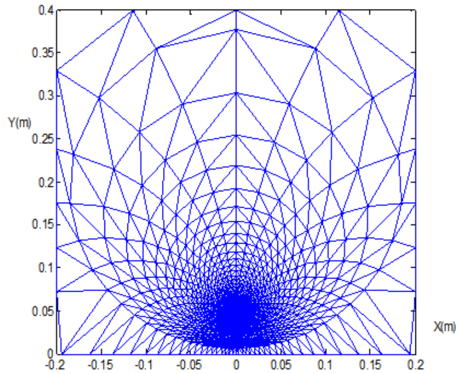
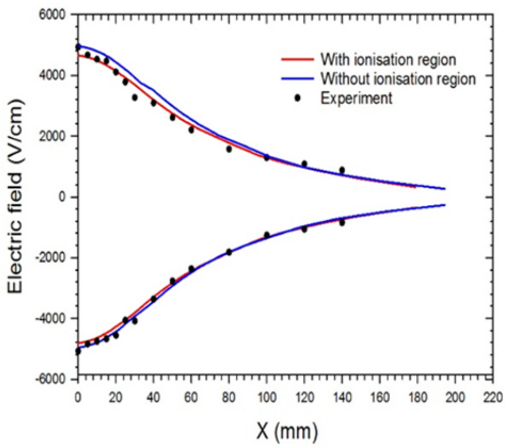


Fig. 3. First grid generated

When corona layer is taken into account the amount of space charge is maximum at the border of the ionization region then decays due to the drift region were charges of the same polarity as the applied voltage went away from the conductor. The effect of space charge is further reduced due to the loss of charge through neutralization or recombination processes. Electric field and current density due to space charge is maximum near the conductor then decays while attending the plane and when we move away from the conductor. This can be seen in the obtained figures of electric field and current density shown by figures (4, 5, 6, 7).



ig. 4. Electric field distribution at the plane vs normal axis (corona wire radii R=0.4mm, applied corona voltage V=±25 kV)

Results show also and clearly that the calculated current and field agreed well with measured values as from values and shapes and looked a bit more accurate when the ionization is included. With V_{app}=18 kV, the corona radius is R_c=7.27.10-4 m (from (5)) for positive polarity and is R_c=6.91.10-4 m for negative polarity and for an applied voltage of V_{app}= 25 kV, it is about 0.0012m for both polarities.

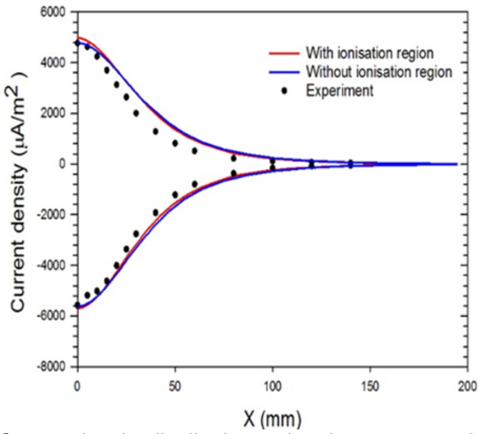


Fig. 5. Current density distribution at the plane vs normal axis (corona wire radii R=0.4mm, applied corona voltage V=±25 kV)

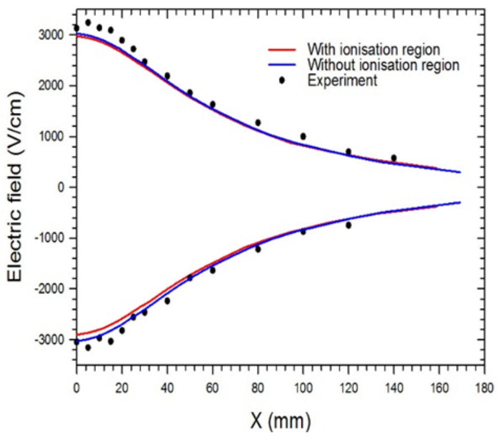


Fig. 6. Electric field distribution at the plane vs normal axis (corona wire radii R=0.2mm, applied corona voltage V=±18 kV)

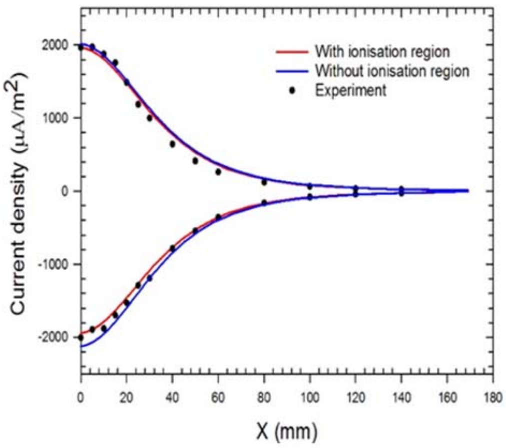


Fig. 7. Current density distribution at the plane vs normal axis (corona wire radii R=0.2mm, applied corona voltage V=±18 kV)

So from the figures obtained corona radii has not a considerable influence on numerical computations for both cases of study. Errors between numerical and computation data can be attributed to the difficulty to get accurate value of the first estimation of space charge on the borderline of the ionization region or on the wire.

Conclusion

Numerical computations were carried on for predicting corona with and without the corona layer (avalanche) near the active electrode. Poisson's equation is solved using the finite element method and the current continuity equation which updates the space charge density is solved using the simplified method of characteristics. Numerical results were compared with experimental one for both polarities of corona for **electric** field and current density distributions on the plane. Curves obtained show clearly that corona radius has no considerable influence on numerical computation as such layer is very thin but it seems that numerical computations are reduced while introducing it as find in [9,10].

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