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## A Computational Algorithm for Corona Power Loss in Grid

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#### Abstract

In this paper a new efficient algorithm for computation of corona power loss in grid is described. The algorithm is based on a new finite element method (FEM) which allows computing corona power loss in high-voltage lines transmission. The new algorithm method is intended for considering the effects of various parameters on corona current such as: the height of conductor, the radius of conductor, the surface factor, distribution of electric potentials in space of between conductor and ground plane with applying space charges, and ambient temperature. The algorithm results were compared with the existing methods and the result accuracy was confirmed. Also, the results show that the new algorithm has positional to reduce the number of iteration for calculation of the corona current. The knowledge of the corona phenomena discharge will assist in monitoring and controlling the reliability of high voltage systems. This information can be monitored for measuring, detecting and taking appropriate control actions.

Keywords: Corona Power Loss; Finite Element method (FEM); Algorithm

## Introduction

According to a report from the Department of Energy, California two major sources of loss in high voltage AC transmission lines are: resistive and corona loss [1]. Resistive loss (3.91%) occurs because of the non-zero resistance found wire's metal. Corona loss (2.89%) is an ionization of the air that occurs when the electric fields around a conductor exceed a specific value. Unlike resistive loss which amount of power lost was a fixed percentage of input, the percentage of power lost due to corona is a function of the signal's voltage. Corona discharge power losses are as well extremely dependent on the weather conditions such as: ambient pressure and temperature [2,3] . Some methods were used to explain ionized field such as: Charge Simulation Method (CSM) [4] Boundary Element Method (BEM) [5] and Finite Element Method (FEM) [6]. Aboelsaad et al. [7] used the numerical assessment of unipolar corona ionised field quantities using the FEM that deal only with the potentials in conductor and ground plane and check the field only on conductor surface later. Abdel-Salam and Z. AI-Hamouz [8] proposed a new FEM analysis of space-charge modified fields around uni polar transmission lines without resort to Deutsch's assumption. The method attempted a solution of only one secondorder Partial Differential Equation (PDE). Based on the above method [8] Mohammadi and Ebrahimi [9] compared the corona losses power for high voltage AC and DC. The results showed that the effect of recombination corona phenomena in the state of equivalent DC voltage instead of AC voltage is not considered, and finally leads to incorrect results. Regarding to the computational complexity of calculation of corona phenomena, the study try to lead and reduce the number of iterations. Despite the ongoing investigation of the corona power loss in grid, there is still a gap. Most of the existing works do not take into account the effects of various parameters on corona current such as: the height of conductor, the radius of conductor, the surface factor, distribution of electric potentials in space of between conductor and ground plane with applying space charges, and ambient temperature impacts on corona phenomena.

Main contributions of this paper are as follows:

• Investigate an in-depth understanding of the impacts of the corona phenomena

- Create a new computational efficient algorithm for corona power loss based on FEM including all impacts on the corona phenomena with and without considering ion diffusion
- Reduce the total number of iteration for convergence
- Considering ion diffusion as variable parameter

The paper is organized as follows. Section 2 described the theory and mathematical formulation. Section 3 presents the proposed computational algorithm. The results and discussion is presented in Section 4, and finally the concluding remarks are given in Section 5.

## **Mathematical Formulation and Assumptions**

### Mathematical formulation

The corona loss is caused by the ionization of air molecules near the transmission line conductors and it appears from the Gauss's low as follows:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} = \frac{\rho_{io} + \rho_P}{\varepsilon_0} , \quad \vec{E} = -\nabla\Phi$$
(1)

Where  $\bar{E}$  is electric field intensity,  $\rho$  is the space charge,  $\rho_{io}$  is summation of the ion charge density,  $\rho_p$  is particle charge density,  $\epsilon_0$  is the permittivity of air, and  $\Phi$  is the potential. Based on the continuity current density in a line the following equation is appears:

$$\nabla \cdot J = 0, \ J = J_{io} + J_P = (K_{io}\rho_{io} + K_p\rho_p)E$$
 (2)

Where  $\vec{J}$  is current density,  $k_{io}$  and  $k_p$  are the mobility's for ions and particles. Also the corona critic voltage gradients for electrical conductors are given by Peek's equation [10,11]:

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$$E_0 = \delta (31.53 + \frac{9.63}{)\delta r})$$
(3)

$$\delta = \frac{2.94P}{273+T} \tag{4}$$

Where *r* is electrical conductor radius, *P* is atmospheric pressure, *T* is temperature,  $\delta$  is relative air density respect air density at standard conditions (25°C and 101 kpa)

## Simplifying assumptions

- i. The ion mobility is assumed constant.
- ii. Ion diffusion is ignored.
- iii. The entire electrode spacing is filled with uni polar space charge of the same polarity as the coronating conductor.

#### **Boundary conditions**

The potential at the discharging wire is V. The  $E_o$  assumption for conductor to plane has been considered by [12] with following equation:

$$E_0 = 30\eta [1 + \sqrt{(0.0906 \ / R] \ KV \ / cm} \tag{5}$$

The coronating conductor surface electric field with following equation:

$$E_{crit} = E_0 f_1 (V / V_0)$$
(6)

Where  $E_{Crit}$  is coronating conductor surface electric field,  $V_o$  corona onset voltage and  $f_i$  is function of  $V/V_o$ . These parameters had been determined by [12] as follows:

$$f_1(V/V_0) = 1.1339 - 0.1678 \left(\frac{V}{V_0}\right) + 0.03 \left(\frac{V}{V_0}\right)^2 \tag{7}$$

### **Computational Algorithm Model**

To be able to produce the efficient corona calculation, we propose the corona calculation block diagram as displayed in Figure 1. The algorithm is based on a finite element method for computing corona power loss which allows reducing iteration calculation of the corona current. The algorithm includes a number of mechanisms ensuring its correctness and stability. The proposed algorithm operation starts by inputting the model configuration with several input data including conductor and other related elements and follow the subsequent steps:

#### Model configuration and data

The single conductor above ground plane consists of a single smooth cylinder of radius r<sub>c</sub> at a height H is shown in Figure 2. As shown in Figure 2, The bipolar co-ordinates  $\alpha$  and  $\beta$ , are employed, which are related to the Cartesian co-ordinates x and y by the following relations [13]:

$$y = \frac{a}{s} \sinh \beta$$
,  $x = \frac{a}{s} \sinh \alpha$  (8)

Where

$$a = (H^2 - r_c^2)^{1/2} , s = \cosh\beta + \cos\alpha$$
(9)

The metric coefficients are given by the following expressions:

$$h_{\beta} = h_a = \frac{a}{s} \tag{10}$$

and the co-ordinates of the coronating conductor and the ground plane are given by:

$$\beta_c = \cosh^{-1}\left(\frac{H}{r_c}\right) , \beta_g = 0 \tag{11}$$

For steady-state corona, the total current per unit length is

$$I = \int J . dA \tag{12}$$





By using Equations 1-2, the expression for the current becomes

$$I = \int k \varepsilon_0 [\nabla . (\nabla \phi)] \nabla \phi . dA \tag{13}$$

By transforming to bipolar co-ordinates and assuming that the elemental surface area dA is on one of the cylindrical surfaces where  $\beta$  = constant, then

$$dA = \hat{\alpha}_{\beta} a (\cosh \beta + \cos \alpha)^{-1} d\alpha \tag{14}$$

Where  $\hat{\alpha}_{\beta}$  is a unit vector in the  $\beta$  co-ordinate direction. Because the electric field is assumed to have the same direction as that of the space-charge-free field, the expression for the electric field becomes:

$$(\nabla\phi).\hat{\alpha}_{\beta} = \frac{\cosh\beta + \cos\alpha}{a} \frac{d\phi}{d\beta}$$
(15)

Substituting this expression in Equation15, and integrating between the limits  $\alpha = -\pi$  to  $\alpha = \pi$  gives:

$$I = -\frac{\pi\varepsilon_0 k}{2a^2} (2\cosh^2\beta + 1) \frac{d}{d\beta} (\frac{d\phi}{d\beta})^2$$
(16)

Integrating Equation 13, and imposing the boundary condition at the conductor surface,

$$\left(\frac{d\phi}{d\beta}\right)_{\beta=\beta_c} = \frac{f_1 V_0}{\beta_c} \tag{17}$$

The following equation is obtained:

$$\frac{d\phi}{d\beta} = \left[ \left( \frac{f_i V_0}{\beta_c} \right)^2 + \frac{a^2 I}{\sqrt{3} \pi \varepsilon_0 k} \ln \frac{\sqrt{3} + \tanh \beta_c}{\sqrt{3} - \tanh \beta} \times \frac{\sqrt{3} - \tanh \beta}{\sqrt{3} + \tanh \beta} \right]^{1/2} (18)$$

To obtain current/voltage relationship, Equation18 is integrated between  $\beta = \beta_g$  and  $\beta = \beta_c$ , to give the following expression:

$$\frac{V}{V_0 f_1} \beta_c = (1 + Y_G)^{1/2} \times \int_0^{\beta_c} \left[ 1 - \frac{2}{\sqrt{3}G f_1^2} \frac{Y_G}{1 + Y_G} In \frac{\sqrt{3} + \tanh \beta_c}{\sqrt{3} - \tanh \beta} \right]^{1/2} d\beta$$
(19)

Where the parameters  $\beta_c$ ,  $Y_G$  and G are given by the following expressions  $\beta_c = 0$ ,  $\gamma_G =$ 

$$\beta = In \left[ \frac{H}{r_c} + \left( \left( \frac{H}{r_c} \right)^2 - 1 \right) \right]$$
(20)

$$Y_G = \frac{GI}{2\pi\varepsilon_0 k} \left(\frac{H}{E_0 r_c}\right)^2 \tag{21}$$

$$G\left(\frac{H}{r_{c}}, \frac{V}{V_{0}}\right) = \frac{2}{\sqrt{3}f_{1}^{2}} \ln \frac{\sqrt{3} + \left[1 - \left(\frac{r_{c}}{H}\right)^{2}\right]^{1/2}}{\sqrt{3} + \left[1 - \left(\frac{r_{c}}{H}\right)^{2}\right]^{1/2}}$$
(22)

Equations 17-20 describe the general *I/V* characteristic for a smooth cylinder above plane configuration without Kaptzov's assumption. The space charge densities located at nodes (i, 1), around the periphery of the conductor is assumed initially as:

$$\rho_{i,1} = \rho_e \cos\left(\frac{\theta_i}{2}\right), i = 1, 2, \dots M$$
(23)

Where M is the total field lines (was equal to 35 in this work) and  $\rho_{\epsilon}$  is the value of  $\rho_{i,1}$  at  $\theta$  =0; The value of  $\rho_e$  was estimated using an approximate expression reported by [9] for the charge density at the ground plane:

$$\rho_{e} = \frac{E_{g}H}{E_{crit}R} 4\varepsilon_{0} \frac{V_{0}(V - V_{0})}{H^{2}V(5 - 4\frac{V_{0}}{V})}$$
(24)

Where E  $_{p}$  the space charge free electric field at the ground plane is, E  $_{crit}$ 

is determined by analysis of model in each step in ANSYS and V $_{_0}$  is the onset voltage. Using Equations 1-4, the Equation 23 can be obtained as:

$$\nabla \rho \cdot \nabla \Phi = \frac{\rho^2}{\varepsilon_0} \tag{25}$$

Substituting Equation 4 into Equation 25, one obtains

$$\frac{\partial \rho}{\partial l}\hat{u}_{l} = -\rho^{2} / E\varepsilon_{0} = h(\rho, l)$$
(26)

Starting at conductor's surface, Equation 26 is integrated along each line to estimate the nodal space-charge densities. For the first step  $\rho$  is determined by Equation 23, and initial value of E, is E <sub>crit</sub>. This estimate of the space charge density is utilized to determine the distributed space charges at the FE mesh nodes. By Equation 26 and using Rung-Kutta method the value of  $\rho$  (l +  $\Delta$  l).was estimated:

-the previous steps to calculate  $\rho$  (l + 2  $\Delta$  l).and  $\rho$  (l + 3  $\Delta$  l)., was performed to estimate the space charge densities at all nodes in each integration nodes.

- The two previous steps was performed for all integration routes (M=35) to identify the space charges at all nodes around the conductor.

In Rung-Kutta integration method [10], the Simpson method is used. In each step of integration for calculation  $\rho$  (l +  $\Delta$  l), the four parameters *K* (*i*=1... 4) were used to determine it. For calculation  $\rho$  (l +  $\Delta$  l), along electric field by transferring bipolar co-ordinates to Cartesian co-ordinates, the Equation27 is used:

$$\rho_{i+1} = \rho_i + \frac{\Delta l}{6} [K1 + 2K2 + 2K3 + K4]$$
(27)

Where *K1* to *K4* is determined from Equations 26-29 [10]:

$$K1 = h(\rho_i, l_i) \tag{28}$$

$$K2 = h(\rho_i + \frac{K1}{2}, l_i + \frac{\Delta l}{2})$$
(29)

$$K3 = h(\rho_i + \frac{K2}{2}, l_i + \frac{\Delta l}{2})$$
(30)

$$K4 = h(\rho_i + K3, l_i + \frac{\Delta l}{2}) \tag{31}$$

After calculation  $\rho$  (l +  $\Delta$  l), the processes were repeated to evaluate  $\rho$  (l + 2  $\Delta$  l).

#### Mesh generation

FEM method was performed for calculation of electric field and potential. Therefore the model must to be meshed. The meshing process was made with triangular element (see Figure 3). It is well known that FEM calls for bounded regions in which the mesh to be generated.

#### Estimation electric field and potentials

In this step the estimated space charges in previous step were applied to model in ANSYS software to calculate the potentials and electric fields in all nodes. These values of potentials and electric fields were used in next step of updating space charges.

#### Space charge densities correction

The last two estimated of potentials at each node,  $\Phi^{(l)}$ ,  $\Phi^{(l+1)}$  are compared. Nodal potentials error  $E_v$  is obtained. Relative to the average value of nodal potential  $\Phi_{av}$  is defined as:

$$E_{v} = \frac{|\Phi' - \Phi^{l+1}|}{\Phi_{av}}$$
(32)

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Where

$$\Phi_{av} = \frac{|\Phi^{l} + \Phi^{l+1}|}{2}$$
(33)

If the maximum nodal potential error exceeds a specified error  $\delta_{l}$ , a correction of  $\rho_{l,N}$  which is the space charge density at the last node of each field line, was made. The correction follows by Equation 32,

$$\rho_{i,Nnew} = \rho_{i,Nold} \left[ 1 + f \max\left\{ E_{v} \right\} \right]$$
(34)

Where f is an acceleration factor, take equal to 0.5.

## **Converge condition**

The C-D steps repeated until the maximum error in calculation of potential become less than a specified error  $\delta_2$  which is in our study 0.05.

## Calculation of corona current

For each applied voltage above the onset value, corona current is equal to the sum of current flowing, i.e.

$$I = \sum_{i=1}^{M} J_i A_{i,1}$$
(35)

$$J = k\rho E \tag{36}$$

Then:

$$I = k(\rho_{1,1}E_{1,1}A_{1,1} + \dots \rho_{M,1}E_{M,1}A_{M,1})$$
(37)

# Calculation of corona current considering ion diffusion factor

When the diffusion ions considered by Equation 36 as function of electric field *E*, ion draft velocity v relative air density  $\delta$  [14], then in step of updating space charges, instead of Equation 26, Equation41 must to be solved. In this state the corona current can be calculated as under expression:

$$D = [0.3341 \times 10^{9} (E' / \delta)^{0.54069}][\upsilon / E] \quad cm^{2} / s$$
(38)

$$\vec{J} = k\rho\vec{E} - D\frac{\partial\rho}{\partial l}$$
(39)

$$\frac{\partial \rho}{\partial l} = \frac{1}{D} (k \rho \vec{E} - \vec{J}) \tag{40}$$

$$\frac{\partial \rho}{\partial l} \,\hat{a}_l = \frac{1}{D} (k \cdot \rho (l + \Delta l) \cdot E(l + \Delta l) - J(l)) \tag{41}$$

$$I = k \sum_{i=1}^{M} \rho_{i,1} E_{i,1} A_{i,1} - D \sum_{i=1}^{M} \frac{\rho_{i,1} - \rho_{i,2}}{\Delta r_i}$$
(42)

For solving above equations, ANSYS software is implemented.

## **Result and Discussion**

Proposed method was applied for two conductors to plane configuration. A sample of grid for one investigated configuration [7], [8] is shown in Figure 3. The number of element is 703 with 1445 unknown nodal potentials. V-I characteristics of this configuration for present method and previous method [8] as well experimental result are shown in Figure 4. The specifications of studied conductor are: height H=0.495m, Radius R=0.00165m and surface factor  $\eta$ =1.

It is clearly that obtained results with proposed method is closer to the experimentally values. In this case study, the differences between results of proposed method with experimental value under various









applied voltage, is shown as histogram in Figure 5. The maximum mismatch between proposed method and experimental value is 2.5%, which shows the accuracy and persistence the proposed method. In Figure 6 the effects of diffusion coefficient is shown.

This figure shows that the result value when considering ion diffusion is closer to experimental value. To investigate the result of

this method for full scale model a real transmission line is analyzed. The specifications of studied full scale line is height H=9.35m, radios R=0.01020m and surface factor  $\eta = 0.75$ . It is worth mentioning that when ion diffusion D as defined by Equation 38 is considered and used in calculation, the number of iterations was increased; however the number of iteration in two state, with and without D calculation, is less than previous method. The numbers of iteration for convergence for two case studies are reported in Table 1. From this table, the total numbers of iteration for convergence of proposed algorithm without considering ion diffusion are less than [15]. Also the table show that the numbers of iteration for convergence with considering ion diffusion by proposed algorithm.

It is worthy to mention that when space charges were applied to model, the distribution of electric and potentials were changed that this effect is shown in Figure 7-a and7b. The applied voltage in this state is 60 kV. The variation of electric field on ground plane before and after applying space charges was shown in Figure 8a and 8b. To investigate the accurate of this method the characteristic of electric field on ground plane with this method and experimental values is shown in Figures 9 and 10.

The figure shows that result of proposed method is closer to



 $\label{eq:Figure 6: Calculated V-I characteristics of a conductor with and without considering ion diffusion in comparison with obtained experimentally.$ 

With considering ion diffusion		Without considering ion diffusion	
Proposed Algorithm	Proposed Algorithm	Reference [15]	Configuration
9	6	15	R=0.00165 H=0.495
15	12	21	R=0.0102 H=9.35

Table 1: Total number of iteration for convergence.



**Figure 7:** Distribution of electric potentials in space of between conductor and ground plane, (a) Before applying space charges and (b) After applying space charges.



space charges (b) after applying space charges.





experimental value. Figures 11 and 12 shows the great effect of changing the conductor radius on corona current. As can be seen from the figure, by increasing the radius of conductor the amount of the corona is decreased. Finally, at large conductor radius, corona current has been disappeared.

It has been found that when the distance of two electrodes is increased, the onset field reduced, and this effect decreases the probability of ionization, and leads to lower corona current. Another case that is worthy to investigate is the effect of surface factor and roughness of the surface on corona current. The surface factor is depended of quality of conductor surface, and when it washed this

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factor improved and reduced (Figure 13). The large surface factor means that the surface is better and the corona current is lower.

Figure 14 shows the corona critic voltage for electrical conductors under different ambient temperature in standard atmospheric pressure (101 kPa). As can be seen from the figure, the corona voltage is greatly affected by the ambient temperature.

## Conclusion

A new computational finite element method for corona power loss was presented. In this new computational algorithm, some effects of various parameters on corona current were investigated such as: the height of conductor, the radius of conductor, the surface factor,



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distribution of electric potentials in space of between conductor and ground plane with applying space charges, and ambient temperature. The proposed results compared with the previous method and confirmed the result accuracy.

Some of the novel results from the proposed method are:

- Reduce the number of iteration for calculation of the corona current.
- Considering ion diffusion as variable parameter.
- Updating space charges

The effect of ion diffusion coefficient is as function of electric field in calculation of power corona loss.

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