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CORONA MODEL FOR SURGE WAVE PROPAGATION ALONG THE TRANSMISSION LINES

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Abstract. Drift-diffusion model of the corona discharge is used to simulate the charge-voltage dependence for wire conductors. Simplifications of the calculations are examined in order to implement the corona model for analysis of the surge wave propagation along the transmission lines due to atmospheric discharges.

1. INTRODUCTION

Atmospheric discharges are observed by its pronounced visual and sound effects. For the engineering practice the atmospheric discharges between clouds and ground are of the most importance, causing the damage to objects and the electronic devices and injuring the people. Lightning strokes to the parts of the energy distribution system such as transmission lines and substations can lead to interruptions in the electricity supply to a large number of people and industrial plants (see Hileman 1999). A large number of lightning strokes affect transmission lines that stretch over long distances and areas of diverse relief. Overvoltages caused by lightning discharges travel along the conductors and they can reach substations.

After the overvoltage is generated by lightning stroke into the tower or in one of the conductors, the surge waves propagate along the overhead lines. In the analysis of the propagation of voltage and current waves along the overhead line due to direct lightning stroke, the corona envelope that forms around the conductor has the prevailing effect on the change of the magnitude and the velocity of the surge pulse during the propagation. Corona discharge causes the attenuation and the distortion of surge waves due to the losses that occur due to air ionization as well as the delay of the pulse caused by increasing the line capacitance. Part of the surge voltage wave which is above the corona threshold will propagate with a speed less than the speed of the light (see Cooray 2008).

2. CORONA MODEL

Corona is a partial discharge that occurs around the tip of sharp electrodes in air with a small curvature radius, inside the volume with a very inhomogeneous electric field. It can be described by the continuity equations for one or more types of particles involved in the discharge (see Morrow 1985). For our simulations, we used the drift-diffusion model for the particles' dynamics with four continuity equations for electrons, positive ions, O^- and O_2^- negative ions,

$$\frac{\partial n_e}{\partial t} + \vec{\nabla} \cdot \left(n_e \overrightarrow{W_e} - D\nabla n_e\right) = S_{ph} + n_e(\alpha - \eta_2 - \eta_3)\left|\overrightarrow{W_e}\right| - n_e n_p \beta + k_{det} n_{O_2^-}, \quad (1)$$

$$\frac{\partial n_p}{\partial t} + \vec{\nabla} \cdot \left(n_p \overrightarrow{W_p}\right) = S_{ph} + n_e \alpha \left|\overrightarrow{W_e}\right| - \left(n_e + n_{O^-} + n_{O_2^-}\right) n_p \beta, \quad (2)$$

$$\frac{\partial n_{O^-}}{\partial t} + \vec{\nabla} \cdot \left(n_{O^-} \overrightarrow{W_n}\right) = n_e \eta_2 \left|\overrightarrow{W_e}\right| - n_{O^-} n_p \beta, \quad (3)$$

$$\frac{\partial n_{O_2^-}}{\partial t} + \vec{\nabla} \cdot \left(n_{O_2^-} \overrightarrow{W_n}\right) = n_e \eta_3 \left|\overrightarrow{W_e}\right| + n_e \alpha \left|\overrightarrow{W_e}\right| - n_{O_2^-} n_p \beta - k_{det}\cdot, \quad (4)$$

respectively. On the right hand side of the equations (1)-(4) the terms containing the coefficients α, η_2, η_3, β and k_{det}, represent the gain and the loss of the particles due to electron impact ionization, two-body attachment, three-body attachment, the recombination and the detachment, respectively. The term S_{ph} denotes the generation of electrons and positive ions through the photoionization, whereas W_e, W_p and W_n are the drifts of electrons, positive and negative ions, respectively. The diffusion coefficient for electrons is denoted as D whereas the diffusion of heavy ions is neglected. Therefore the ionic current has only a drift component. Other details about the values of the transport and the reaction coefficients, boundary and initial conditions are given in Ignjatovic and Cvetic 2021.

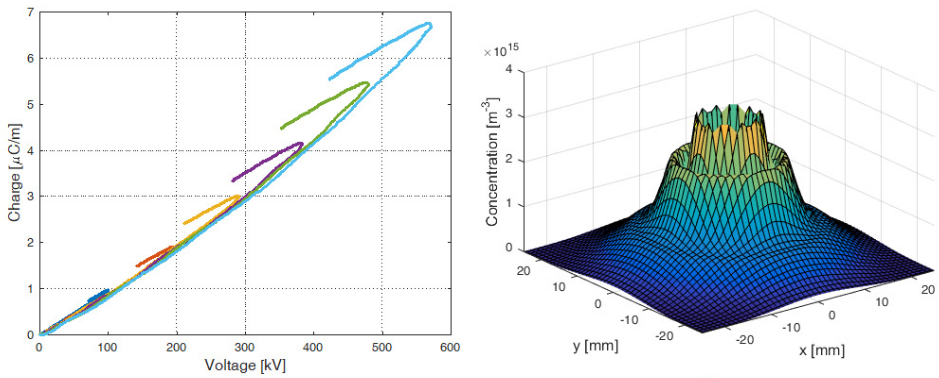
This model allows a detailed analysis of the temporal evolution and the spatial dependence of the concentration of several types of particles involved in the gas discharge. Equations can be solved for two configurations of electrodes: coaxially placed wires and cylinders and the wires placed above the plane. In the case of the coaxial configuration, due to the radial symmetry, the problem is reduced to 1D equations with one radial coordinate. In the case of wire above ground that exists below the overhead lines, it is necessary to solve the equations of the drift-diffusion model in 2D geometry.

3. DISCUSSION AND RESULTS

In order to simulate the propagation of the surge wave along the overhead line, it is necessary to solve the equations of the drift-diffusion model coupled with the telegraphers' equations. The drift-diffusion model is used to calculate charge-voltage dependence (QV curve) for the conductor, which is then implemented in the telegraphers' equations. Noda et. al. measured QV curves for overhead wire with a radius of 5 mm, which is located at height of 1.83 m above ground (Fig. 1a), for the voltage pulse amplitudes of 100-600 kV.

The corona discharge simulation requires a large number of time steps. It takes a million time steps to calculate a discharge that lasts 5 μs, so the execution of the program takes a long time, especially when coupling with the telegraphers' equations. For this reason, there is great necessity for speeding up the calculations. Therefore, corona is simulated only at a certain number of positions along the wire, and the values of the charge in the space in between are obtained by linear interpolation.

Other important goal is to try to reduce a calculation in 2D geometry to 1D equations. The simulation of corona discharge in the geometry used by Noda is performed. Entire duration of the voltage pulses is 6.5 μs. The result for electron concentration in the immediate vicinity of the wire in 1.71 μs using 2D equations is shown in Fig. 1b. In the area where the corona discharge takes place, there is a high degree of radial symmetry of the electric field, and thus the concentration of charged particles. That means that radially symmetric 1D equations can be used for the simulation, which significantly reduces the time needed for the calculations.



(a) (b)

Figure 1: (a) QV curves measured by Noda, (b) Electron concentration around the wire for the 600 kV voltage pulse

In order to simplify the calculations even more, the photoionization can be neglected. All these calculation optimizations are justified, since we are not interested in detailed microstructure of the corona discharge, but only the QV curve is needed, which is an integral characteristic of the discharge. Additionally, optimization of the coefficient α is performed in order to take account the effect of streamers (see Ignjatovic et al. 2019). Due to the existence of the streamer, additional charge will be generated in the area away from the central wire in which the electric field has lower values. The modification is performed so that the coefficient α has a sufficient value for the impact ionization even when the value of the electric field drops to a certain limit, which is in this case 1.5 MV/m. In this way, we were able to obtain good agreement with the experimental measurements, as can be seen in Fig 2.

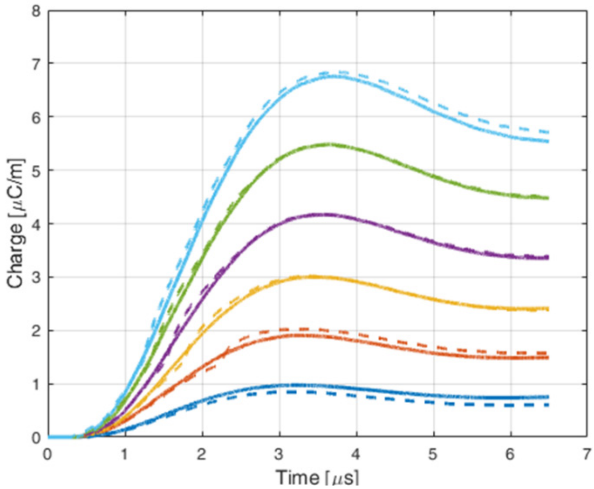


Figure 2: Measured (solid line) and calculated (dashed line) line charge density for the voltage pulses used by Noda

4. CONCLUSION

Having in mind the significant effect of the corona in the propagation of surge impulses along transmission lines, the possibilities of using drift-diffusion model for estimating the QV curves are examined. It was found that the results of 2D simulations give radially symmetric solutions of the electric field and the concentration of the particles in the vicinity of the wire. Therefore 1D equations can be used for the simulations which is less time consuming. Additionally, for the calculation of the overall generated charge, the influence of the photoionization can be neglected. With these simplifications, a very good agreement with the results of the experiments performed by Noda was obtained.

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