

MODELLING OF ELECTRIC FIELD DISTRIBUTION FOR PARTIAL DISCHARGES IN AIR

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Abstract: Partial discharges in air exhibit different forms which depend on such factors as air condition, electrode arrangement and the waveform of the test voltage. The main mechanisms of partial discharges in air are electron avalanches, local streamer discharges and surface discharges. The paper refers to corona discharges, which occurrence in high voltage overhead transmission lines lead to electromagnetic interferences and losses during power transmission. Initiation and development of this phenomenon depends on the electric field in the proximity of the phase conductors. The electric field strength on the surface of the corona source influences the size of the ionization air zone, thus the radius of the corona zone. In the modelling of partial discharges the distribution of the electric field is a key parameter. In simulations of corona discharges the point-to-plane configuration (characteristic for corona initiation) was used. On the basis of numerical modelling the ionization zone of corona discharges and the influence of point-to-plane electrode parameters are presented.

Keywords: Corona discharges, ionization zone, electric field distribution, FEM simulations.

1. INTRODUCTION

Partial discharges (PDs) in air exhibit different forms depending on air condition, electrode arrangement and a voltage waveform [1-3]. Corona is a form of partial discharges in air, which appears around the high voltage overhead line conductors, assuming the electric field strength on their surface has sufficient value for the impact ionization and development of electron avalanches. Initial corona field strength is typically determined from an empirical Peek formula [3], which takes into account the radius of the phase conductors and atmospheric conditions. A model distribution of the electric field and potential in the environment of a single wire of an overhead line is shown in Figure 1. Regardless of weather conditions (rain, ice), especially significant decrease in the initial field strength E_0 is caused by roughness of the surface of the phase conductor, for example due to breaking of a single wire in the multiconductor line. It leads to local enhancement of the electric field strength and an increase of corona intensity. Defects on fittings and insulators give similar effects.

In air insulating systems, the corona inception field E_0 is related to the inception voltage U_0 . Due to a change of the electric potential gradient in the inter-electrode space, the corona zone is limited to the immediate proximity of the high voltage electrode.

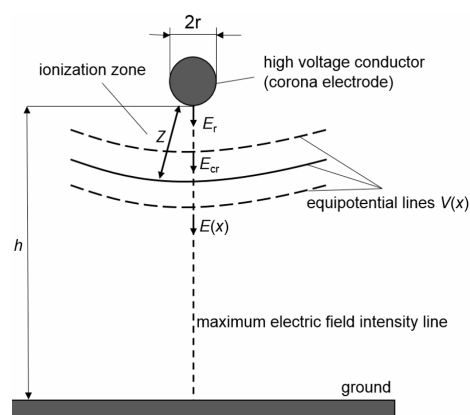


Fig. 1. Model setup: conductor of the overhead line and ground surface: r – radius of the HV conductor, h – distance between the conductor and ground, E_r – electric field strength on the conductor surface, E_{cr} – critical corona field strength

In this article the influence of various factors on the electric field distribution and ionization zone in the proximity of the corona electrode is presented based on the FEM simulations.

2. MODEL ARRANGEMENT OF CORONA DISCHARGES

Both in laboratory research and theoretical analysis corona is modelled by point-to-plane arrangement (Fig. 2), in which the point electrode may have a positive or negative potential at DC voltage as well as high or ground potential at alternating voltage. Characteristic areas of electron impact ionization (α processes) and electron attachment (η processes) form the following zones:

- I: $r < x < r_s$ – ionization zone and streamer discharges,
- II: $r_s < x < r_u$ – electron avalanche zone, $\alpha > \eta$,
- III: $x > r_u$ – zone where both impact ionization and electron attachment in air are equally possible $\alpha = \eta$,

where: α – Townsend impact ionization coefficient, η – electron attachment coefficient [2].

The ionization and space charge build-up zone is represented by the capacitance C_c (Fig. 2). A sudden discharge of this capacitance causes current pulses with a high frequency bandwidth.

At alternating voltage those PD pulses, having different amplitudes and waveforms, are localized in various phase

ranges of the voltage [4]. The streamer discharges having velocity in the range of 1 m/μs develop in the ionization zone. The boundary of this zone is determined by the conditions: $E_r > E_0$ and $E(x) = E_0$. It is the area of photoionization and luminescence.

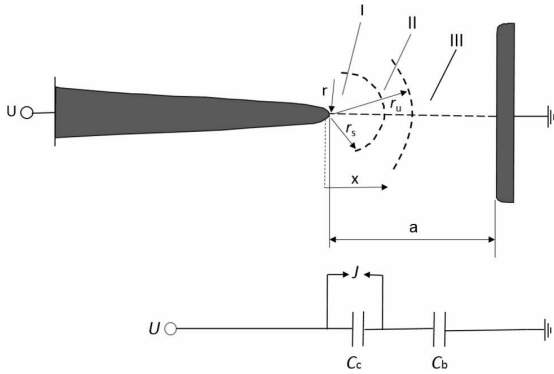


Fig.2. Point-to-plane electrodes configuration (top) and its equivalent circuit (bottom), J - spark gap representing the corona zone, C_c - capacitance of the corona zone, C_b - capacitance of the remaining area

3. ELECTRIC STRESS IN THE POINT-TO-PLANE ELECTRODE SYSTEM

The corona inception conditions and the range of the corona zone ξ depend on the curvature radius of the HV electrode, distance between electrodes and applied voltage. In calculations of the electric field distribution in the point-to-plane electrodes configuration one can assume that the needle electrode can be represented by a hyperboloid surface. The electric stress distribution along the axis of the needle-to-plane electrode arrangement can be approximated by the equation (1) [1].

$$E(x) = \frac{2U}{\ln(4a/r)} \cdot \frac{1}{2x + r - (x^2/a)} \quad (1)$$

where: U – applied voltage, a – distance between the needle and the plane electrodes, r – radius of the needle electrode tip, x – distance from the needle tip.

Equation (1) describes the axial electric field $E=f(x)$ in the needle-to-plane electrodes configuration according to Figure 3. Distance $\xi = r_u - r$, from the point electrode, determines the range of the corona zone where $E(x) = E_0$.

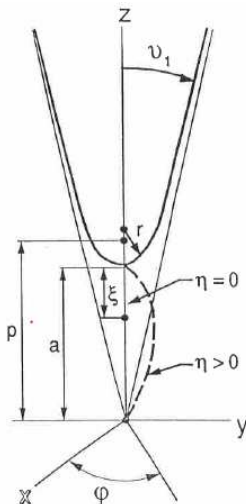


Fig. 3. Configuration of the needle-to-plane electrode system: a - distance between the needle and the plane electrode, r – radius of the needle tip, ξ – distance from the needle electrode [1]

4. MODELLING APPROACH

Simulations of the electric field distribution have been done by means of the COMSOL Multiphysics v5.1 software. A two dimensional axis-symmetrical simulation model was created using the *Electric Currents* program interface according to Figure 3. The following stationary equation is being solved for the voltage field in the frequency domain [5]:

$$\nabla \cdot [-(\sigma + j\omega\epsilon)\nabla V] = 0 \quad (2)$$

where: σ – electrical conductivity, V – electric potential, ϵ – dielectric permittivity, ω – angular frequency.

Then, the electric potential that was obtained by solving the equation (2) is used to find out the electric field strength E in every point in space:

$$E = -\nabla V \quad (3)$$

The simulation model assumes that the needle electrode is on HV potential, while the plane is grounded. The space between the electrodes was defined as air in normal atmospheric conditions.

5. RESULTS AND DISCUSSION

5.1. Scope of work

The scope of the simulations cover the analysis of the influence of the voltage U level, radius r of the needle electrode and the distance a between the electrodes on the electric field distribution and the ionization zone ξ near the HV electrode. The ξ values have been determined for the following parameters:

- radius of the needle tip: $r = 85, 345$ and $518 \mu\text{m}$,
- distance: $a = 10, 30$ and 100 cm ,
- voltage (RMS value): $U = 10, 20$ and 50 kV .

The initial corona field strength E_0 was assumed to be equal to 21 kV/cm (at normal atmospheric conditions).

5.2. Electric field strength in the proximity of the needle electrode

The surface plot of the electric field intensity distribution in the proximity of the needle electrode is presented in Figure 4.

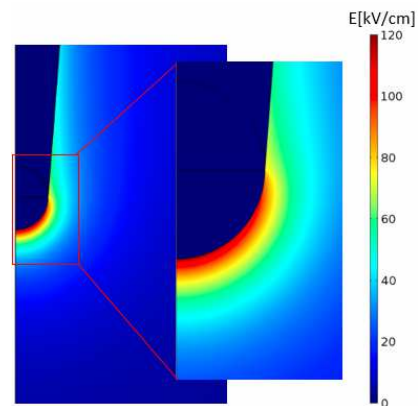


Fig. 4. Electric field intensity in the proximity of the needle electrode, $U = 10 \text{ kV}$, $a = 10 \text{ cm}$, $r = 518 \mu\text{m}$

As can be seen the electric field distribution is strongly non-uniform what is a result of a small radius of the needle. The field intensity is the highest at the surface of the needle tip and decreases with increase of the distance from the electrode.

5.3. Influence of the voltage level

The ionization zone is the area where the field strength $E > 21$ kV/cm. A change of the ionization zone ξ relative to the voltage level is presented in Figure 5.

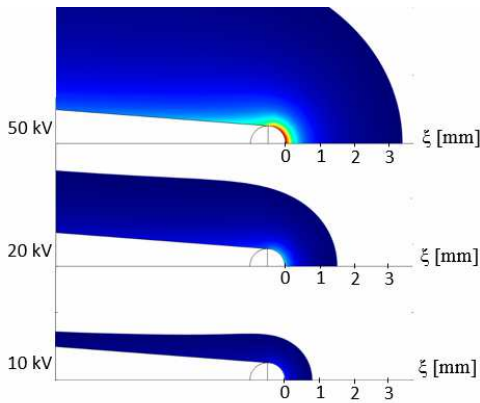


Fig. 5. Corona zone ξ ($E > 21$ kV/mm) dependence on the applied voltage U , $a = 10$ cm, $r = 518 \mu\text{m}$

The corona zone ξ increases with an increase of the applied voltage U level. For $U = 10$ kV the ξ is equal to 0,8 mm, while for $U = 50$ kV, the ξ equals to 3,43 mm.

The distribution of the electric field strength along the axis of the needle-to-plane electrode configuration is presented in Figure 6.

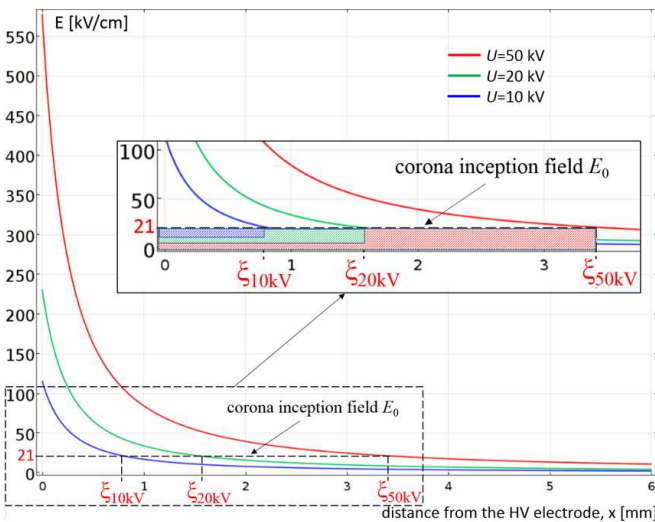


Fig. 6. Influence of the applied voltage U on the corona zone ξ - electric field strength distribution along the axis in the needle-to-plane electrode system; $a = 10$ cm, $r = 518 \mu\text{m}$

It can be seen that the electric field distribution is nonlinear and strongly dependent on the voltage U level. At the beginning portion of the distance a between the electrodes the field strength rapidly drops down and then is kept at almost constant level until reaches the ground electrode.

5.4. Influence of the HV electrode tip radius

The influence of the tip radius r of the needle electrode on the ionization zone ξ is presented in Figure 7. The distribution of the electric field strength is strongly non-uniform. The significant dependence of the maximum field strength E_{max} on the tip radius can be observed – the smaller is the radius of the needle electrode, the higher is the maximum field strength. The corona discharges zone is also dependent on the electrode radius but its dependence has

a lower significance comparing to the relation $E_{\text{max}}(r)$. The corona zone ξ increases with an increase of the tip radius of the HV electrode (for the assumed values of U and a).

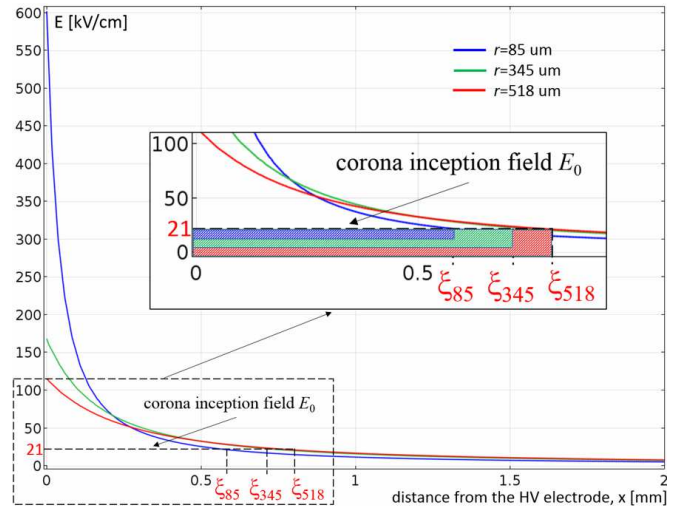


Fig. 7. Influence of the electrode tip radius r on the corona zone ξ - electric field strength distribution along the axis in the needle-to-plane electrode system; $a = 10$ cm, $U = 10$ kV

5.5. Influence of the distance between electrodes

The influence of the distance a between the test electrodes on the electric field strength E distribution and the ionization zone ξ is presented in Figure 8.

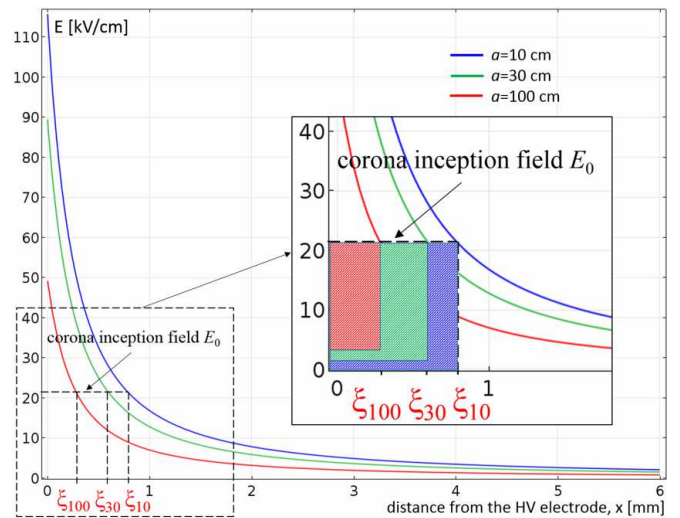


Fig. 8. Influence of the distance a between electrodes on the corona zone ξ - electric field strength distribution along the axis in the needle-to-plane electrode system; $U = 10$ kV, $r = 518 \mu\text{m}$

The electric field strength E distribution is of a similar character as in Figure 6. The longer is the distance between the electrodes, the lower is the maximum electric field strength E_{max} and the corona discharges zone ξ . The highest field intensity occurs at the HV conductor surface and decreases towards the grounded plane electrode.

5.6. Ionization zone ξ

As it was presented above, the corona or ionization zone ξ changes relative to the variation of the voltage level and geometrical properties of the model electrode setup.

The comparison of the ξ values depending on the voltage U , the electrode radius r and the distance a between the electrodes is presented in Table 1.

Table 1. Comparison of the ζ values depending on the voltage U , the electrode tip radius r and the insulation distance a

Values of ζ at $U=10$ kV			
$r \backslash a$	10 cm	30 cm	100 cm
85 μm	0,59 mm	0,5 mm	0,33 mm
345 μm	0,77 mm	0,61 mm	0,34 mm
518 μm	0,81 mm	0,61 mm	0,28 mm
Values of ζ at $U=20$ kV			
$r \backslash a$	10 cm	30 cm	100 cm
85 μm	1,09 mm	0,91 mm	0,6 mm
345 μm	1,44 mm	1,15 mm	0,67 mm
518 μm	1,55 mm	1,21 mm	0,69 mm
Values of ζ at $U=50$ kV			
$r \backslash a$	10 cm	30 cm	100 cm
85 μm	2,44 mm	2 mm	1,31 mm
345 μm	3,16 mm	2,51 mm	1,54 mm
518 μm	3,43 mm	2,67 mm	1,59 mm

As can be seen, the value of ζ is significantly dependent on the voltage U and geometrical properties (r and a) of the electrode arrangement. In the analyzed case of the model electrode setup, the ζ parameter was the lowest (0,28 mm) for $U=10$ kV, $r=518$ μm and $a=100$ cm. The highest ζ value (3,43 mm) refers to the case with $U=50$ kV, $r=518$ μm and $a=10$ cm. Based on the results presented in Table 1, it can be concluded that level of the applied voltage U and the distance a between the electrodes has a significant impact on the ζ value. The influence of the electrode tip radius r on the ζ is of lower significance. The radius r has the major impact on the maximum electric field E_{max} strength at the electrode surface.

Figure 9 show how the ζ value changes with the variation of r and a at constant voltage $U=10$ kV ($\zeta=f(r,a)$, $U=\text{const.}$)

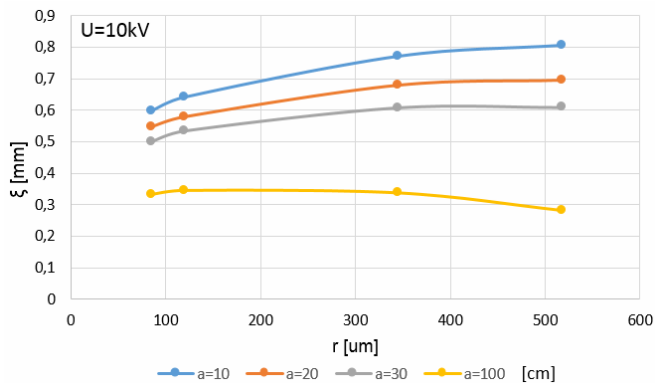


Fig. 9. Characteristic $\zeta=f(r,a)$ at constant AC voltage $U=10$ kV

MODELOWANIE POLA ELEKTRYCZNEGO PRZY WYŁADOWANIACH NIEZUPEŁNYCH W POWIETRZU

Wyładowania niepełne w powietrzu, występujące w otoczeniu elementów o dużej krzywiznie oraz w polu elektrycznym silnie nierównomiernym, charakteryzuje mechanizm lawinowo-strimerowy. Artykuł dotyczy jednej z form wyładowań niepełnych w powietrzu jaką jest ulot elektryczny w elektroenergetycznych liniach przesyłowych wysokiego napięcia. Od wartości natężenia pola elektrycznego przy powierzchni elektrody ulotowej zależy wielkość strefy zjonizowanego powietrza w jej otoczeniu, a więc tzw. zasięg strefy ulotowej. Dla modelowej konfiguracji elektrod, reprezentującej warunki inicjowania i rozwoju wyładowań ulotowych, przedstawiono numeryczne symulacje wpływu krzywizny elektrody ulotowej, odstępów między elektrodami i wartości napięcia przemiennego na zasięg strefy ulotowej.

Słowa kluczowe: Wyładowania niepełne, ulot elektryczny, strefa jonizacji, rozkład pola elektrycznego, modelowanie MES.

It can be seen that at constant voltage U , with simultaneous increase of the electrode tip radius r and the distance a between the electrodes, the ζ values firstly rise up to a certain point and then start to decrease.

6. CONCLUSIONS

The corona type partial discharges create the ionization zone in the proximity of the high voltage electrode. The range of this zone ζ depends mainly on the applied voltage U and distance a between the electrodes, whereas the influence of the radius r of the corona electrode is smaller. The radius r has the dominant impact on the maximum electric field strength E_{max} at the corona electrode surface. For the assumed values of various parameters the ζ ranges from fraction of mm up to few mm.

The air ionization zone is an area of space charges. At AC voltage those charges practically have no influence on the electric field distribution, thus also on the partial discharge mechanism. However, at DC voltage those charges distort the field distribution and the effect depends on the polarity of the high voltage electrode. This problem is currently analyzed and the modelling results of the range of corona zone for positive and negative polarity of the HV electrode will be presented in the next paper.

7. REFERENCES

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