Numerical simulation of the outdoor insulator breakdown

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Abstract. The article is devoted to the development of a mathematical model of an insulator breakdown and the methodology for assessing the development of a breakdown. The main calculation expressions are presented in the article. The design of a real insulator (the outdoor voltage insulator of 35 kV type IOSK 3/35 UHL1) is presented as an example of the technique applicability. The datasheet of this outdoor isolator was used to verify the mathematical model and the results of numerical simulation. The results of numerical simulation and the outdoor insulator breakdown voltage are presented in the article. Numerical simulation was carried out in Comsol Multiphysics software. The obtained results can be applied in the engineering design of outdoor insulators and elements of electrical constructions.

1. Introduction
The reaction properties necessary for calculating the discharge are described by the cross section, more precisely, by the dependence of the reaction cross section on the electron energy $\sigma(\varepsilon)$ [1]. However, there is a more convenient value for estimates and engineering calculations and it’s the number of collisions per unit length of the drift. This quantity is simply called the ionization coefficient ($\alpha$) for ionization and the sticking coefficient ($a$) for sticking [1]. And usually use values of electric field distribution because it is the source that is known in the task (or can be easily found) [2-10]. As a result, it is possible to imagine that the electron moves along the force line of the electric field and experiences ionization and sticking on a unit length.

The coefficients ($\alpha$ and $a$) depend on pressure and the law of similarity is true for them:

$$\frac{\alpha}{p} = f \left( \frac{E}{p} \right),$$

where $f \left( \frac{E}{p} \right)$ is some specific function for different gases. This function can be described by polynomial dependence in a given approximation for dry air:

$$\alpha = p \left( 1.605 \left( \frac{E}{p} \right)^2 - 6.951 \left( \frac{E}{p} \right) + 7.2371 \right)$$

Avalanche process is possible, if the probability of sticking is less than the probability of ionization, then the number of electrons will increase in an avalanche:
\[ \alpha (E) > a(E) \] (3)

When \( E \to 0 \) the ionization coefficient tends to zero and the sticking coefficient tends to infinity. The fact is that the ionization process has an energy threshold, and it cannot be overcome in the absence of an electron energy source, the sticking reaction does not have a threshold, because it is energetically favorable. Thus, condition (3) establishes the lower limit of electric field value at which the development of an avalanche is possible. The avalanche fades quickly with less electric field. This limit is about 24.5 kV/cm at atmospheric pressure in air and this value usually use as breakdown criteria [6,8,11-15]. But this method of assessment is not sufficiently accurate and ineffective.

It is important to remember that the limits of applicability of the sticking and ionization coefficients are narrower than the limits of applicability of the reaction cross section. The main condition is the collision of electrons only with neutral unexcited molecules, collisions with "secondary particles" can be neglected. The secondary particles are all those particles that are not in the initial gas composition - they appear as a result of the discharge process (ions, excited molecules, dissociation products). Thus, the ionization and sticking coefficients are applicable at low electron concentrations (i.e., prebreakdown and recombination modes).

The integration of the ionization coefficient along the electric field lines is used as a criterion for the probability of breakdown/recombination for engineering calculations:

\[ \int \alpha dl = K \]

where \( K \) is criterion (\( K=18 \) for dry air).

The mathematical model was developed on the basis of the described theory, completely repeating the actual design of the outer insulator in order to test the proposed methodology.

The geometry of the outdoor insulator and some of the parameters are shown in Figure 1.

Figure 1. The geometry of outdoor insulator (IOSK 3/35 UHL1).

2. Description of outdoor insulator breakdown model

Numerical simulation is implemented in the Comsol Multiphysics software using the physical interface "Electrostatics". The basis of the physical interface is the Gaussian law for the electric field. The variable is scalar electric potential.
The basic equations of "Electrostatics" physical interface:

\[
\begin{align*}
E &= -\nabla V \\
\nabla \cdot (\varepsilon_0 \varepsilon, E) &= \rho_v
\end{align*}
\]  

(5)

It is necessary to select the line with the maximum value of the electric field for integrating the ionization coefficient in accordance with the expression (4), which is possible using the "Mathematical Particle Tracing" physical interface, which is based on the following equation:

\[
\frac{dq}{dt} = \nu
\]  

(6)

Setting of the particles motion of (excluded their masses) along the lines of electrical field is carried out by velocity which is described by normalized electric field (see Figure 2) from the results of solving the electrostatic task.

![Figure 2. Settings of particle velocity.](image)

The computational domain is presented in Figure. 3 in full accordance with the geometry of the outdoor insulator (see Figure. 1).

![Figure 3. The computational domain of outdoor insulator.](image)

“Electric potential” \((V=V_0)\) boundary condition is also the inlet boundary condition of "Mathematical Particle Tracing" physical interface and shown in Figure. 4. Opposite side of outdoor insulator is “Ground” boundary condition \((V=0)\).
Figure 4. “Electric potential” and “Inlet” boundary condition.

Separate elements of the mesh are presented in Figure 5. Number of finite elements is 75374.

Figure 5. Mesh of the computational domain.
3. Simulation results

One of the main results of numerical simulation is the electric field distribution. The maximum value of the electric field distribution corresponding to the pre-breakdown state is about 123 kV/cm (see Figure 6). This value is much higher than the critical value of 24.5 kV/cm. This demonstrates the impossibility of the breakdown predict only by the value of the electric field distribution.

The voltage value at which the integration of the ionization coefficient along the lines of the electric field exceeds the critical value is about 104.5 kV. The trajectory of the insulator complete overlap is shown in the Figure 7.

![Figure 6. Electrical field distribution.](image)

![Figure 7. Breakdown trajectory with integral value of the ionization coefficient.](image)
4. Conclusion
The method for calculating breakdown voltage of an insulator is proposed in the article. The proposed method was tested on the example of the outdoor voltage insulator of 35 kV type IOSK 3/35 UHL1. The obtained simulation results are consistent with outdoor insulator datasheet and with Russian GOST standards 52082-2003 (Support polymeric outdoor insulators for voltage 6-220 kV. General specifications). The proposed method can significantly reduce the number of experimental studies in the design of insulators, which will lead to a decrease in financial costs.

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