Simulation of an impulse arc discharge in line lightning protection devices.

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1. Introduction

The phenomena of lightning remains to be open problem for both fundamental and applied science. Among most important lightning associated issues to solve is the lightning protection of overhead power lines. Overhead line itself is an extended conducting object with sufficient height making it vulnerable to lightning strikes which can cause insulation breakdown and formation of electric arc burning in open air. In recent years Line Lightning Protection Devices (LLPD) devices were successfully applied for solution of this problem [1]. The example of LLPD is depicted in Fig.1. In general LLPD consists of large number of discharge chambers connected in series. The example of discharge chamber is given in Fig.2. Each electrode consists of two nested tubes – inner and outer tube (see Fig.3). While the outer tube is constantly copper the material of inner tube can be copper, steel or tungsten. During normal grid operation, the device works as an insulator since the voltage over the device is insufficient to cause dielectric breakdown and arcing. Under the lightning overvoltage electrical breakdown occurs in every single chamber resulting in impulse current flowing through the LLPD. Initiated arc discharge causes erosion of the electrode material and chamber wall evaporation due to arc-wall interaction which leads to intensive pressure buildup, plasma outflow and eventually to arc extinction.

Figure 1. Multi-chamber arrester

Figure 2. Discharge chamber.

Experimental investigations allowed to discover that certain chamber designs perform arc interruption with more efficiency meaning that geometry optimization is possible. Since pure empirical approach for solving optimization problem poses severe requirements on time consumption and investment method of numerical experiment was employed to look for better chamber design.

2. Physics of Impulse Arc Discharge

In order to simplify the model and emphasize the most important processes involved several assumptions were made:

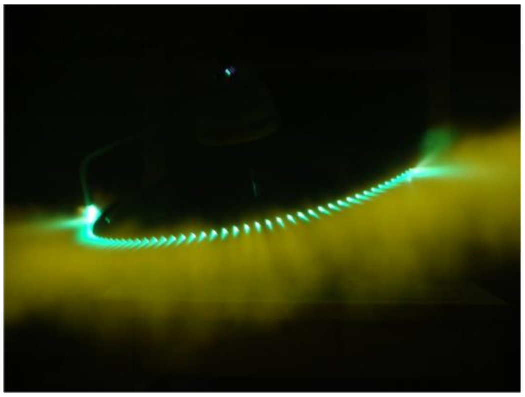

Figure 2. Multi-chamber arrester in operation mode in operation mode.

1. The flow is laminar
2. The plasma is in Local Thermodynamic Equilibrium (LTE), i.e. electron and heavy particles have the same temperature
3. Thermodynamic properties only depend on temperature
4. The influence of magnetic forces
5. The influence of electrode erosion and material ablation is taken into account

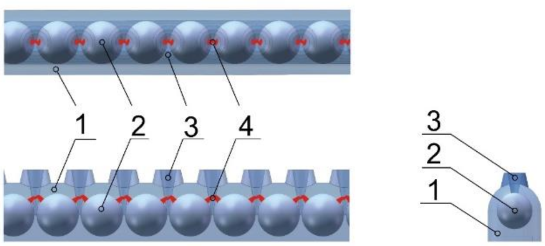

Figure 3. Multi-chamber system:1 - silicone rubber, 2 - electrodes, 3 - nozzle, 4 - arc discharge.

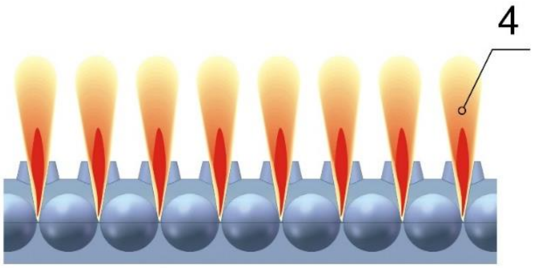

Figure 4. Multi-chamber system, plasma jet:1 - silicone rubber, 2 - electrodes, 3 - nozzle, 4 - arc discharge.

3. Governing equations

LTE allows to use conventional approach to thermal plasma simulation based on MHD equations [2]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \quad (1)$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u}) = -\nabla p + \nabla \cdot \hat{\boldsymbol{\tau}} + [\mathbf{j} \times \mathbf{B}] \quad (2)$$

$$\frac{\partial (\rho \boldsymbol{h})}{\partial t} + \nabla \cdot (\rho h \boldsymbol{u}) = \frac{\partial p}{\partial t} + \nabla \cdot (\hat{\boldsymbol{\tau}} \boldsymbol{u}) + \boldsymbol{j} \cdot \boldsymbol{E} + $$
$$+ \nabla \cdot (\boldsymbol{q}_{cond} + \boldsymbol{q}_{rad}) \quad (3)$$

Here, ρ represents the mass density of the plasma, the **u** is the gas own velocity, p is the static pressure, $\hat{\boldsymbol{\tau}}$ is the viscous part of the stress tensor, and h is the specific enthalpy. The last term of Eq. (26) represents the heat flux, which has been split into a heat conduction $\boldsymbol{q}_{cond}$ and radiative heat flux $\boldsymbol{q}_{rad}$. In order to solve the above set of equations, it is necessary to add state equations,

$$\rho = \rho(T)$$

and

$$h = h(T)$$

Data for viscosity, heat conductivity, and the electric

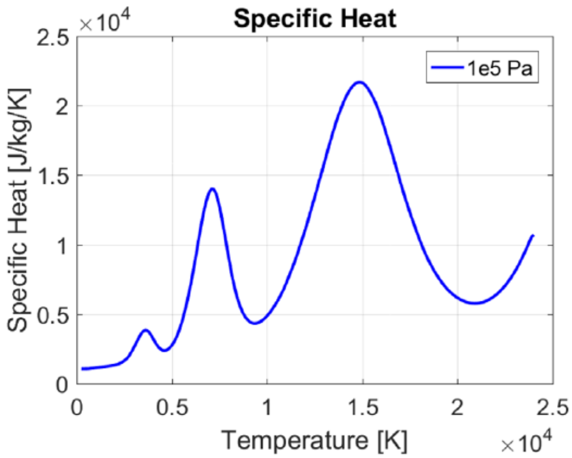

Figure 5. Lightning current pulse.

conductivity of the plasma is also needed. The coupling to the electromagnetic field is realized by

ohmic heating **j** · **E**, where **j** is the electric current density, **E** is the electric field.

The influence of self-generated magnetic field **B** such as Lorentz force [**j** × **B**], was not considered for simplification. The current density in a conducting fluid is given by

$$\mathbf{j} = \sigma \mathbf{E} \tag{6}$$

,where σ is the conductivity of the plasma.

$$\mathbf{s} \cdot \nabla I_\nu(r,s) = \kappa_\nu \left[I_\nu^b(T) - I_\nu(r,s) \right] \tag{7}$$

$$I_\nu^b(T) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{k_B T}} - 1} \tag{8}$$

$$I_\nu(r,s) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} I_m^l(r) Y_m^l(s)$$

$$G_\nu(r,s) = \int_{4\pi} I_\nu(r,s) d\Omega \tag{4}$$

$$\boldsymbol{q}_\nu(r,s) = \int_{4\pi} I_\nu(r,s) s d\Omega$$

$$\nabla G_\nu(r,s) = -3\kappa_\nu \boldsymbol{q}_\nu$$

$$\nabla \cdot \boldsymbol{q}_\nu = -3\kappa_\nu \boldsymbol{q}_\nu$$

$$\nabla \cdot \boldsymbol{q}_\nu = \kappa_\nu (4\pi I_{b\nu} - G_\nu) \boldsymbol{q}_\nu$$

$$\nabla \cdot \left(\frac{1}{\kappa_\nu} \nabla G_\nu \right) = \kappa_\nu (4\pi I_{b\nu} - G_\nu) \boldsymbol{q}_\nu$$

4. Validation of physical model

In order to verify the applicability of developed arc's model we performed a series of tests for simplistic case of open spark gap. Experimental setup is depicted on Fig. The spark was triggered in spark by pulse generator which function was to simulate lightning current. Tests were conducted for current magnitudes 3,10,20 kA, both current and voltage waveforms were recorded for all measurements. For corresponding numerical experiments we prepared 2D-axisymmetric model based on equations (1)-(3) and previously described assumptions. Computational domain mimics the arrangement of experimental setup representing the gap between electrodes and adjacent air volume. The following approximations were considered: laminar flow, turbulent flow, laminar flow with Lorentz force included, turbulent flow with Lorentz force included.

5. Use of Comsol Multiphysics

The implementation of previously described MHD equations was made by coupling CFD and ACDC module, Laminar Flow and Electrical Currents correspondingly. To model the imposed lightning current Terminal boundary condition was applied to oe of the electrode's edge. The analytic function describing the current pulse is depicted on Fig.5.

Figure 5. Lightning current pulse.

The Ohmic heating is included by addition of Heat Source in Laminar Flow with Electromagnetic volumetric loss density set. Initial temperature up to 5000 K was set in the gap between electrodes meaning to model preheating of conducting channel during breakdown stage. The total duration of simulation was set to 200 μs which stands for typical duration of lightning pulse.

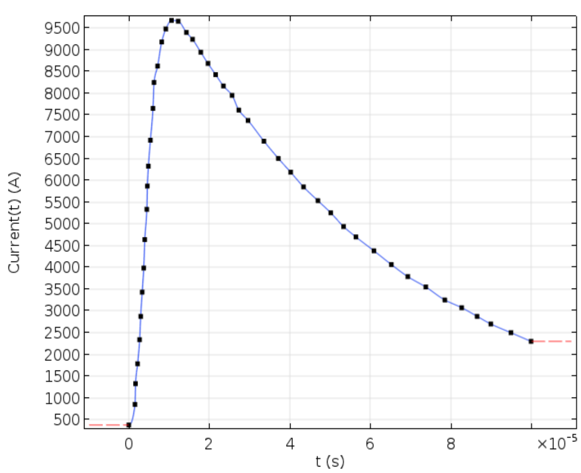

Figure 5. Lightning current pulse.

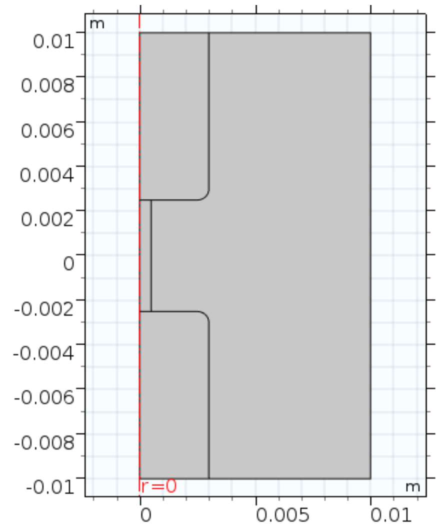

Figure 6. Pressure in discharge chamber #1 for 8 μs (top) and 100 μs (bottom)

6. Results and Discussions

You may include color simulation images. Please export your simulation images such that the final resolution of your figures is at least 300dpi.

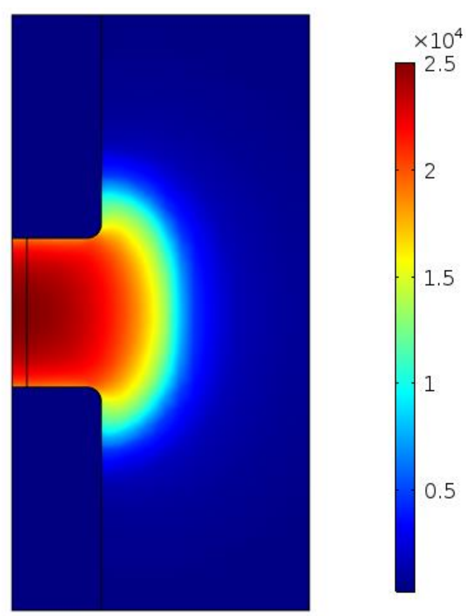

Figure 7. Pressure in discharge chamber #1 for 8 μs (top) and 100 μs (bottom)

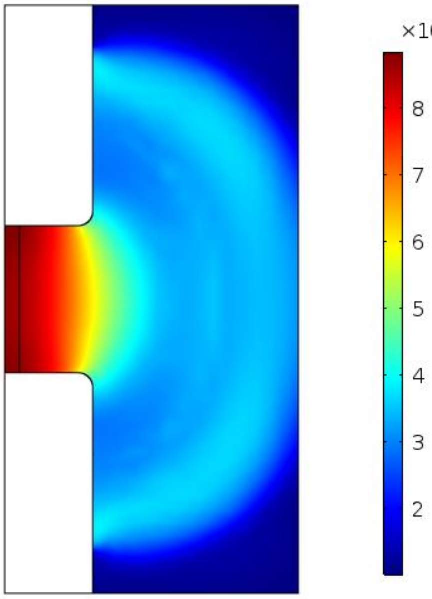

Figure 5. Lightning current pulse.

7. Conclusions

You may include any implications or conclusions obtained from your work. You may include plans for future work.

8. References

1. G. V. Podporkin, E.Yu. Enkin, E. S. Kalakutsky, V. E. Pilshikov, A. D. Sivaev. “Overhead lines lightning protection by multi-chamber arresters and insulator-arresters.” IEEE Transactions on Power Delivery, *l*, 26(1):214-221, 2010.
2. Author, *Book title*, page numbers. Publisher, place (year)

Acknowledgements