Application of numerical simulations for improvement of line lightning protection device efficiency

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***Abstract*—In this paper we report on recent progress in application of numerical modeling for development of Line Lightning Protection Devices. The ability of previously developed arc model to predict the current interruption capability of certain LLPD designs is demonstrated on real LLPD prototypes tested in high-voltage laboratory. As a case of particular design improvement we describe the calculation of optimal value of LLPD additional chamber volume.**

Keywords—lightning protection, line lightning protection device, arc, simulation, fault current

I. Introduction

The numerical modeling is being actively used for analysis of arcing processes in electrical equipment for several decades. Sufficient progress was achieved for switchgear where the method of arc simulation in its current state can be recognized as a tool for design improvement [1]. The first attempts to employ similar approach for problems of lightning protection were made quite recently. Application of thermal plasma simulation methods allowed to model the complex process of lightning attachment in case of lightning strike to aircraft [2]. Encouraged by those promising results group of researchers developed arc model to investigate the impulse discharge in Line Lightning Protection Device (LLPD) [5], [6], [7], [9]. Further research provided methods to model arc quenching process and evaluate fault current capability of certain LLPD geometry [8]. Our work is an extension of previous research made on LLPD, in this paper we describe in details the first results of LLPD design assessment using arc simulations. The paper consists of four chapters. First, we will give the brief introduction of LLPD. Second, we will describe the arc model developed previously. The third part of the text contains description of obtained results. In the last part we will give conclusions.

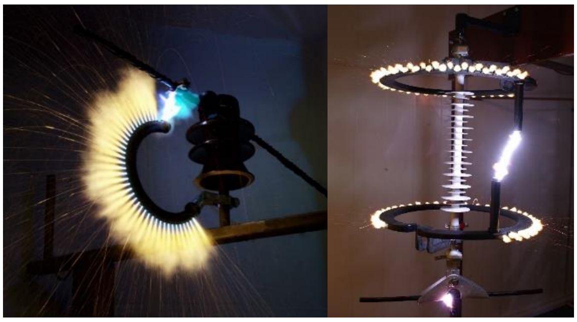

Fig. 1. LLPD testing in high-voltage laboratory

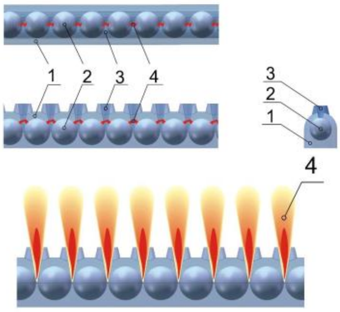

Fig. 2. LLPD: left – breakdown stage, right – plasma jet formation, 1 – silicone rubber, 2 – steel electrode, 3 – nozzle, 4 – arc channel

II. Line Lightning Protection Device

A. Principles of operation

The main element of LLPD (see Fig.1) is the system of electrodes placed in silicone rubber profile [3]. Additionally drilled channels in combination with electrodes form so called Multi-Chamber System depicted on Fig.2. LLPD must be installed in parallel to insulator of overhead power line (OHL). The electrodes are intentionally arranged in a way to provide lower critical flashover voltage in comparison to insulator so in case of lightning overvoltage applied to LLPD and arrester the arc will be initiated in LLPD discharge chambers instead of insulator surface. The breakdown in each spark gap will form the conductive path between the phase wire and the ground allowing both lightning current and fault current to flow through LLPD. The associated Ohmic heating leads to large pressure buildup, together with Lorentz forces driven by large currents they cause strong gas outflow and consequent intensive cooling of arc channel. This process eventually must result in arc quenching and recovery of dielectric strength of each spark gap i.e. successful fault current interruption. Experimental data obtained in high-voltage laboratory gives evidence to strong dependence of LLPD performance on discharge chamber geometry. The search for optimal chamber design however is extremely challenging due to complexity of testing procedure and manufacturing expenses. Numerical simulation in this context is considered as a tool for prospective design assessment.

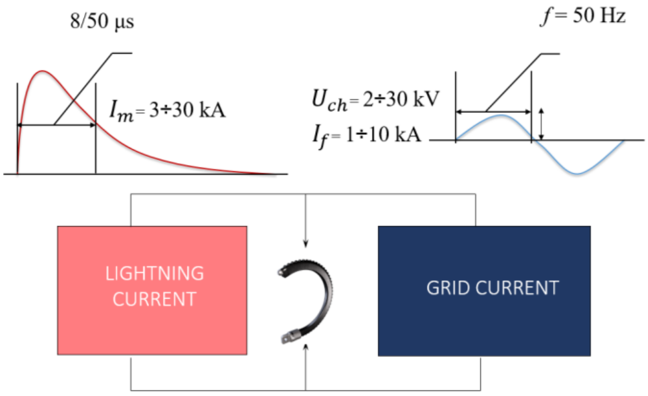

Fig. 3. Principal scheme of LLPD testing

B. *Modes of arc quenching*

The performance of LLPD under the effect of lightning overvoltage is investigated in high-voltage laboratory. In order to reproduce the conditions of lightning stroke special experimental setup was developed. The setup consists of two main parts: current pulse generator which is supposed to model the effect of lightning and oscillation circuit which stands for power grid. To conduct the test, the LLPD must be installed in parallel to both parts. The principal scheme of setup is depicted on Fig.3. From the early stage of development LLPD was meant to operate in a mode called Zero Quenching (ZQ) [3]: the fault current is suppressed in the vicinity of zero crossing analogous to circuit breakers (Fig. 4). Apparently this feature places restrictions on applicability of LLPD for power lines with large short-circuit currents since with the magnitude of fault current grows the erosion intensity. However, it was later discovered that alternative mode called Impulse Quenching (IQ) does exist and can be reliably maintained. The IQ is characterized by almost complete absence of follow current because it is damped at initial stage. The IQ goes on a much shorter scale then ZQ: 100 μs against 10 ms (Fig. 4).

III. ARC SIMULATIONS

The thorough description of arc discharge model used in calculations was given in previous papers ([5], [6], [7], [8], [9]) therefore we will not go into details and only point out model's key features. First of all, it must be said that employed approach is based on approximation of Local

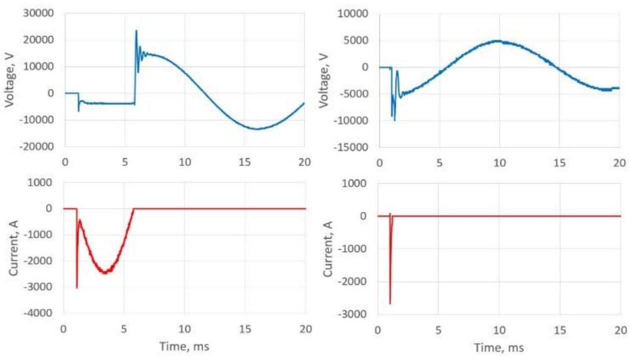

Fig. 4. Oscillogramms of LLPD's current and voltage for two quenching modes: left - ZQ, right - IQ

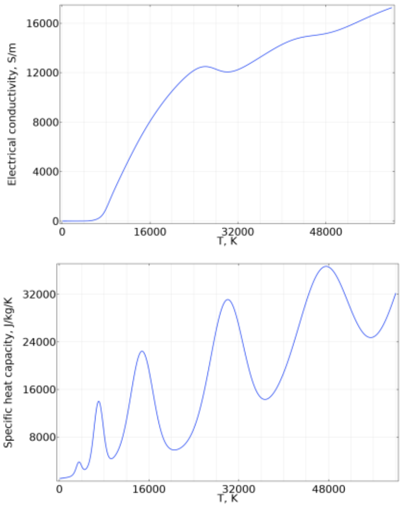

Fig. 5. Temperature dependence of air electrical conductivity (top) and specific heat capacity (bottom)

Thermal Equilibrium or thermal plasma approximation, thus the equations of Magneto-Hydrodynamics (MHD) are placed in the core of the model.

A. *Thermal plasma approximation*

The system of MHD equations consists of coupled Navier-Stokes equations and Maxwell equations:

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

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

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

In order to close the system (1)-(3) it is necessary to add equation of state. The thermodynamic and transport properties of plasma must be precomputed as functions of pressure and temperature. As an example the temperature dependences of electrical conductivity and specific heat capacity are given on Fig.5.

B. *Radiation transfer*

It is important to note that since we are dealing with pulse discharge sustained by lightning current i.e. with extremely rapid process the radiation transfer becomes the major mechanism of heat transfer. To provide the complete description of radiation dynamics one should add to system

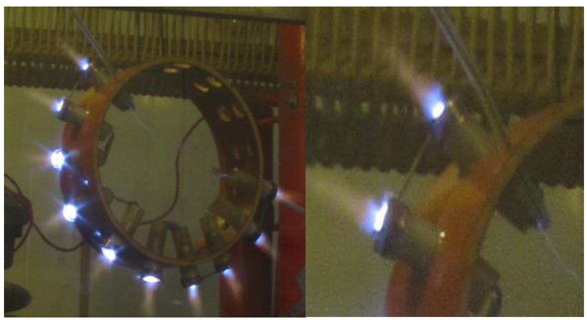

Fig. 6. Novel LLPD prototype: left – LLPD, right – LLPD discharge chamber

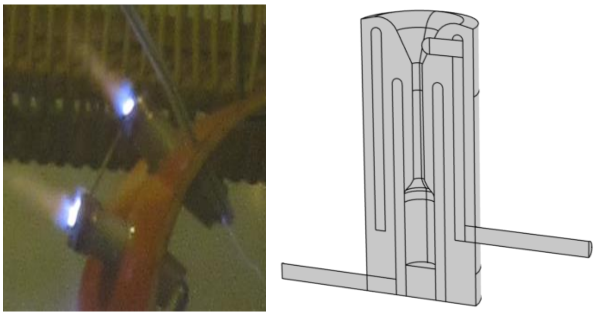

Fig. 7. 3D-model of LLPD discharge chamber

(1)-(3) the Equation of Radiation Transfer (RTE):

$$\boldsymbol{s}\cdot\nabla I_\nu(\boldsymbol{r},s)=\kappa_\nu[I_\nu^b(T)-I_\nu(\boldsymbol{r},s)] \quad (4)$$

,where $I_\nu(\boldsymbol{r},s)$ - radiation intensity in direction $\boldsymbol{s}$, defined at point $\boldsymbol{r}$, $I_\nu^b(T)$ – Planck function:

$$I_\nu^b(T)=\frac{2h}{c^3}\frac{\nu^3}{\exp\left(\frac{h\nu}{kT}\right)-1} \quad (5)$$

At the same time, it is crucial to find compromise between calculation accuracy and computation complexity because the solution of RTE often requires sufficient computational resources. Simple and efficient approach to problem was introduced in paper [8], where authors used only two spectral bands, high-frequency band and low-frequency band: from 0 to 120 nm and higher than 120 nm. The same approach was applied in our paper.

C. Arc quenching simulation

To take into account arc-circuit interaction one should include the equations of experimental setup electrical circuit which describe the transient process caused by lightning overvoltage.

IV. RESULTS

The developed simulation method was applied for investigation of novel device designed to work in IQ mode. The main problem was to determine the accuracy of LLPD switching capacity estimation obtained by modeling.

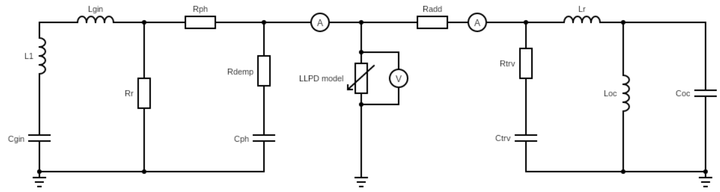

Fig. 9. Electrrical circuit scheme of experimental setup designed for LLPD testing

A. Novel LLPD prototype

The device prototype and its discharge chamber are pictured on Fig.6. This particular LLPD totally contains eight chambers however there the number of chambers can vary. The 3D model of discharge chamber is depicted on Fig.7. Each chamber consists of silicone rubber nozzle and a pair of cylindrical coaxial electrodes connected by attached rods with adjacent chambers (see Fig.8, chamber conductive part marked in blue). The coaxial electrodes are separated by rubber layer. External cylinder is supplemented by tungsten electrode which protrudes outwards from silicone rubber. Incase of lightning overvoltage this electrode will initiate the stemming of streamer discharge along the air gap between the cylinders. The discharge chamber also contains special cavity,so called additional chamber, aimed to increase the intensity of arc cooling due to back flow effect.

B. Evaluation of LLPD switching capability

For the means of developed model validation, we arranged a set of simulations according to real test conditions. In the framework of numerical experiment, we coupled the LLPD model with the model of experimental setup. As it was explained before the experimental setup consists of two principal parts: current pulse generator and oscillation circuit (Fig.3). The detailed scheme of testing electrical circuit is depicted on Fig.9. By varying the charging voltage of oscillation circuit capacitor U_{ch} one can set different values of follow current amplitude. Thus increasing the follow current up to transition from IQ to ZQ one can determine the switching capacity of LLPD. The same routine was employed

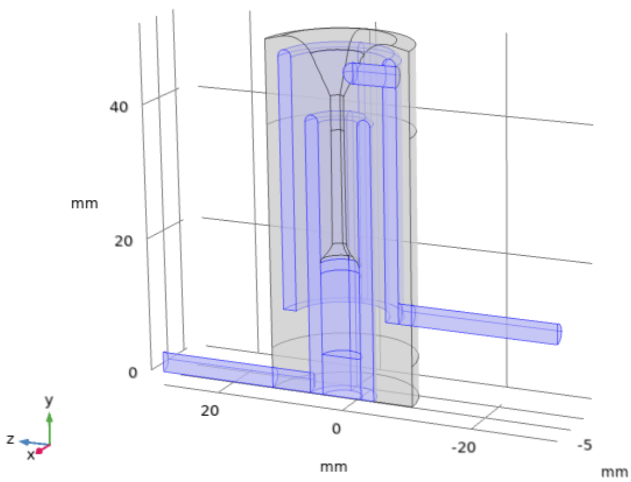

Fig. 8. 3D-model of LLPD discharge chamber (transparency)

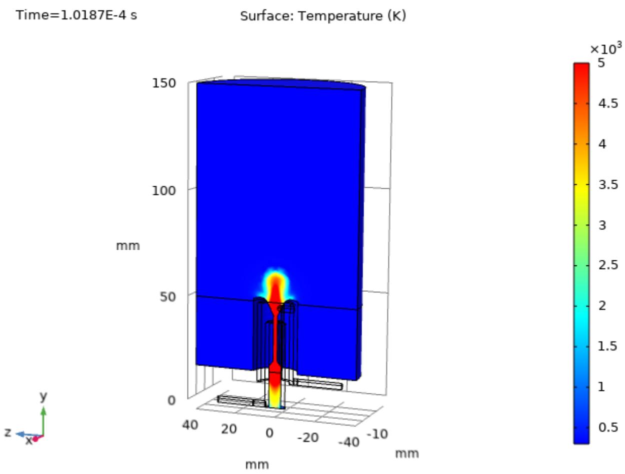

Fig. 10. Calculated temperature distribution in LLPD discharge chamber

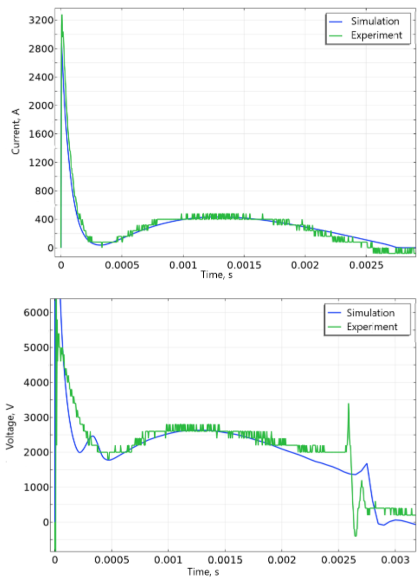

Fig. 11. Comparison of simulation results and experimental data for LLPD consisted of 4 chambers. Top – current, bottom - voltage.

in modeling, as a result the threshold value of charging voltage U_{th} corresponding to transition between the quenching modes was obtained. To simplify the plasma flow simulation, the symmetry of chamber geometry relative to vertical plane passing through the axis of nozzle and axis of electrodes was taken into account what allowed to consider only half of discharge chamber. The full current determined by circuit transient process was set on one electrode while the other electrode was grounded. Typical simulation results are depicted on Fig.10, here the temperature distribution in discharge sustained by the lightning current pulse is presented. Next, several LLPD test data samples were sorted out in order to assess the simulation precision by comparing measured and calculated voltage and current. As an example we took the case of LLPD consisted of four chambers. Pulse generator parameters were set to provide current pulse 1/50 waveform with peak value I_{peak} = 3 kA. Such moderate value of current peak corresponds to the case of back flashover. The oscillation circuit capacitor was charged to U_{ch} = 4 kV level. Both experimental and numerical results are plotted on Fig.11. The measured and calculated current and voltage are in quite a

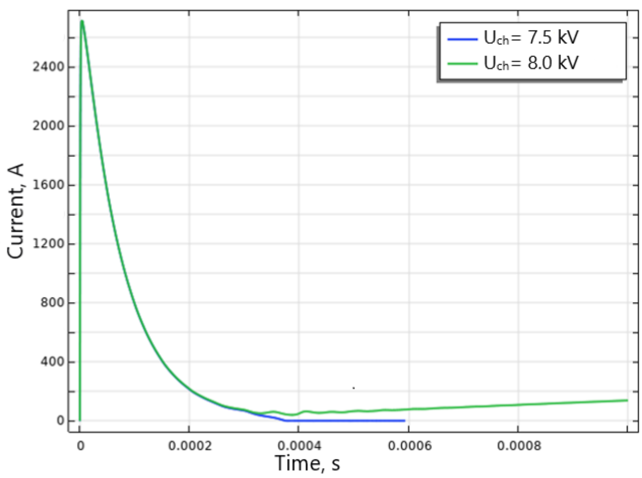

Fig. 12. Calculated current for two charging voltages 7.5 kV and 8 kV

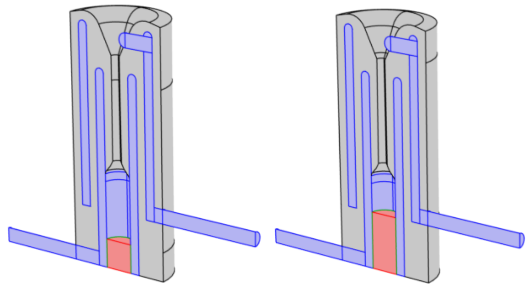

Fig. 13. Geometry of discharge chambers with different additional chamber volumes. Metall plug is marked by red: left – size of the plug - 6 mm, right – 12 mm

good agreement. It is seen that the grid current is not suppressed and since for given test conditions the ZQ was achieved both in test and in numerical experiment. In order to evaluate the ability of develped simulation procedure to predict the threshol for transition from ZQ to IQ another one numerical test was conducted. This time the device with 8 chambers was considered. The results are depicted on Fig.11: here the blue curve rperesents the current time dependence calculated for U_{ch} = 7.5 kV and the green cureve stands for current achieved for U_{ch} = 8 kV. It can be noticed that in case of 7.5 kV the current passes zero around 400 us while in case of 8 kV the current starts to grow again i.e. the follow current starts to develop. Thus the transition from ZQ to IQ mode occurs in the interval between 7.5 kV and 8 kV and the switching capacity could be roughly estimated as 7.5 kV. According to laboratory tests the threshold value $U_{th,exp}$ = 8 kV, while the calculated value $U_{th,sim}$ = 7.5 kV, meaning that the error of estimation is around 0.5 kV or 6%.

C. Calculation of additional chamber optimal volume

One of the key parameters of discharge chamber design is the volume of additional chamber – the cavity placed under the chambers nozzle. This parameter governs the intensity of air backflow which is supposed to play crucial role in arc extinction. The additional chamber volume is defined by the size of the special metal plug inserted in the chamber from the bottom. Two alternative chamber designs with plug sizes 6 mm and 12 mm are depicted on Fig.12, the plug is marked in red. As it was already mentioned several times before before the inclusion of additional chamber is expected to increase the arc cooling rate due to formation of cold gas back flow however the exact value of additional chamber volume

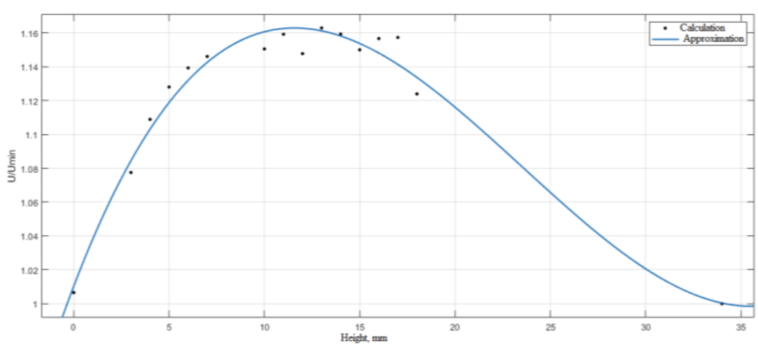

Fig. 14. Dependence of residual voltage on the size of additional chamber

which will maximize this effect is unknown and must be determined by some means. From general point of view, it should be assumed that the optimal design lies in the interval between degenerate cases – the absence of additional chamber and the additional chamber with infinite volume (open chamber). The determination of corresponding optimal volume value would be hard to accomplish by experiment since it would require enormous number of tests. Thus for such a problem statement the computational method seems to be more appropriate. To accelerate the computation process instead of switching capacity it was decided to calculate the residual voltage induced by the lightning current pulse passing through LLPD. All simulations were performed with current pulse of 1/50 waveform and peak value I_{peak} = 3 kA (back flashover rgime). Obtained dependence of calculated residual voltage on additional chamber volume (plug size) is depicted on Fig.13. As can be seen from the graph the optimal value does exist, the increase of quenching efficiency in comparison to initial design is about 16%.

V. CONCLUSIONS

Both experimental and theoretical investigations on LLPD allowed us to develop the pulsed arc model capable of reproducing the transition from Zero Quenching to Impulse Quenching mode. The further validation with the help of previously obtained test data proved the feasibility of accurate calculation of LLPD current and voltage. Which is even more important, it is possible to estimate the interruption capability of certain design with decent precision. Next, we used arc simulations for finding the optimal size of additional chamber and thus increasing the efficiency by approximately 16%. All listed achievements look promising and gives reason to consider the numerical modeling as an effective tool and use it for LLPD development on regular basis.

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