Modeling and Experimental Measurements of Parameters of Simulated Fault Arc in Air

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Abstract—**The paper presents preliminary model of the fault arc parameters with application of the experimental measurements results. The arc model is now only the part of work aimed in elaboration of the full model of fault arc simulation in the first phase of its development. In the model the equations of magneto-hydrodynamic plasma theory were used. The observations of the arc form and measurements of the temperature and pressure inside a switchgear housing have been made in laboratory conditions. The results were useful in the modeling and will be taken in to account in verification of the model in the future.**

Keywords-fault arc; internal arcing fault; arc in air; modeling

I. Introduction

The fault arc in power electrical equipment, especially in switchgears, belongs to the most dangerous and serious failures in the supplying system. There are a few main causes of such phenomena, first of all: breakdown of insulation during overvoltages, penetration of small animals into interiors of switchgears and errors of servicing personnel. In spite of the fact that the fault arc could be treated as a “rare event”, it is still a very dangerous phenomenon for the human life and it can cause serious losses in equipment. The most important effect here is very high temperature and pressure of the surrounding gases. Because of it there is still a need of methods which enable the fault arc extinguishing in an extremely short time, before the thermal and dynamical effects of the arc can cause any significant damages [1,2,3].

These methods need information about the increase in temperature and pressure of the surrounding gases. Such data are also important in the digital modeling of the described phenomena and the proper arc models are required for analysis of fault arc parameters. The fundamentals of arc modeling are described in detail in the literature. However, in practice there still exist the need of digital arc models elaborated as the proper tool to different practical applications. Particularly the fault arc model is useful in design of switchgear devices and their mechanical constructions in order to withstand the stress caused by the fault arc pressure as well as solve problems related with arc temperature.

The paper presents considerations aimed at elaboration of the fault arc model, which is dedicated to perform a simple calculation of some physical parameters inside the arc and in its surroundings. The full model of fault arc requires taking into account many physical processes. The next stages of modeling will introduce new processes, that will make the results more exact. The first stage of modeling refers to arc plasma and bases on the magneto-hydrodynamic plasma equations in order to consider ionization and dissociation processes as well as electromagnetic and thermodynamic properties of the arc plasma. The presented here part of the full model is not a finished task yet and it will be successively improved in the future work.

II. Experimental Measurements

Parallel to the theoretical considerations concerning the arc model, a series of experimental work was performed. The fault arc burning in air was examined in laboratory conditions. The aim of the work was to measure some physical parameters, which can be useful in verification of the model. All experiments were performed on the arc burning in air. The main measured parameters were temperature and pressure of the gas and its increase rate in the first phase of the arc development. Thus, the development of the arc in this range of time is significant in order to optimize the extinguishing methods and arc modeling during the first burning phase. In the performed experiments the arc development was observed in the first half-wave of 50 Hz period, i.e. in the first 0.01 s.

The arc was ignited inside a metal chamber representing a switchgear housing with volume of 0.006 m3. The arc current was set in the range (700 A – 1500 A) rms. At the bottom of the arc chamber a piezoelectric pressure sensor was placed in order to measure pressure increase inside the closed volume. Dynamic changes of the temperature were recorded with use of infra-red camera of appropriate parameters. Additionally, the arc movement was recorded with use of high-speed digital camera with 2240 frames per second. The experimental results were used in the elaboration of the model presented in the paper. The exemplary results of measurements are presented in Fig.1.

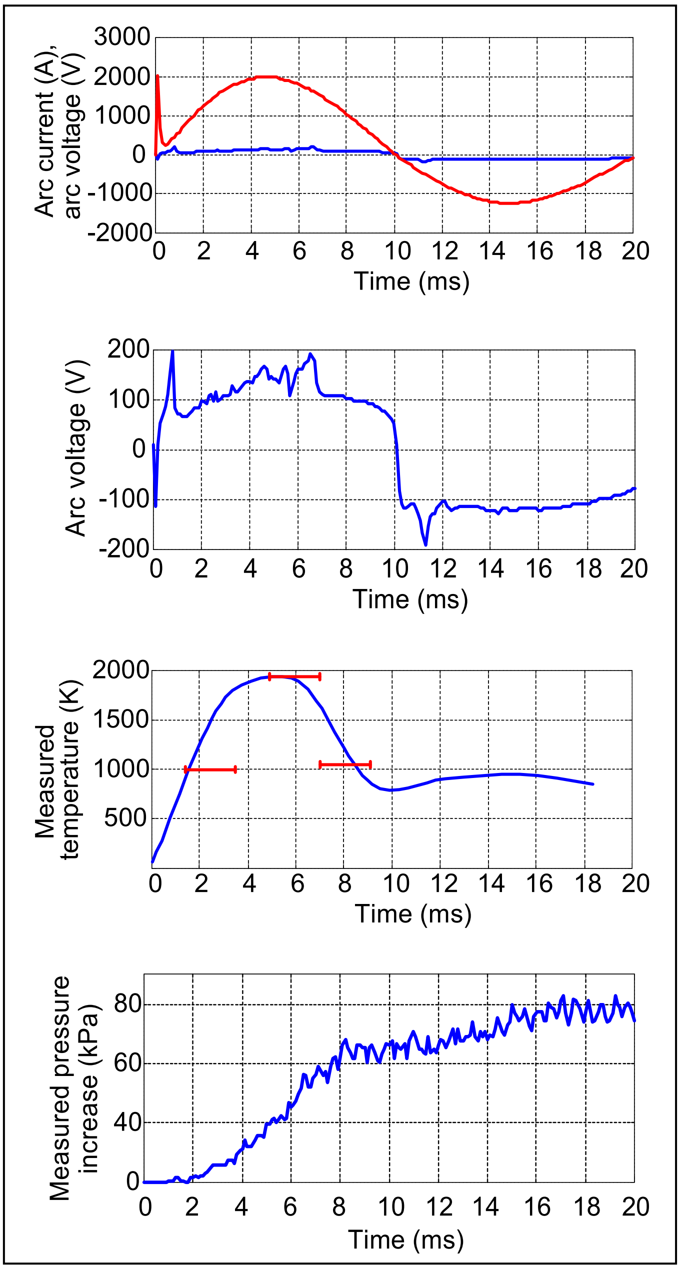

Figure 1. Arc current, arc voltage, measured temperature and pressure increase waveforms for exemplary value of arc current (1414 A rms value).

III. Description of the Model

The full model of an electrical arc requires taking into consideration: processes which occur inside the arc plasma column, exchange of heat between arc and its surroundings and thermodynamic processes and turbulences of heated air in the closed volume, inside which the arc burns, e.g. in the interior of a switchgear. The presented model simulates changes of temperature and gas pressure which are the results of the physical process related with arc plasma fluid. It bases on the well-known magneto-hydrodynamic (MHD) equations described by the three following formulas [4]:

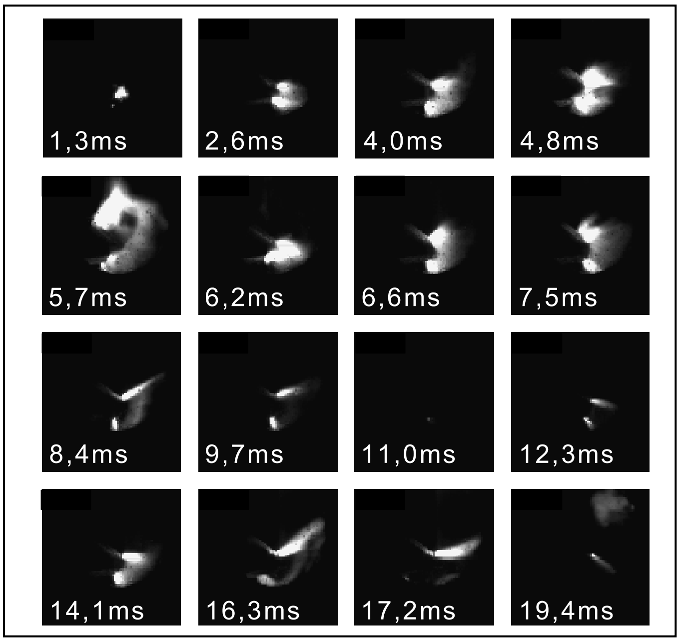

Figure 2. Fault arc development, for exemplary value of arc current (1414 A rms value).

mass balance:

$$\frac{\partial \rho}{\partial t} + div(\rho \vec{w}) = 0 \tag{1}$$

momentum balance:

$$\frac{\partial(\rho w_i)}{\partial t} + div(\rho w_i \vec{w}) = -[\nabla p]_i + \mu[\nabla^2 \vec{w}]_i + \rho g_i + (\vec{j} \times \vec{B})_i \tag{2}$$

energy balance:

$$\frac{\partial}{\partial t}\left[\rho\left(c_p T + \frac{w^2}{2}\right)\right] + div\left[\rho \vec{w}\left(c_p T + \frac{w^2}{2}\right)\right] = div(\lambda\, gradT) + \frac{\partial p}{\partial t} + \vec{j}\vec{E} \tag{3}$$

where

ρ – mass density,

p – pressure,

T – temperature,

$\vec{w}$ - velocity vector,

c_p – specific heat at constant pressure,

λ – thermal conductivity,

μ – dynamic viscosity,

$\vec{j}$ – current density,

$\vec{B}$ – magnetic flux density,

$\vec{E}$ – electric field intensity.

The formulas describe the gas-dynamic processes in the plasma fluid, let say, in the macro-scale, i.e. without detailed relations between particles in the fluid. Before the equations can be applied to the model, some important physical parameters of the gas, in which the arc burns, have to be defined. The executed analysis of these parameters allowed to simplify the MHD equations to the form adequate to adapt them into the common calculation program.

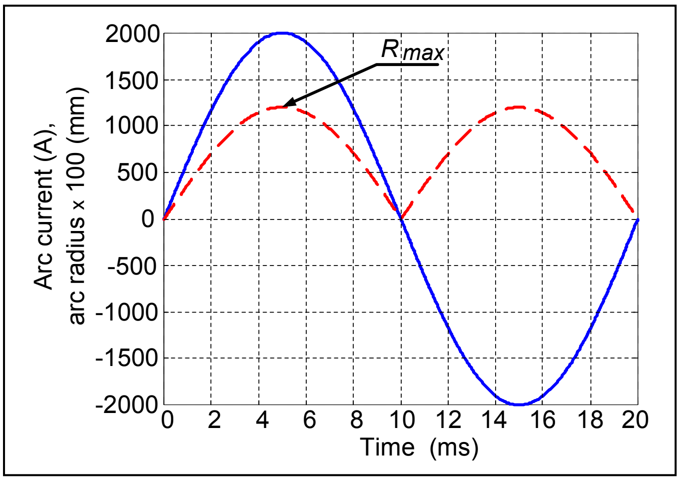

Figure 3. Examplary plot of arc current (solid line) and corresponding arc column bonduary radius (dotted line) in time.

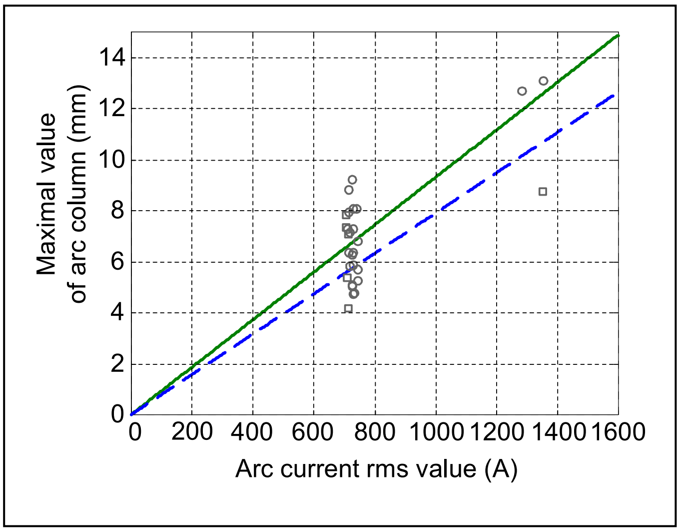

Figure 4. Maximal value of arc column boundary radius *Rmax* in dependence on arc current rms value: in the closed volume (dotted line) and in the open volume (solid line)

At this stage of the work, the model is limited to the interior of the arc column. Because the fault arc in air is analyzed, it is assumed that gas medium is gaseous mixture of nitrogen (79%) and oxygen (21%). In order to simplify the notation of MHD equations, cylindrical co-ordinates (r, φ, z) are applied. The arc column was represented as a cylinder, located between two electrodes: anode and cathode. Additional assumption was that for particular value of r co-ordinate, all parameters in MHD equations are constant in the axes φ and z. In this way, the model can be graphically represented as a group of long coaxial cylinders with variable radius.

The r co-ordinate varied from $r=0$ to $r=R$, where R is the radius of the arc column boundary. The arc radius (R) is a function of time. The character of this function was estimated on the laboratory research basis. It was assumed, that changes of arc radius (R) in time are strictly related to the arc current, which is presented in Fig.3. and Fig.4.Another assumption of the model was that the velocity vector has only two components, in the r and z-direction. The velocity in the φ -direction was not considered. The radial velocity was assumed as an expression with a time derivative of arc radius (R) what is presented in Fig.5. Both radial and axial velocity are functions of position and time (r, t).

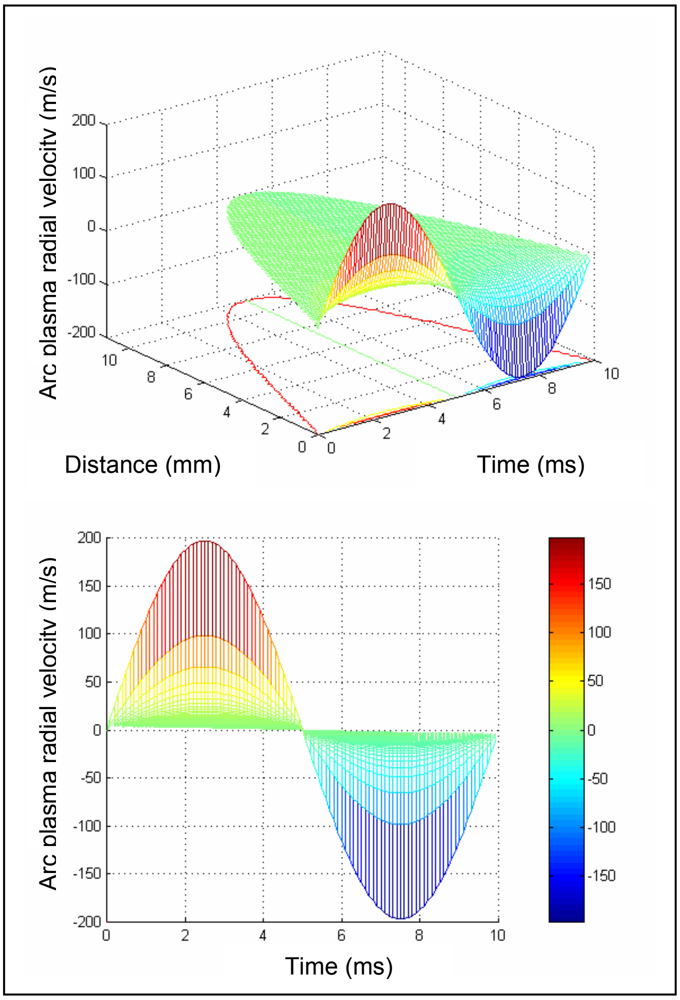

Figure 5. Radial velocity of arc plasma as a function of distance from the centre of the arc column and time, for exemplary value of arc current 1414 A (rms value).

The current density vector and electric field intensity vector have only axial components, which are only time functions. However, in the case of the magnetic induction vector, only the „self" magnetic field of plasma is taken into account and it is dependent on both distance and time (*r, t*).

According to the earlier assumptions, the temperature and the pressure are variables which change with the *r* co-ordinate and time only. For the parameters, which appear to have stronger dependence on temperature than on pressure a plot for the exemplary value of pressure (100 kPa) was made and then, in order to simplify the notation of equations, the linear approximations of these parameters was applied.

In the presented model all parameters are dependent on temperature and pressure or only on one of them. With this notation and all presented simplifications the solving of MHD equations was possible.

IV. Simulations Results

The MHD equations in simplified form were applied to the appropriate numerical computational program (MATLAB) and solved.

The exemplary results of simulations are presented in Fig.6-9., where some arc plasma parameters are shown as function of the distance from the centre of the arc column and time.

The calculations were performed for a relatively small value of current 1414 A (rms value), maximal value of arc radius (*Rmax*) was about 11.5 mm and arc length was about 0.1 m. The given above arc current value is small in comparison with the current values of a real fault arc, which can reach few tens of kilo amps. However, the reason of it was, to compare directly the obtained measuring results in laboratory arrangement. The same remark considers the arc radius.

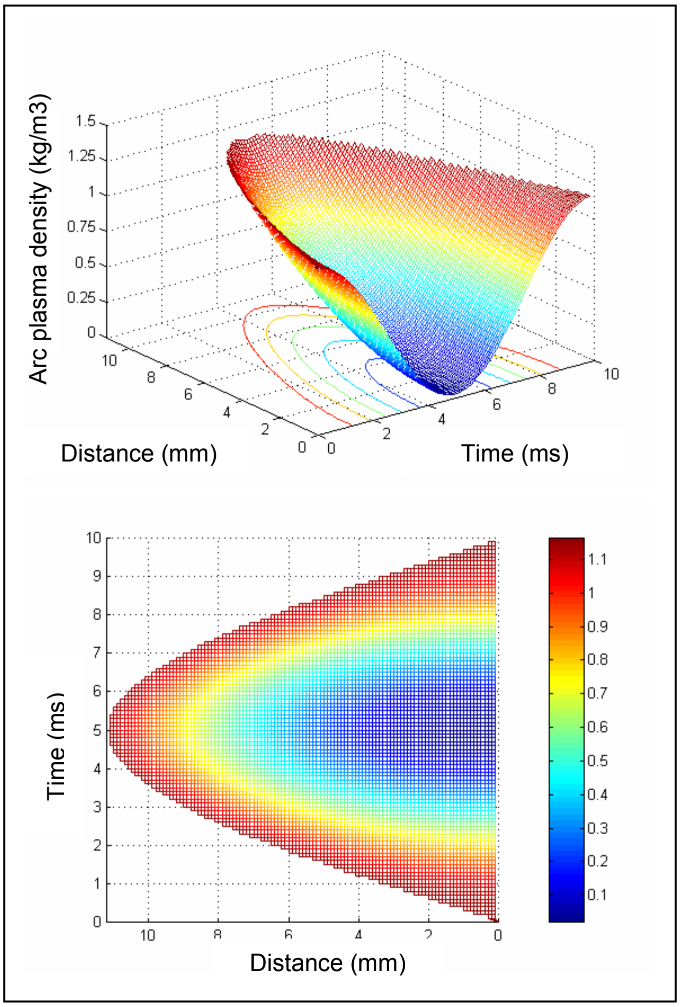

Figure 7. Arc plasma density as a function of the distance from the centre of the arc column and time, for exemplary value of arc current 1414 A (rms value).

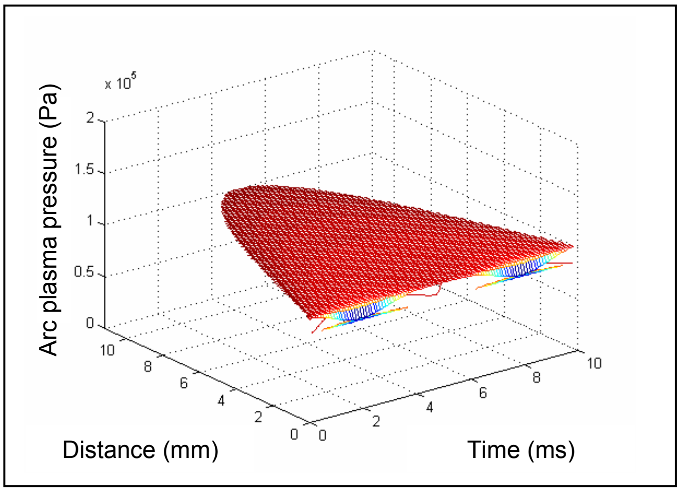

Figure 6. Arc plasma pressure as a function of the distance from the centre of the arc column and time, for exemplary value of arc current 1414 A (rms value).

The obtained results show (Fig. 6-9) that all the analyzed parameters change with the time in accordance with the instantaneous value of the arc current. No time delays between the arc current and the analyzed parameters inside the arc column can be observed. The calculated parameters are in relatively good agreement with the expected results.

The model gives the description of the arc as the source of heat. The interaction of the arc with surroundings will be the next stage of the described model.

V. Summary

The presented arc model illustrates the way of possible application of the magneto-hydrodynamic equations of the arc plasma for modeling of the fault arc in air. The model deals with phenomena inside the arc column and its development in the first half-wave of the arc current. Because of this, the model can be first of all applied for modeling of the beginning stage of the fault arc.

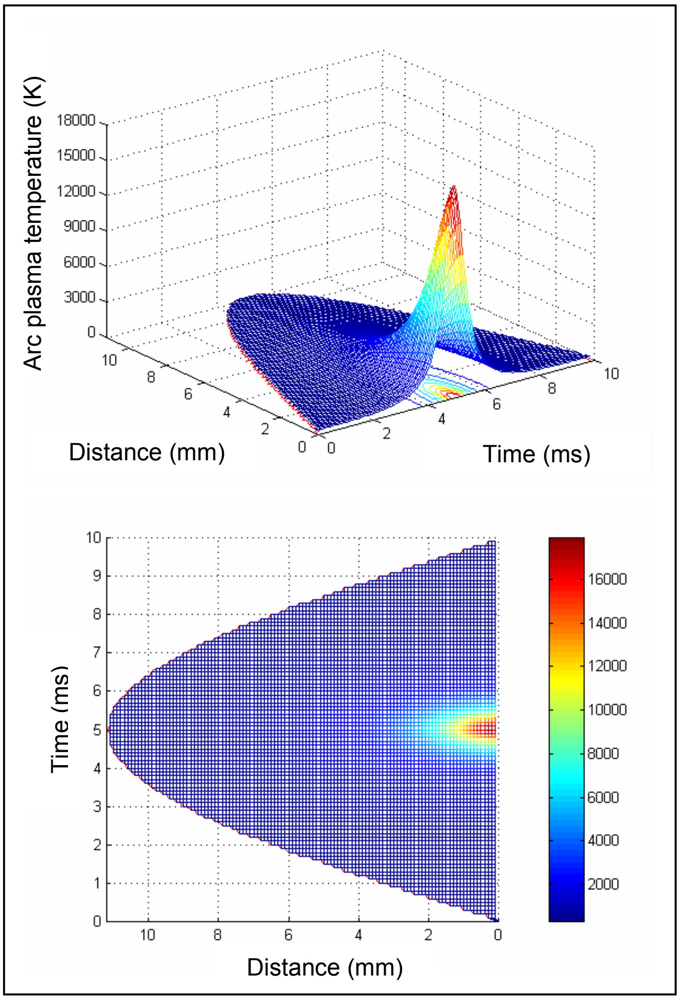

Figure 8. Arc plasma temperature as a function of the distance from the centre of the arc column and time, for exemplary value of arc current 1414 A (rms value).

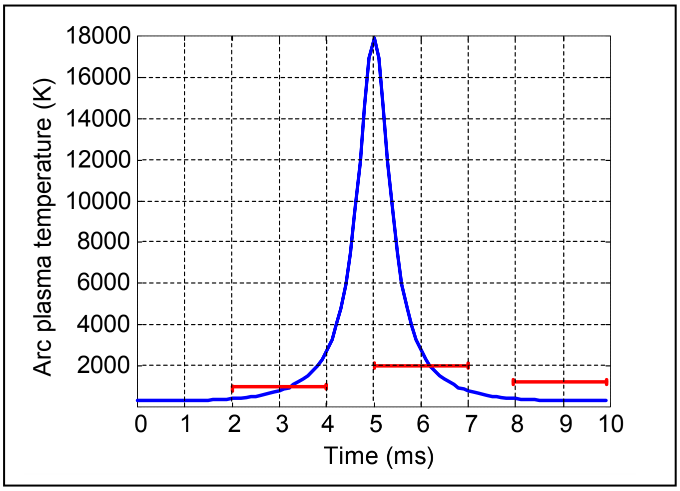

Figure 9. Comparison of arc temperature near arc column centre and results of measurements, for exemplary value of arc current 1414 A (rms value).

The main results of simulation, concerning arc plasma temperature, density and pressure inside of arc column are in agreement with the real values. However, the verification of the presented parameters is foreseen in the next works.

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