A Study of Arc Modelling in Low-Voltage Switching Devices

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The motion of an arc plasma in a quenching chamber has a significant influence on the interruption performance of low-voltage switching devices (LVSDs). It is necessary to build an arc modelling tool, which can predict an arc behavior during an interruption process, to minimize development cost and time. This paper presents a numerical model of an arc plasma in LVSDs, which can reduce complexity and calculation load of an arc simulation by avoiding fully coupled modelling between fluid dynamics, and electromagnetism. There are two steps in the proposed arc modelling: the first is the finite element analysis of Lorentz force generated by nonlinear ferromagnetic material and current path in a quenching chamber, the second is the finite volume analysis of arc motion from the perspective of fluid dynamics and heat transfer. The present modelling takes into account a contact motion, potential drops in the sheath layers of splitter plates and plasma radiation. It is shown that the simulated result has a similar trend with experimental data in terms of the arc motion as well as current and voltage waveforms.

***Index Terms*— Arc image measurement, arc modelling, low-voltage switching devices, splitter plates.**

I. Introduction

Low-voltage switching devices (LVSDs) are usually utilized in a power distribution network to turn on and off electric circuits and to protect humans and other connected equipment against overload or short circuit accidents. The current market trend of LVSDs is towards a compact product with high breaking capacity. In order to produce competitive products meeting this demand with low development costs in a short time, it is essential to predict the switching performance and optimize a product prior to manufacturing a real device. An arc simulation is one of the most effective tools to evaluate a switching performance of a LVSD because arc behavior, which is fundamental in determining a LVSD performance, can be calculated by an arc simulation.

Arc behavior in a LVSD is very complex and it is influenced by several interactions; fluid dynamics, electromagnetic phenomenon and heat conduction. Some researchers have investigated arc modelling based on magnetohydrodynamics theory to get a deep understanding about a LVSD arc and to improve commercial products. Karetta *et al.* analyzed the arc motion by considering fluid dynamics, heat conduction, current flow and Lorentz force in the simple chamber [1]. Lindmyer *et al.* implemented the effect of linear ferromagnetic properties on the arc motion by applying the surface current density within a thin layer on iron material [2], and also extended the arc modelling to include the arc splitting process by introducing the nonlinear relationship between the potential drop and current density in the arc root region of the splitter plates with commercial software CFX [3]. Rümpler *et al.* conducted the numerical analysis about the influence of wall ablation on the arc behavior in the miniature circuit breaker through the finite volume and finite element code connected by the mesh matching tool [4]. Rondot *et al.* presented the magnetic moment method to model the arc motion affected by nonlinear iron material in the LVSD chamber [5].

This paper focuses on the accurate and inexpensive numerical analysis for arc modelling in LVSDs. Lorentz force depending on the position of an arc column and current value is calculated by the finite element code and this result is imported into the finite volume code, which can solve fluid dynamics and heat transfer. The arc images are empirically measured by using a high speed arc imaging system connected to a switching test apparatus. To validate the arc model, the simulated arc motion, current and voltage waveforms are compared with experimental results.

II. Numerical Analysis

A. Analysis of Lorentz Force

Lorentz force is calculated by a commercial finite element method software depending on the current (from 0 A to 2000 A) and arc position (from the ignition region to splitter plates). Figure 1 shows the geometry and some simulated results of Lorentz force.

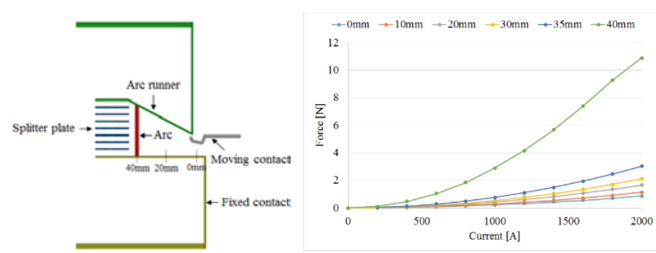


Fig. 1. The geometry and simulated results of Lorentz force.

To consider the influence of Lorentz force on the arc motion, the external magnetic flux density, B_{ex} is computed by (1) and (2)

$$F_{Lo} = IB_{ex}L, \tag{1}$$

$$B_{ex} = F_{Lo}/(IL), \tag{2}$$

where F_{Lo} is Lorentz force, I is the current and L is the arc length at the specific position (the arc column is assumed to be perpendicular to the fixed contact in the quenching chamber). In the second step, B_{ex} is used as the input parameter that generates Lorentz force on the arc in a fluid domain. Total Lorentz force per unit volume acting on the arc is expressed as

$$f_{Lo} = J \times B_{ex}\,, \tag{3}$$

where f_{Lo} is Lorentz force per unit volume and J is the current density.

B. Arc Simulation

The arc modelling is composed of procedures of arc ignition, fluid dynamics computation, electromagnetic calculation and contact motion (see Fig. 2). In the modelling, some assumptions and simplifications are adopted: an arc is considered to be in a state of local thermodynamic equilibrium, the initial state of an arc is modelled as a hot channel in a small contact gap, a gas motion is regarded as a laminar flow and any vaporization from metal and plastic are not taken into account.

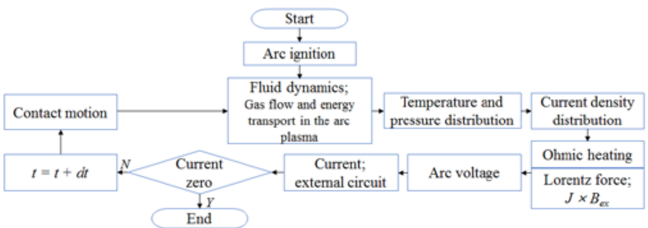
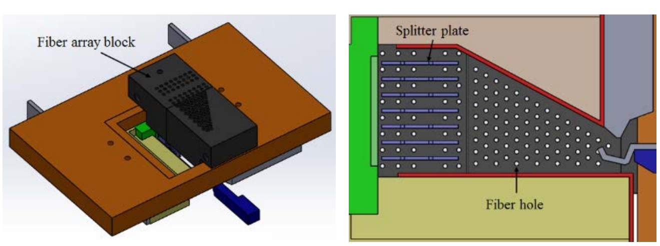


Fig. 2. Diagram of the arc modelling process.

III. Arc Image Measurement

The flexible test apparatus (FTA) is designed as the quenching chamber of a miniature circuit breaker as shown in Fig. 3 and it is used to record the arc motion under controlled test conditions [6]. 109 optic fibers are fitted into the holes of the fiber array block, which are distributed over the whole quenching chamber; including 32 fibers allocated to the region of the splitter plates. The fibers are connected to photodiode sensors in the arc image system (AIS), which have a spectral response range from 320 nm to 1060 nm. It enables the tracking of the arc motion through the light intensity and position in the chamber during an interruption operation at 1 MHz sampling rate [7]. A half cycle wave of a short circuit current is provided by a capacitor bank and its magnitude is changed by adjusting a charging voltage of a capacitor.

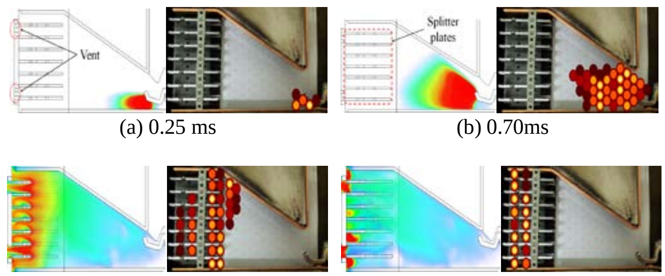


(a) External configuration (b) Internal configuration

Fig. 3. The flexible test apparatus for the arc image measurement.

IV. Results and Conclusion

Figure 4 and 5 show the arc motion and electrical waveforms when the FTA operates with 1050 A peak current. After the contact separation, the arc is established across the contact gap and it gradually elongates as the contact gap increases. The arc moves towards the splitter plates by Lorentz force and gas pressure. When the arc enters the splitter plates, the arc voltage significantly rises due to the multiple anodic and cathodic potential drops in the surfaces of the plates. It is seen that the simulated arc voltage is higher than the measured one from 1.5 ms to 3.1 ms because the arc reaches the plates quicker in the simulation than the real case. But, in general, the similar trend between the simulated and experimental data is observed.



(a) 0.25 ms (b) 0.70ms

(c) 2.60 ms (d) 3.30 ms

Fig. 4. The simulated temperature distribution and measured arc image data.

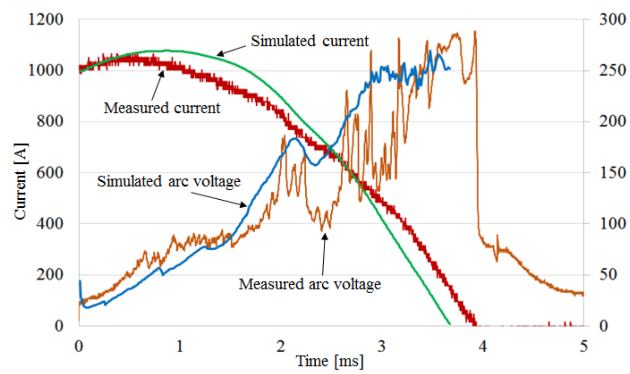


Fig. 5. The simulated and measured electrical waveforms.

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