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NUMERICAL ANALYSIS OF SWITCHING PERFORMANCE EVALUATORS IN LOW-VOLTAGE SWITCHING DEVICES

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Abstract* – An arc modelling is a valuable and useful tool to evaluate the switching performance of low-voltage switching devices (LVSDs) during breaking operation before testing real products. Moreover, it helps improve interruption capability of LVSDs and optimize them. This paper focuses on the numerical simulation of the arc behavior in AC devices before zero current and prediction of the re-ignition after current zero based on the simulated arc voltage. The 3-D arc modelling is based on the conventional magnetohydrodynamics theory and it considers the motion of a contact, arc root, radiation and air properties which vary with the temperature and pressure.

Introduction

Low-voltage switching devices (LVSDs) are essential to turn on and off electric current and to protect humans and other connected equipment against overload or short circuit accidents in the distribution power network. A quenching chamber of a LVSD is the main volume for switching current and is composed of a movable and a fixed contacts, splitter plates, vents, a magnetic yoke and an arc runner as shown in Fig.1. When the movable contact is just separated from the fixed contact, an arc plasma is established between the contacts and it elongates as the gap between two contacts increases. Afterward the arc moves toward the splitter plates by the gas pressure and the magnetic Lorentz force. At the same time, the arc voltage between contacts dramatically increases due to the multiple anodic and cathodic voltage drops at the splitter plates. Ideally the arc is extinguished at the moment of first zero current event, but sometimes the arc can be re-ignited. During this breaking process, the arc parameters have a great influence on the interruption performance of the LVSD [1]. Therefore, reliable arc modelling is vital to predict the interruption performance of LVSDs and to improve their interruption capability.

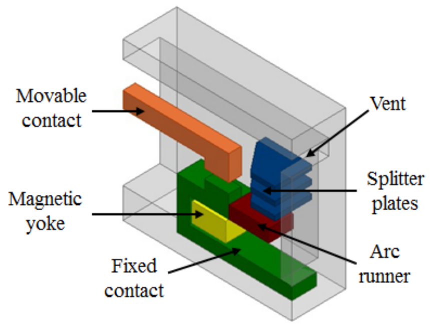


Fig.1 Half symmetric schematic structure of a quenching chamber in a LVSD.

There have been considerable amount of experimental investigations on the arc characteristics and the prediction of successful interruption of LVSDs. McBride *et al.* carried out the experimental studies of the influence of the opening speed, the contact material, the wall material and the venting condition on the arc motion in the miniature circuit breaker (MCB) using the optical fiber imaging system, pressure gauges and spectrograph [2]. With similar measuring system, Li and Chen *et al.* investigated the effect of the configuration of the quenching chamber, the venting condition and the wall materials on the interruption performance of LVSDs [3], [4]. Balestrero *et al.* introduced performance evaluators which can predict the re-ignition by calculating the arc current or the arc voltage over a very short period like 10 μs just before current zero event [5]. Hauer *et al.* presented that the probability of the re-ignition after current zero heavily depends on the 'exit arc voltage' which is the value of the voltage between contacts just before current zero [6]. This methodology can be used in the 2-steps design procedure: first we need to establish a threshold arc voltage and secondly we need to simulate the arc characteristics up to zero current moment. The advantage of such approach is that a complex simulation of plasma processes during arc re-ignition can be omitted.

Arcs are non-linear phenomena and their properties strongly depend on length, attachment points, temperature and pressure of the arc. So for accurate predictions of the exit voltage the arc behavior needs to be modeled with a high accuracy. In terms of the arc simulation, Karetta *et al.* analyzed the arc motion with 3-D magnetohydrodynamics (MHD) model considering heat conduction, gas flow, current flow, magnetic forces [7] and Lindmyer *et al.* proposed the arc modelling that can simulate the arc root formation on the splitter plates by using a thin layer of current-dependent resistivity [8]. Rong and Ma *et al.* conducted the numerical researches of the influence of metal erosion and wall ablation on the arc behavior in the LVSD and predicted arc motion and voltage waveforms were verified by experiments but the erosion rates were not measured [9], [10].

Although the design and analysis technology of LVSDs have noticeably developed thanks to the previous researches, there are still some limitations to improve the switching performance of LVSDs and to optimize them. The experimental approach is very expensive and time-consuming. Moreover, it is hard to obtain internal arc parameters such as the gas velocity, the current density and the temperature that are useful to re-design LVSDs. Concerning the simulation model, most of the previous numerical investigations have focused on the behavior of the arc plasma before current zero without evaluating the probability of the re-ignition after current zero, even though the avoidance of the re-ignition is the key factor for designing the quenching chamber of the LVSD.

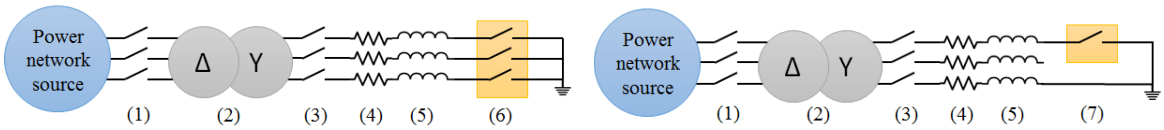
This paper mainly presents the numerical simulations of the arc behavior before current zero and the performance evaluators which can predict the re-ignition after current zero based of the 3-D arc modelling within the MHD approach. The developed arc model takes into account the motion of the contact, the arc root formation, the plasma radiation and the air properties which vary with the temperature and the pressure. The simulation results are compared with the experimental ones to validate the proposed arc model.

Experiments on Arc Re-ignition

The experimental investigation for predicting the re-ignition is carried out by two kinds of interruption tests. One is the large current test for a single pole MCB with around 10 kA and the other is the small current test for a 3 pole magnetic contactor (MC) with about 800 A current. Fig.2 shows an equivalent test circuit for a 3 pole MC and a single pole MCB. 13.8 kV commercial power line supplies the electrical energy to the test circuit whose voltage and current are adjusted by the transformer, resistors and reactors. For single pole tests, only two phases of the test circuit are used as shown in Fig.2 (b).

Fig.3 shows the voltage and current waveforms in both successful and failed interruption of MCBs when the system voltage is 252 V, the prospective current is 10 kA and the power factor is 0.45. In the successful case, the arc voltage reaches relatively a high value over than 400 V and remains high until current zero. However, the arc voltage is low, unstable and there is small value of the exit arc voltage in the failed case. If the MCB fails to interrupt the arc at first current zero like Fig.3 (b), the arc current flows until next current zero and it severely damages the products because of the large current and the long duration of arcing time. It is clear from the Fig.3 (a) that in successful test the inductance effects are strong and the arc voltage is greater then the system one. It does not allow the arc to re-ignite since after the zero current moment the voltage across the contacts drops to the system value which is not sufficient to support the arc.

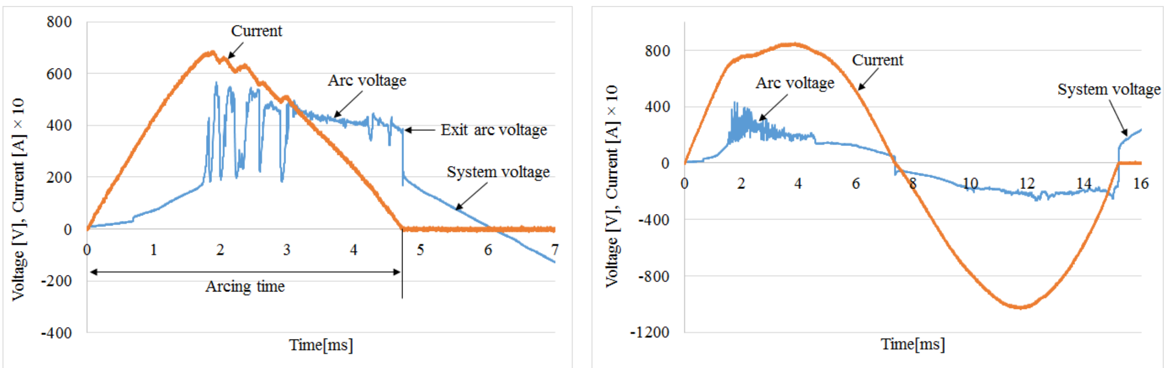
Fig.4 presents the mutual relation between the re-ignition and the exit arc voltage at the first current zero in the MCB's interruption test. There is a clear threshold that distinguishes the successful or failed interruption. If the exit arc voltage is above 83 V, the arc can be iterrupted at first current zero. These test results illustrate that the probability of the re-ignition is strongly correlated to the exit arc voltage and the exit arc voltage can become an evaluator to predict the re-ignition of LVSDs.



(a) 3 phases test for the MC

(b) single phase test for the MCB

Fig.2 Equivalent test circuits for the MC and MCB: (1) back-up circuit breaker, (2) 3 phase transformer, (3) making switch, (4) resistor, (5) reactor, (6) test MC, (7) test MCB.



(a) Successful interruption test

(b) Failed interruption test

Fig.3 Voltage and current wave forms during interruption operation of MCBs.

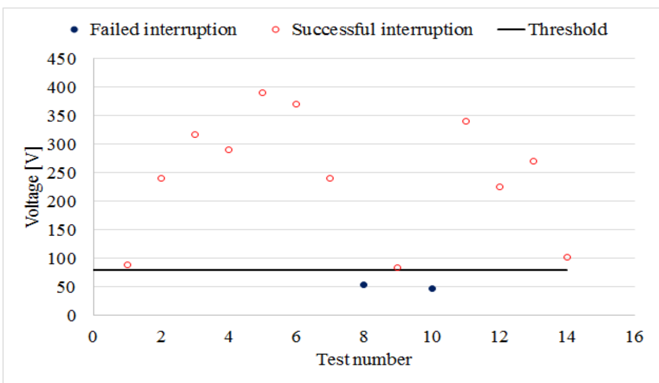


Fig.4 Relation between interruption performance and arc voltage of MCBs at current zero.

Fig.5 shows the experimental set-up for the making and breaking test of the MC. The control circuit powers the MC and the test circuit is turned on or off by the operation of the MC. There is typical voltage and current waveforms of the 3 pole MC during the breaking test in Fig.6. T phase is firstly interrupted at around 8 ms and then the currents of other phases are terminated at the same time after about 3 ms. T phase experiences the current zero event twice during breaking operation while the re-ignition takes place in the first current zero and the arc is extinguished at the second current zero. 34 results of breaking tests in T phase of the MC are shown in Fig.7 when the system voltage is 462 V, the prospective current is 800 A and the power factor is 0.45. The threshold of the exit arc voltage between successful and failed interruption is also observed and the probability of the successful interruption is around 83% if the exit arc voltage is above 135 V.

Fig.5 Experimental set-up of the MC.

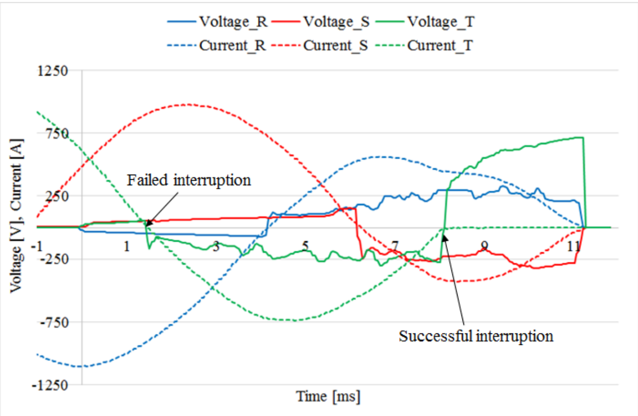


Fig.6 Voltage and current waveforms of the 3 pole MC during the breaking operation.

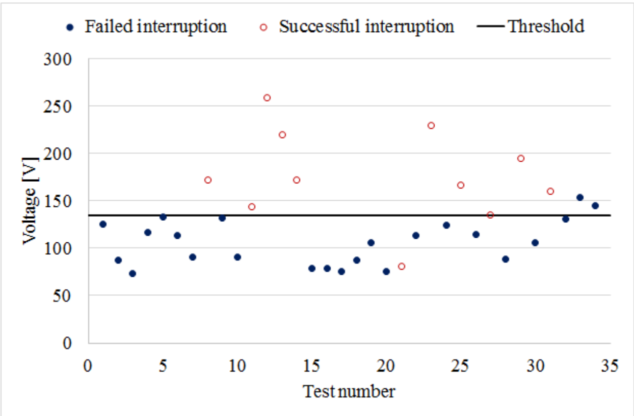


Fig.7 Relation between interruption performance and arc voltage of the MC at current zero.

Numerical Model and Simulation Results

Assumptions and simplifications for arc model

In order to reduce the complexity of the arc in the LVSD, it is necessary to adopt some assumptions and simplifications for the arc modelling as follows,

- The arc column is considered to be in a state of local thermodynamic equilibrium (LTE).
- The arc simulation starts from a small gap between contacts which is applied initial temperature distribution.
- The gas flow of the arc is regarded as a laminar flow.
- The metal erosion and the wall ablation are not taken into account in the arc model.
- The splitter plates are considered as linear ferromagnetic materials.

MHD equations in arc column

It is regarded that the arc column is electrically neutral and thermally equilibrium mixture of electrons and heavy particles such as ions, atoms and molecules at the high temperature. If the assumption of LTE holds in the arc column, the arc can be treated as a single fluid and the mass, momentum and energy conservation equations can describe the relation between the velocity, pressure, temperature in the arc column as given below [7], [11],

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V} \right) = 0 \quad , \tag{1}$$

$$\frac{\partial \left(\rho v_i \right)}{\partial t} + \nabla \cdot \left(\rho v_i \vec{V} \right) = -\nabla p + \nabla \cdot \left(\eta \nabla v_i \right) + (\vec{J} \times \vec{B})_i \quad , \tag{2}$$

$$\frac{\partial \left(\rho H \right)}{\partial t} + \nabla \cdot \left(\rho H \vec{V} \right) = \nabla \cdot \left(\frac{\lambda}{c_p} \nabla H \right) + \frac{\partial p}{\partial t} + \sigma E^2 + S_{rad} + S_{\eta} \quad . \tag{3}$$

In the previous equations, ρ is the density (kg/m^3), t is the time (s), $\vec{V}$ is the velocity (m/s), v_i is the velocity component in i direction, p is the pressure (Pa), η is the dynamic viscosity ($kg/(m{\cdot}s)$), $\vec{J}$ is the current density (A/m^2), $\vec{B}$ is the magnetic flux density (T), H is the dynamic plasma enthalpy (J/kg) expressed by $h+\vec{V}^2/2$, h is the static enthalpy (J/kg) determined by $\int c_p dT$, λ is the thermal conductivity ($W/(m{\cdot}K)$), c_p is the specific heat capacity ($J/(kg{\cdot}K)$), σ is the electrical conductivity (S/m), E is the electric field intensity (V/m), S_{rad} is radiation energy source (W/m^3) and S_{η} is the heat due to viscous dissipation (W/m^3).

The electric field E, which determines the ohmic heating source in energy equation, is calculated from Gauss law, Equation (4) and (5),

$$\nabla \cdot \left(\sigma \ \nabla \Phi \right) = 0 \quad , \tag{4}$$

$$\vec{E} = -\nabla \Phi \quad , \tag{5}$$

where Φ is the electric scalar potential (V).

Moreover, $\vec{J}$ and $\vec{B}$, which are used to calculate Lorentz force in the momentum equation, are obtained from next equations,

$$\vec{J} = \sigma \vec{E} \ , \tag{6}$$

$$\nabla^2 \vec{A} = -\mu \vec{J} \ , \tag{7}$$

$$\vec{B} = \nabla \times \vec{A} \ , \tag{8}$$

where A is the magnetic vector potential (Wb/m) and μ is the permeability (H/m).

The simplified net emission coefficient method is employed to calculate the radiation energy due to its simplicity, and the net emission coefficients are computed from Equation (9),

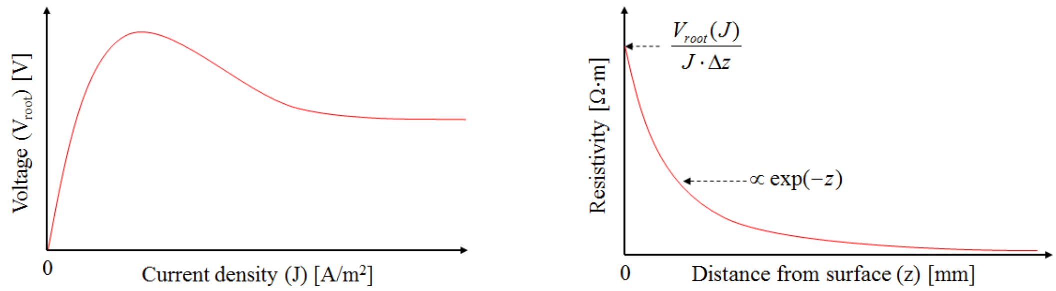
$$\varepsilon = A\left(\exp\left(BT\right) - \exp\left(BT_r\right)\right) \ , \tag{9}$$

where A and B are constant coefficients, which are 300 W/m^3 and 0.0011 K^{-1} respectively, T_r is the room temperature and T is the arc temperature [12].

Numerical model for arc root

The arc root is a thin region between the arc column and the metal surface of the cathode or anode. Before entering the splitter plates, the arc gradually bends and stretches around the plates in order to get some voltage that is necessary to form the arc root on the plates [8]. The voltage drops in the arc roots on the cathode and anode are quite high compared to that in the arc column and it is important to distribute the arc over several plates to get a sufficient voltage drop. So this arc root formation plays an important role in the arc behavior before current zero and the value of the arc voltage which can be the evaluator for the re-ignition after current zero. In order to consider the arc root area, the special arc root modelling is necessary because LTE condition does not hold in the arc root and the ordinary MHD theory cannot simulate the arc root phenomena [12].

The nonlinear resistivity dependent on the current density in Fig.8 (a) is applied to the arc root area in order to take into account the arc splitting phenomenon on the splitter plates and the high arc voltage in the arc root [8]. Moreover, the resistivity in the arc root varies with the distance from the cathode or anode surface as shown in Fig.8 (b) to implement the thin layer of the arc root which has the continuous resistivity distribution.



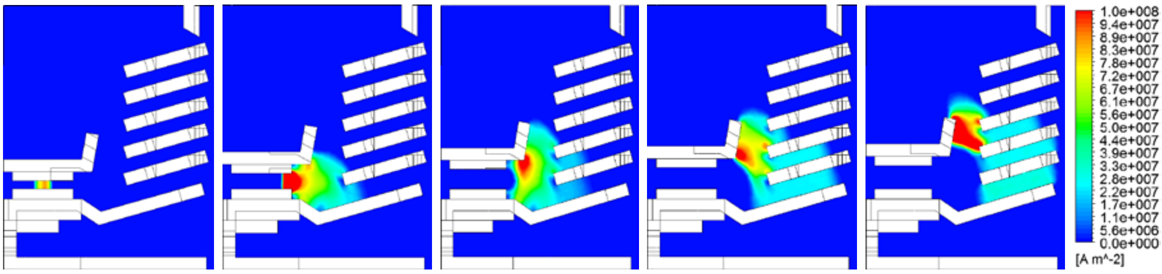
(a) Relation between voltage and current density (b) Relation between resistivity and distance

Fig.8 Modelling method for the arc root.

Simulation results

The arc modelling process mainly consists of the arc ignition, the MHD simulation, the motion of the movable contact and the evaluation for the re-ignition. The MHD calculation includes the radiation and the formation of the arc root. This arc modelling is carried out by Ansys CFX commercial program which has been used in previous studies [8], [12].

Fig.9 illustrates the arc behavior expressed by the current density distribution in the quenching chamber of the MC when 2 kA sinewave current flows through the MC. At the beginning of the simulation, the arc is modeled as a hot channel between contacts, and then it leaves from the contact area toward the splitter plates by the gas flow force and the Lorentz force. Afterward, the arc is divided into multiple segments by the plates and the high value of the arc voltage is generated between contacts.



(a) t = 0.04 ms (b) t = 2.0 ms (c) t = 3.0 ms (d) t= 3.4 ms (e) t = 4.0 ms (f) index

Fig.9 Current density distribution on the symmetry plan of the quenching chamber of the MC.

Validation of Arc Simulation

Fig.10 shows the comparison between experimental and arc simulation results of the MC. The simulated arc voltage is very high at the beginning of the calculation because the thin hot conductive channel is modeled between contacts for the arc ignition. In general, the computed voltage has the same trend with the experimental one before current zero although there is some difference after 1.2 ms, which could be caused by the ignorance of the metal erosion on the contacts and the splitter plates in the arc modelling. Furthermore, the exit voltage of the arc modelling is calculated as a similar value with the measured one, having about 13 % difference.

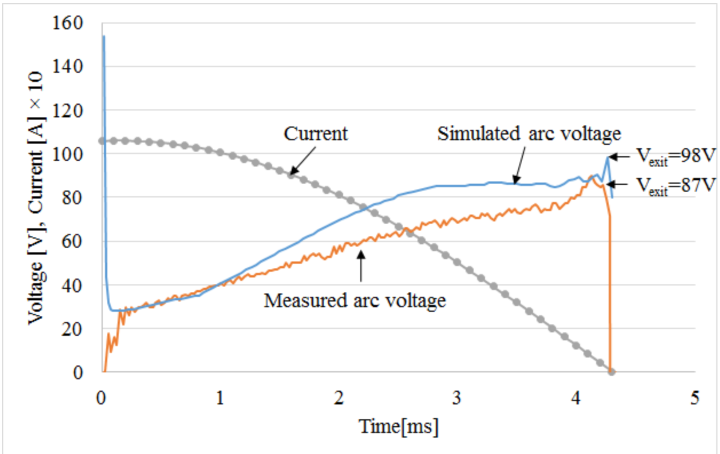


Fig.10 Comparison between experimental and simulation results of the MC.

Conclusions

The experimental and numerical investigations on the arc behavior and the evaluators for the re-ignition of LVSDs have been studied in this paper. The following conclusions can be drawn:

- The interruption test results support the exit arc voltage concept for the evaluating of the probability of the re-ignition after current zero moment. This is true for a single phase as well as for 3 phase systems.

- The arc model based on the 3-D MHD approach has been implemented. It has been validated by the experiment.
- The arc simulation including the nonlinear relation between the voltage and the current density in the arc root can be used to predict the interruption performance of LVSDs before and after current zero.
- Modelling of re-ignition process needs to include detailed analysis of the phenomena at the surfaces of the electrodes and the splitter plate. It is a part of ongoing research.

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