

## Considerations for Simulation of the Switching Arc

**Abstract.** Electric arc is a complex phenomenon that appears in Low Voltage Circuit Breakers (LVCB) during the current interruption process. The optimization of these LVCBs makes necessary a deep understanding of the phenomena involved in the electric arc. The aim of this paper is to describe the physical process of the electric arc in LVCB, as well as specify the mathematical, physical and software needs for its modelization and simulation.

**Streszczenie.** Łuk elektryczny może pojawiać się w niskonapięciowych wyłącznikach LVCB przy przerywaniu przepływu prądu. Aby można było wyłączniki optymalizować trzeba gruntownie przeanalizować zjawisko łuku. Celem artykułu jest opisanie fizyki łuku elektrycznego w LVCB oraz zaproponowanie narzędzi do jego modelowania. (**Możliwości symulowania łuku elektrycznego w wyłącznikach**).

**Keywords:** Electric Arc, Low Voltage Circuit Breaker, Simulation, CDF.

**Słowa kluczowe:** łuk elektryczny, wyłącznik.

### Introduction

Low Voltage Circuit Breakers (LVCBs) are switching devices which can open or close an electrical circuit in a small fraction of time, being their purpose the establishment or interruption of the electrical current through the circuit.

The most used CBs are conventional ones [1], which usually uses air as quenching medium. Typical construction of these devices includes fixed and movable contacts, rail electrodes and the arc chute with splitting plates [1, 2]. Their operating principle is mainly based on the extinction of the electric arc that appears between the fixed and movable contacts when establishing or interrupting the electric current in the circuit [3-5].

In this paper the characteristics of the electric arc are described with the aim of characterizing the interruption process in low voltage devices. In addition, an overview of the mathematical description of the physical models proposed in the literature is exposed, as well as the models, parameters and results obtained in different simulations.

### Physical phenomena of the electric arc in LVCB

The interruption process in a CB begins when the movable contact starts to separate. As a consequence, the contact area between contacts is reduced and the current density gets larger, until the energy associated causes the metal of the contacts to begin to vaporize and an electric arc appears. In spite of the existence of a physical separation of the switching contacts, the established arc makes possible that current continues flowing. Thus, current interruption involves the extinction of the electric arc. This can be achieved by means of the movement and elongation of the electric arc along rail electrodes into an extinction chamber. This chamber is usually provided with splitter plates which divide the arc into multiple smaller arcs, increasing the arc voltage. So the extinction of the arc is achieved, becoming again the intercontact gap an insulating medium [1, 3, 6-10].

During the appearance and extinction of the electric arc a strong interaction between heat conduction, current flow, gas flow and magnetic forces takes place. Thus, the simulation of the electric arc makes necessary the study of the gasdynamic and electromagnetic processes, both of them coupled. Temperature and pressure values in the arc chamber determine the electric conductivity of the intercontact gap and so the electric potential and the current density distribution of the arc. This current density distribution leads to Ohmic heating and magnetic forces, which influence in the gas flow and energy transport within and out of the plasma. This leads again to a change in the temperature and pressure distribution within the arc

chamber, determining the electrical conductivity of the plasma, and so on [2, 11].

### Mathematical description of physical models

Despite the complexity associated to the arc interruption process, several methods have been developed to model and simulate its behaviour. Models and simulations make possible the analysis of the time evolution of some physical magnitudes that are difficult to measure in laboratory tests.

Arc electric models can be classified in three groups (physical models (PM), "Black box" models (BB) and models based on graphics and diagrams (GD)) whose main application fields are shown in Table 1 [12].

Table 1. Application field of different switching models

Problem type	Application		
	Development	Test	Operation
-Physical processes' understanding	PM		
-Mechanics dimensioning	PM	GD	
-Dielectric recovery description	PM, GD	GD	GD
-Influence of the arc on the current	PM, GD, BB	GD, BB	BB
-HVDC breakers	PM, GD, BB	GD, BB	GD, BB
-Small inductive currents	PM, GD, BB	GD, BB	GD, BB
-SLF (Short Line Fault)	PM, GD, BB	GD, BB	GD, BB
-Design and verification of test circuits	GD	BB	

Physical models represent in detail the physical processes that take place in the interruption process, defining them by means of mathematical equations that govern those processes. Even if those models are more complex than the others, they allow to study, improve and optimize the development of circuit breakers.

The particular behaviour of the electric arc is represented by a set of thermodynamic and electromagnetic laws, known as MHD –magneto-hydrodynamics. In particular, these equations are the Navier-Stokes conservation equations and the Maxwell equations. Navier-Stokes equations represent the fluid dynamics of the quenching gas, composed by three transport equations coupled to each other: mass balance (1), momentum balance (2) and energy balance (3). These equations can be expressed as follows [3, 11, 13, 14]:

- Conservation of mass (1):

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

- Conservation of momentum (2):

$$(2) \quad \rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \vec{\nabla}) \vec{v} = -\vec{\nabla} p + \frac{4}{3} \vec{\nabla} \mu (\vec{\nabla} \cdot \vec{v}) - \vec{\nabla} \times \mu (\vec{\nabla} \times \vec{v}) + \vec{j} \times \vec{B} + \rho \cdot \vec{g}$$

- Conservation of energy (3):

$$(3) \quad \rho \frac{\partial h}{\partial t} + \rho (\vec{v} \cdot \vec{\nabla}) h - \frac{\partial p}{\partial t} - (\vec{v} \cdot \vec{\nabla} p) = \vec{\nabla} \cdot \frac{\lambda}{c_p} \vec{\nabla} h - \vec{\nabla} \cdot \vec{q}_R + \Phi + \vec{j} \cdot \vec{E}$$

Maxwell equations describe the interaction between electrical and magnetic field intensity,  $\vec{E}$  and  $\vec{H}$  [15] (4):

$$(4) \quad \begin{aligned} \nabla \times \vec{E} &= - \frac{\partial \vec{B}}{\partial t}; \nabla \times \vec{H} = j \\ \nabla \cdot \vec{E} &= \rho_q; \nabla \cdot \vec{B} = 0 \end{aligned}$$

where:  $t$  - time,  $\rho$  - gas density,  $v$  - velocity of the gas,  $p$  - pressure,  $\mu$  - viscosity of the fluid,  $E$  - electric field,  $j$  - current density,  $B$  - magnetic flux density,  $h$  - enthalpy,  $\lambda$  - thermal conductivity,  $c_p$  - specific heat under constant pressure,  $g$  - gravity acceleration.

Thus, electric arc physical models consider the conservation laws for mass, momentum and energy for arc macroscopic elements, but extra source terms are added.

On one hand, a Lorentz-force density term is added in the momentum balance. On the other hand, the Ohmic heating term is also considered in the energy balance. Those extra terms couple flow dynamics with the electromagnetic process, described by the Maxwell's equations [11, 13-14]. Therefore, it should be pointed out that both, electromagnetic and fluid dynamics phenomena, have to be solved simultaneously as they are completely coupled.

The magnetic field is obtained by applying the Biot-Savart law (5), once the current distribution is known, or by calculating the magnetic vector potential (6) and (7), if ferromagnetic materials have to be taken into account.

$$(5) \quad \vec{B}(\vec{r}) = \vec{B}(\vec{r})_{ext} + \frac{\mu_0}{4\pi} \iiint \vec{j}(\vec{r}') x \frac{\vec{r} - \vec{r}'}{|\vec{r} - \vec{r}'|^3} dV'$$

$$(6) \quad \vec{B} = \nabla x \vec{A}$$

$$(7) \quad \Delta \vec{A}_m = -\mu_0 \mu_r \vec{j} - \frac{1}{\mu_0} (\text{grad} \mu_r) x \vec{B}$$

where  $\vec{A}$  is the magnetic vector potential [2, 11, 16]

For the thermal behaviour, most of researchers use a simplified model to represent the radiative cooling.

Finally, an important characteristic of physical models is that they require the knowledge of plasma properties such as mass density, specific heat, viscosity and electrical and thermal conductivity. These properties are strongly dependent on temperature and pressure values and, in the presence of vaporized metal or plastic, they depend also on the characteristics of the mixture.

### Electric arc simulation, parameters and results

In this section the software tools needed to simulate the physical models for the electric arc are exposed. Then, the

parameters necessary to implement the model are defined and finally examples of models and the results obtained in literature are exposed. After that, an analysis comparing the results and benefits achieved in each model is performed, explaining the limitations and difficulties that each model entails.

#### A. Software Tools

Different commercial software can be applied to simulate physical models describing the behaviour of the electric arc. However, those software tools must be able of model the coupling between fluid dynamics and electric and magnetic phenomena. For that purpose, the most appropriate are Finite Volume and Finite Element based ones. Researchers have proposed 2D or 3D models to study the behaviour of circuit breakers using this approach. In those models, the fluid dynamics part of the problem is solved by means of a CFD (computational fluid dynamics), whereas electromagnetic issues are solved by a FE (finite element) solver.

#### B. Parameters

In order to define the model, materials parameters are needed. For solid material, constant material parameters for cooper at ambient temperature are valid. For the fluid part, however, temperature dependant parameters are needed.

Thus, density ( $\rho$ ), viscosity ( $\mu$ ), enthalpy ( $h$ ), thermal conductivity ( $\lambda$ ), specific heat ( $c_p$ ) and electrical conductivity ( $\sigma$ ) are defined as transport coefficients of air for a temperature range of 50-30000 K, assuming that the plasma is in local thermodynamic equilibrium (LTE). The literature exposes the range of values shown in Table 2 [17].

Table 2. Range of values of physical properties of air

T [K]	50 ÷ 30000
$\rho$ [gm <sup>-3</sup> ]	7018.1 ÷ 2.4137
$\mu$ [kgm <sup>-1</sup> s <sup>-1</sup> ]	0.3479E-5 ÷ 0.1125E-4
h [calg <sup>-1</sup> ]	121.77 ÷ 80033
$\lambda$ [Wm <sup>-1</sup> K <sup>-1</sup> ]	0.5085E-2 ÷ 0.6494E+1
$C_p$ [calg <sup>-1</sup> K <sup>-1</sup> ]	0.24193 ÷ 7.1159
$\sigma$ [Sm <sup>-1</sup> ]	0.00 ÷ 0.1399E+5

#### C. Examples

As it has been said in the introduction, the most relevant components for the electric arc behaviour in a LVCB are the arc chute, the electrical contacts and the quenching medium. The main characteristics of different models proposed in the literature to study the behaviour of the electric arc, show the effect of some aspects of these components such as: existence of ferromagnetic material in the arc chute [17], venting size in the arc chute [2][19], existence and shape of splitting plates in the arc chute [7, 14, 20] and gassing material composition [2, 21].

Representing each parameter has its benefit in the simulation, as the model approaches more to a real one but it also implies a higher computational cost, since it is more complicated to define and solve.

In [11] a simple geometry is considered consisting in two parallel rails, so the electric arc is established in a completely sealed arc chamber. Considering a symmetry plane as well as temperature and pressure dependent properties for air, magnetohydrodynamics equations and radiation are solved, and time evolution position, temperature and voltage are obtained for a simulation time of 1.2ms. The simulation confirms the influence of heat transmission inside the electrodes and the emission mechanism on arc motion.

In [13, 18], a two parallel U-shaped rails electrodes geometry with ferromagnetic material on their reverse side

is analyzed. The presence of ferromagnetic material requires expressing the magnetic field by means of the vector potential formulation, (6) and (7), instead of using Biot-Savart (5), whose application is restricted to domains with a constant magnetic permeability like air, plasma or nonferromagnetic materials. The results obtained show that the arc moves faster when ferromagnetic material is included in comparison with the case without ferromagnetic material, being the time to reach the electrode end as shown in Table 3. However, forward commutations founded in tests could not be treated.

Table 3. Arc position with the influence of the ferromagnetic material

Model	Arc position [mm]	Time [ms]	Arc position [mm]	Time [ms]	Arc position [mm]	Time [ms]
Without Fe	24	0.08	30	0.13	40	0.19
Fe in U-form around arc runner		0.12		0.16		0.35

Table 4. Arc position with the influence of opening

Model	Arc position [mm]	Time [ms]	Arc position [mm]	Time [ms]	Arc position [mm]	Time [ms]
Closed	20	0.25	30	---	40	---
21% open		0.125		0.625		0.7
40% open		0.16		0.46		0.48
Open		0.125		---		---

In [19] the movement of the arc is simulated between two divergent runners, and the effect of the provision of different types of barriers at the end of the arc chamber is assessed (open, closed, 21% vent and 40% vent). The simulation shows that, until 0.15ms the venting size has no effect. However, after those 0.15ms the arc moves faster

the biggest the venting is. This way, it is dissipated earlier in the case with better venting. These results match with the results in [2], where it is exposed that reducing the venting size decreases the velocity of the arc motion and electric potential as it is shown in Table 4. In addition, the model succeeds in reproducing back-commutations during arc elongation.

In [14, 22] the analysis of the arc division process by means of metallic splitting plates inside the arc chute is shown, considering a single plate inside a chamber with two parallel rails. The current interruption by splitting the arc into series arcs, using metal plates, needs to take into account the ferromagnetic material considerations exposed before, as the splitting plates are generally made of steel. In fact, the ferromagnetic property is the one that helps to attract and keep the arc in the stack. The division of the arc by the splitting plates implies the formation of new roots on both sides of each plate. Thereby, the arc voltage is increased by multiple anode and cathode falls. To simulate this situation, the authors consider a layer of elements around the plate with nonlinear electrical conductivity, determined in accordance with a curve voltage/current, whereby the voltage approaches a constant value after a certain current value. The role of radiation is also explored to evaluate the influence of radiation models on arc voltage.

The effect of splitter plates is also modeled and analyzed in [7]. In this case, the shape of the three ferromagnetic plates is discussed, comparing rectangular and V-shaped plates. As it is known [6], V-shaped plates increase the attractive magnetic force on the arc. The influence of the radiation model on the calculated arc voltage is also evaluated, obtaining the non-grey P1 radiation model that improves the prediction of the arc.

Table 5. Influence of the external magnetic field value on the arc displacement and arc voltage [23]

	Air	Air-5%PA6	Air-10%PA6
B=0	ddp=25.02 dx=0	ddp=28.15 dx=0	ddp=35.02 dx=0
B=2mT	ddp=25.25 dx=4.48	ddp=41.6 dx=6.64	ddp=60.93 dx=6.14
B=5mT	ddp=29.67 dx=6.47	ddp=60.8 dx=6.97	ddp=108.75 dx=7.47

Table 6. Comparison of different models

Model	Results	Considerations
Two parallel rails [11]	-Time evolution of the arc position and voltage with a symmetry plane -Temperature distribution	-Magnetic field by Biot-Savart, equation (5) -Limitations: Heat conduction and gas flow between the arc chamber and the environment are neglected. The speed of the arc motion is lower than the measured one.
Two parallel rails including Ferromagnetic Material [13, 28]	-Magnetic field intensification -Faster displacement of the arc in presence of ferromagnetic material, half of the time to reach the end of the runner.	- Magnetic field expressed by magnetic vector potential, equations(6) and (7)
Two divergent rails with ventilation [19]	-Faster displacement of the arc as the ventilation increases	-Deviation between simulated and experimentally measured magnitude of arc voltage.
Splitter Plates in the Arc Chute[14, 20]	-Arc voltage increase -V shaped plates involve higher magnetic forces on the arc and faster movement of the arc and higher arc voltages	-Ferromagnetic material considerations -Magnetic self-field has been neglected, arc current is smaller than in experiments. -It is necessary to incorporate the arc root model proposed on the contacts, runners and stacks of metal plates.
Gas Material [2, 23]	-Arc voltage increase -Benefit cooling of the arc	-Transport properties for different mixtures of air with the composite material vapour -Interaction process between the arc and the gassing material should be considered.

Finally, the influence of the composition of the quenching gas on the velocity of the arc movement and the arc re-strikes can be analyzed [23]. Before the ignition of the arc, there is only air in the arc chamber, but as a result of the heat generated during the arc, mixtures of air with vaporized material appear. For that analysis pure air and a mixture of air and PA6 vapour (C6H11O1N1) have been considered in this simulation under the influence of different external magnetic field values. The geometry considered is the simplified CB with a cathode, anode, four splitter plates and an opening. The results of arc voltage (ddp) and displacement of the arc (dx) by the effect of the magnetic field are given in Table 5 for currents of 100 A and magnetic fields of 0.2 and 5 mT. It can be observed that the arc voltage increases with the value of the applied magnetic field and the proportion of PA6 vapour.

Also in [2], the effect of gassing material adapting the transport properties of the quenching medium for a 90% air-10% PA6 gas mixture is analyzed. Adding gassing material increases the arc voltage, benefits the cooling of the arc and helps decreasing arc temperature, improving this way the interruption process, especially in the former stage.

#### D. Comparative analysis

After explaining different models proposed in the literature, Table 6 summarizes the results that can be achieved by each model and the considerations that necessarily have to be taken into account when modelling them.

#### Conclusions

The electric arc is an important phenomenon which determines the operation of LVCBs. The use of modelling and simulation tools can help to improve these devices, reducing the need of prototype development and testing and so, the cost associated to this optimization process.

Physical models result useful for the design of new circuit breakers or to increase the understanding of the interruption process and the optimizing the CBs. For this purpose, the physical model should be as close to real device as possible. However, as it has been exposed, it involves the need for greater knowledge and also leads to a greater complexity in the development of models.

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**Authors:** *Ing. Aritz Iturregi, University of the Basque Country, EUITMOP, Colina Beurko s/n 48901 Barakaldo, Spain, E-mail: araitz.iturregi@ehu.es. Dr. Ing. Esther Torres, University of the Basque Country, ETSI, Alameda Urquijo s/n 48013 Bilbao, Spain, E-mail: esther.torresi@ehu.es. Prof. Dr. Ing. Inmaculada Zamora, University of the Basque Country, ETSI, Alameda Urquijo s/n 48013 Bilbao, Spain, E-mail: inmaculada.zamora@ehu.es. Dr. Ing. Garikoitz Buigues, University of the Basque Country, ETSI, Alameda de Urquijo s/n, 48013 Bilbao, Spain, E-mail: garikoitz.buigues@ehu.es."*