Experimental investigations on arc movement and commutation in the Low-Voltage Circuit Breaker

Jean Quéméneur¹,*, Mathieu Masquère¹, Pierre Freton¹, Jean-Jacques Gonzalez¹, Patrice Joyeux²

¹ Université de Toulouse ; UPS, CNRS, INPT ; LAPLACE (Laboratoire Plasma et Conversion d’Energie) ; 118 route de Narbonne, F-31062 Toulouse cedex 9, France
² Hager Electro SAS, 132 boulevard d’Europe, BP3, 67210 Obernai, France
* E-mail: quemeneur@laplace.univ-tlse.fr

Abstract. Displacement of an electrical arc between two parallel arc runners is studied with high-speed imaging, voltage, current and pressure measurements. The experimental set-up is detailed from the current source to the post-treatment methods. The influence of intensity, gas exhausts and volume behind the moving contact on arc commutation and movement are investigated. In the context of Low-Voltage Circuit Breaker (LVCB), it is shown that for high-intensity arcs, evacuating the hot gas is necessary for a good motion of the arc. Furthermore, a configuration of exhaust allowing a quick movement will not work for all current levels.

1. Introduction

A proper low-voltage breaking goes through the fast movement of the arc from its ignition point to the splitter plates that are responsible for arc extinction by current limitation. One very important force acting upon this displacement is the Laplace force due to the current circulation. In some devices this magnetic force is improved in order to accelerate the arc [1-3].

Another way to speed-up this movement is to design the chamber so that the pressure formation caused by the electrical arc would lead the gas to flow toward the splitters. On the study of McBride & al. [4], the volume behind the moving contact is obstructed in order to accelerate the commutation of the arc from the contact to the arc runner. A numerical study [5] points out that a smaller volume behind the point of arc ignition tends to improve the motion. Influence of the width of the chamber has been studied by Lindmayer & Paulke [6]. It is shown that the chamber must be wide enough to allow the hot gases created in front of the arc to get behind it in a double vortex movement. Otherwise, pressure ahead the arc rises and slows down its displacement. The effect of gas exhausts on arc motion and pressure formation is also investigated. As reported by Berger & al. [7], exhaust of the gas through slits along the arc movement leads to a faster arc movement. The necessity of an opening in the downstream is highlighted by Zeller & Rieder [8]. Reducing the downstream exhaust can lead to immobility of the arc.

All those studies carry valuable clues to understand the arc behaviour but sometimes lacks the statistic treatment required on such erratic phenomena or could use a wider range of measurements. To complete those works, we wanted to perform a statistic investigation on parameters such as exhausts configuration, chamber volume and current level with high-speed imaging, current, voltage and pressure measurements. The aim of this paper is to present a new experimental approach of arc movement and to investigate the impact of gas exhaust and of the upstream volume.
2. **Experimental set-up**

In order to reproduce the principle of the LVCB we created a device with a simplified arc chamber and a mechanism allowing the opening of the mobile contact at a specified time and speed. This system is synchronised with the pulse current source so that the contact opening is made at a specified current while measurements of current, voltage, pressure and high-speed imaging are performed.

2.1. **Pulse current generator**

To reproduce a short-circuit fault, a pulse current generator has been designed. A bench of capacitors is charged at 600 V and discharges through air coils thanks to power thyristors. This creates a 50 Hz half-sine with a prospective current of up to 13 kA. The intensity level is changed by using another inductor-capacitor combination or by lowering the charging voltage.

2.2. **Arc chamber**

In industrial Miniature Circuit Breakers (MCB), the arc chamber has adopted a complex shape for the sake of space saving. Therefore, a lot of geometric parameters appear which makes difficult the analysis of the arc behaviour. For this reason, we used a simplified geometry (Figure 1) where the arc chamber is a rectangular box with two parallel arc runners and a displacement of the arc in only one dimension. We also removed the splitter plates as we focus on arc movement and not on the extinction phase.

![Figure 1: View of the simplified arc chamber](image)

There are less geometric parameters with our device which are also easily modifiable, like the width and length of the chamber, the volume behind the moving contact or the number of gas exhausts of the chamber. Eight positions in the back of the chamber allow pressure measurements along the arc movement. The front wall of the chamber is made of transparent Plexiglas which permits imaging of the arc. In the middle of the chamber is an electrical contact enabling arc ignition by contact opening with a rotation like in MCBs. A dedicated mechanism has been designed in order to perform this opening movement at specified time and speed.

2.3. **Opening mechanism**

We need an instantaneous opening speed among 1 and 10 m/s to investigate the impact of this parameter on arc breaking. Also, a good synchronisation with the current pulse is necessary to ensure arc ignition is performed with the same current. Such an actuator is not commonly found so we conceived our own system.

To achieve this rotation, a lever is hit at high velocity by a mass pulled by a spring and liberated by a lock (Figure 2). For the synchronisation, an optocoupler detects the mass movement before it hits the lever. This optical sensor activates a timer which triggers both the current pulse and the measurements.
2.4. Measurements
Several electrical signals are acquired during the breaking. The arc voltage is measured at 500 kHz and reveals important information such as arc ignition or restrikes. It is also necessary to calculate the energy dissipated in the discharge. Two currents are acquired with Rogowski coils: the total current and the current flowing in the mobile contact. Knowing those two data, we can determine when the current is transferred from the moving contact to the upper arc runner in a process called commutation.

In addition with electrical measurements, pressure inside the chamber is measured at several points in the back of the chamber. We need a good time resolution and to install multiple sensors in a small volume. So, we used the Keller M5HB miniature piezoresistive sensor which has a 6.2mm diameter for the body and a dynamic response of up to 50 kHz. Moreover, it is not sensible to the shock induced by the opening mechanism. A copper muffler is used to protect the sensor head from heat and to remove the dynamic component of the pressure.

The arc movement is quantified thanks to the Photron SA5 high-speed camera with an acquisition frequency of 100,000 frame/second and a spatial resolution about 0.19 mm/pixel. To extract a relevant information of position of the arc from those images we need to develop a method.

2.5. Post-treatment
The arc and arc roots positions are sometimes not easy to determine from the pictures of the camera. It is relevant to define an algorithm that would determine automatically the position out of the frames. Based on the work of McBride & al. [9], where arc position is given by a weighted mean of the detected luminosity, we developed a software that determines the global position of the arc and the position of one arc root for each electrode by examining the pixels intensity in the vicinity of each runners (green and blue areas in Figure 3). This application also edits each frame of the video for more readability with the size of the chamber, the rotation axis of the contact, the pressure sensor location or other information such as the maximum current like written in red in Figure 4. The calculated positions of the arc are also indicated with crosses (red for the global position of the arc, green and blue for upper and lower arc roots) and electrical waveforms are added on the right of the image.
3. Influence of gas exhausts

On each extremities of the chamber, two 5mm diameter openings are performed allowing the gas to flow out of the geometry. By closing them we modify the pressure formation and gas flow which impacts the arc movement. Four configurations are considered namely: Open-Open where all exhausts are open; Open-Closed where the downstream exhausts have been shut; Closed-Open where the upstream exhausts are closed and the downstream exhausts are open; Closed-Closed where there are no gas exhausts. For those configurations, the tests were also performed with three levels of intensity with maxima of 631, 1608 and 2852A. The results presented in this section have been obtained with an opening speed of 2.91m/s and a distance between the ignition point and the upstream exhaust of 45 mm.

3.1. High-speed imaging

The global position of the arc determined using the software previously described is shown for three currents in Figures 5-7. We can see a movement which is generally divided in two phases: a slow movement while the arc is bent between the moving contact and the lower arc runner and then a very fast displacement when hot gasses have been spread inside the chamber and the arc commutates.

In the first phase of the movement (between 1 and 2.5ms), the exhaust configuration does not seem to affect the movement of the arc. In the second phase, we see a fast displacement when the arc commutates for Open-Open and Closed-Open configurations. When all exhausts are closed, this movement is slower due to the stagnation of the gas in front of the arc. The worst case is Open-Closed where we can spot that the arc is hardly moving from the contact since the gas fluxes are directed toward the back of the chamber.
Those results are for single tests. Since breaking arcs behaviour is rather chaotic, we will present a statistic analysis on pressure and electrical measurements in the next section.

![Graph](image)

**Figure 5:** Global position of the arc determined by the method described in §2.5 for different configurations of gas exhaust and a maximal current of 631A.

![Graph](image)

**Figure 6:** Global position of the arc determined by the method described in §2.5 for different configurations of gas exhaust and a maximal current of 1608A.
3.2. Analysis of the electrical measurements

As seen in Table 1, a higher current level tends to start the commutation process sooner except for the cases where the downstream exhausts are closed. A greater current intensity leads to stronger Laplace forces which bend the arc toward the upper arc runner. But if the downstream exhausts are closed, there will be a pressure elevation in front of the arc preventing it to reach the upper rail. Especially in the Open-Closed configuration, the gas flow is directed to the back of the chamber, acting against the Laplace forces.

Exhausts configuration | Open-Open | Open-Closed | Closed-Open | Closed-Closed
--- | --- | --- | --- | ---
Peak current: **2852 A** | 1.25 ± 0.09 ms | 2.46 ± 0.25 ms | 1.41 ± 0.35 ms | 1.25 ± 0.27 ms
**1608 A** | 1.51 ± 0.01 ms | 1.24 ± 0.19 ms | 1.37 ± 0.06 ms | 1.12 ± 0.04 ms
**631 A** | 1.74 ± 0.06 ms | 1.96 ± 0.63 ms | 1.80 ± 0.24 ms | 1.61 ± 0.03 ms

Table 1: Time between ignition and start of commutation for 3 levels of current

Table 2 shows the commutation duration which is the time between the instant when the contact current gets smaller than the total current and the instant where no current is flowing through the contact. The influence of the intensity is very strong for this topic. At high current, the configuration showing the shorter commutation is the one where all exhausts are open although it has rather long commutation length at low current. On the other hand, the Closed-Open proves to be efficient for smaller current but not for high intensity. For low current, closing the upstream exhaust greatly reduces the commutation time as it should push the arc toward the end of the chamber. Generally, we see that closing some exhausts at high current extends the commutation. The hot gas must leave the chamber in order to prevent restrikes on the mobile contact.
3.3. Pressure measurements
Gas exhausts reveal a major impact on the pressure level obtained in the chamber. The 10mm chamber is broad enough to allow the gas to flow on the side of the arc and to spread the pressure homogeneously. Thus, all the pressure difference measured in our experiment is within the exhausts, between the inside of the chamber and the free air. As seen in Table 3, pressure is easily doubled when half the exhausts are shut, except for the Closed-Open case at low current where the amount of hot gases is reduced and pushed out of the geometry as the arc moves forward. Pressure is even more strongly increased if the chamber is hermetic. The pressure level is an important parameter for industrial design of the circuit breaker. High pressure often leads to explosion or deterioration of the devices. Also, pressure has an effect on the properties of the medium and could change the arc voltage which is significant for limiter circuit breakers.

### Table 2: Commutation duration for 3 levels of current

| Exhausts configuration | Open-Open | Open-Closed | Closed-Open | Closed-Closed |
|------------------------|-----------|-------------|-------------|---------------|
| Peak current: 2852 A   | 0.78 ± 0.35 ms | 6.93 ± 0.27 ms | 1.84 ± 0.13 ms | 3.53 ± 0.21 ms |
| 1608 A                 | 1.27 ± 1.58 ms | 5.10 ± 0.82 ms | 0.79 ± 0.63 ms | 3.18 ± 0.27 ms |
| 631 A                  | 1.81 ± 1.82 ms | 5.49 ± 2.23 ms | 0.21 ± 0.16 ms | 0.27 ± 0.10 ms |

### Table 3: Mean maximal pressure relative to atmospheric pressure for 3 levels of current

| Exhausts configuration | Open-Open | Open-Closed | Closed-Open | Closed-Closed |
|------------------------|-----------|-------------|-------------|---------------|
| Peak current: 2852 A   | 0.60 bar  | 1.51 bar    | 1.78 bar    | 3.42 bar      |
| 1608 A                 | 0.46 bar  | 0.99 bar    | 0.81 bar    | 2.82 bar      |
| 631 A                  | 0.17 bar  | 0.39 bar    | 0.18 bar    | 1.43 bar      |

4. Influence of upstream volume
If the pressure formation behind the arc impacts the arc behaviour, reducing the upstream volume should also modify the arc motion. In Table 4, it is clear that reducing the volume behind the moving contact starts the commutation earlier by increasing the pressure force toward the end of the chamber. This result is in agreement with the work of McBride & al [4]. However, investigations on commutation duration do not show a significant influence of this parameter. Pressure level is given in Table 5 to depend on of the chamber volume. This is because all the hot gas produced by the electrical arc does not have the time to evacuate the chamber through the narrow exhausts.

### Table 4: Time between ignition and start of commutation for 3 levels of current

| Exhausts configuration | Open - Open | Closed - Open |
|------------------------|-------------|---------------|
| Distance of upstream wall | 30 mm | 45 mm | 30 mm | 45 mm |
| Peak current: 2852 A | 1.26 ± 0.06 ms | 1.25 ± 0.09 ms | 1.02 ± 0.04 ms | 1.41 ± 0.35 ms |
| 1608 A | 1.04 ± 0.10 ms | 1.51 ± 0.01 ms | 1.08 ± 0.06 ms | 1.37 ± 0.06 ms |
| 631 A | 1.29 ± 0.09 ms | 1.74 ± 0.06 ms | 1.54 ± 0.16 ms | 1.80 ± 0.24 ms |

### Table 5: Mean maximal pressure relative to atmospheric pressure for 3 levels of current

| Exhausts configuration | Open - Open | Closed - Open |
|------------------------|-------------|---------------|
| Distance of upstream wall | 30 mm | 45 mm | 30 mm | 45 mm |
| Peak current: 2852 A | 0.99 bar | 0.60 bar | 2.12 bar | 1.78 bar |
| 1608 A | 0.51 bar | 0.46 bar | 1.11 bar | 0.81 bar |
| 631 A | 0.25 bar | 0.17 bar | 0.54 bar | 0.18 bar |
5. Conclusion & perspectives

Investigation on arc breaking in a simplified low-voltage circuit breaker chamber has been conducted and gives many clues on arc behaviour that can be transferred to the design of industrial devices. The geometry of the chamber is critical for the fast movement of the arc from the contact region to the splitter plates and an efficient working of the system. The exhaust configuration and volume of the chamber have demonstrated their ability to strongly modify the breaking process.

On the one hand, it is necessary to permit the gas to flow out of the chamber to ensure a good displacement of the arc. On the other hand, the amount of hot material escaping the circuit breaker must be controlled to prevent damages to surrounding apparatuses. Considering also that a given configuration would not work for all level of current, it is clear that developing new breaking solutions is very difficult.

Further parameters may be studied with our set-up. The width of the chamber has an impact on the movement of the arc [6] but also for a narrow geometry the thermal plasma could obstruct the chamber and lead to a pressure gradient that would be detected by our sensors. Correlation between arc movement and local pressure variation should carry interesting information. The material of the walls of the experiment could be changed from plastic to non-ablative ceramics, modifying the pressure formation and the nature of the plasma medium. Moreover, movement of the arc root for electrode of different alloys could be compared. Finally, if we focus on extinction of the arc, splitter plates could be added within the chamber.

In parallel with this experimental work, computational fluid dynamics simulation using finite volume method are performed in similar 3-D configurations for both validation of the model and explanation of the measurements [10]. Such numerical tools would greatly help the development of new products by allowing simulation of a specified architecture before the realisation of a prototype.

References

[1] C.W. Brice, R.A. Dougal & J.L. Hudgins, Review of Technologies for Current-Limiting Low-Voltage Circuit Breakers, IEEE trans. indus. app., vol.32 no.5, 1996
[2] Y. Wu, M. Rong, G. Yang & G. Hu, Numerical Analysis of the Arc Plasma in a Simplified Low-Voltage Circuit Breaker Chamber with Ferromagnetic Materials, Plasma sci. & technol., vol.7 no.4, 2005
[3] M. Lindmayer & M. Springstubbe, 3D-Simulation of arc motion between arc runners including the influence of ferromagnetic material, Proceedings of the 47th IEEE Holm Conference on Electrical Contacts, 2001
[4] J.W. McBride, K. Pechrach & P.M. Weaver, Arc Motion and Gas Flow in Current Limiting Circuit Breakers Operating With Low Contact Switching Velocity, IEEE trans. comp. pack. technol., vol.25 no.3, 2002
[5] X.Li, D. Chen, Q. Wang & Z. Li, Simulation of the Effects of Several Factors on Arc Plasma Behavior in Low Voltage Circuit Breaker, Plasma sci. & technol., vol.7 no.5, 2005
[6] M. Lindmayer & J. Paulke, Arc Motion and Pressure Formation in Low Voltage Switchgear, IEEE trans. comp. pack. manufact. technol., vol.21 no.1, 1998
[7] K.A. Berger, B. Gessl, W. Schneider & W. Rieder, Arc Motion and Wave Propagation in Arc Chambers With Lateral Chinks, IEEE trans. comp. pack. technol., vol.25 no.3, 2002
[8] P.R. Zeller & W.F. Rieder, Arc Structure, Arc Motion, and Gas Pressure Between Laterally Enclosed Arc Runners, IEEE trans. comp. pack. technol., vol.24 no.3, 2001
[9] J.W. McBride, P.M. Weaver & P.A. Jeffery, Arc Root Mobility During Contact Opening at High Current, IEEE trans. comp. pack. manufact. technol., vol.21 no.1, 1998
[10] J. Quéméneur, P. Freton, M. Masquère, J.-J. Gonzalez, P. Joyeux, Cathode Arc Root Movement : Models Comparison, Plasma phys. & technol., vol.2 no.2, 2015