

HIGH ACCURACY CHARACTERIZATION OF WALL CONSTRICTED ARCS

MICHAEL M. WALTER¹ AND CHRISTIAN M. FRANCK^{1*}

¹ Power Systems and High Voltage Laboratories, ETH Zurich, Zurich 8092, Switzerland

*email of corresponding author: cfranck@ethz.ch

ABSTRACT

In this contribution, we report on the application of a novel, high accuracy, arc characterization method to wall constricted arcs in cylindrical nozzles with low blow pressure. The method makes use of a novel current source that is able to produce nearly arbitrary current shapes. With it, it is possible to derive the stationary and transient arc characteristic independent of each other but within one experiment. The arcs under investigation are aimed for application in HVDC circuit breakers with passive resonance principle. The example shown in this contribution, an arc axially blown with air at $p_{\text{blow}} = 1.5$ bar, nicely demonstrates the power of this novel characterization method.

1. INTRODUCTION

Black-box models of switching arcs in circuit breakers (CBs) have been successfully used to investigate arc-network interactions [1, 2]. This is extensively done since decades for HVAC CBs, but can also be applied to study HVDC CBs. The passive resonance concept of creating CZs is to excite a current oscillation between the main current path and a parallel resonance path containing passive inductive (L) and capacitive (C) components [3, 4]. The oscillation is unstable, i.e. the current amplitude increases, if the negative differential arc resistance (dU/dI) is larger than the damping losses (R) in the resonance circuit. To achieve a fast CZ crossing, the passive LC -components are chosen that a fast oscillation frequency occurs and that the transient dU/dI is still negative. A correct calculation of the arc-network interaction of this oscillating current with a black-box model requires accurate and precise model parameters. Many high current switching arcs can be represented sufficiently accurate with the *Mayr-* or *Mayr-Schwarz-equation* [5, 6]. The two

model parameters are the stationary cooling power P and the thermal time constant τ that represents the time delay with which the arc adopts to transient changes in the arc current. These parameters can be determined from the arc behavior in measurements with a given test current. Classically, these test currents are sinusoidal currents generated from a rotating machine or an LC-resonance-circuit. However, these test currents are not ideal for an accurate model parameter determination, as the stationary and transient behavior can only be measured coupled.

A novel method for direct black-box arc parameter determination has been presented recently [7]. It makes use of a new current source that enables the creation of arbitrary test currents [8]. In particular, test currents with clearly separated quasi-stationary and transient current section can be created, e.g. step-wise current increase. This way, it is possible to derive the black-box parameters with unprecedented accuracy. In this contribution, we demonstrate the novel parameter determination method on nozzle constricted arcs with moderate blow pressure and varying nozzle cross sections. The increasing influence of a decreasing nozzle cross-section on the black-box parameters can be clearly seen. A systematic measurement of black-box parameters of switching arcs under different external conditions can serve as the basis for the optimization of passive resonant HVDC CBs.

2. METHOD

In this contribution, arcs are characterized from voltage responses to currents that are created with a novel arbitrary current source [7, 8]. The current shape is characterized by alternating section of quasi-stationary and fast varying current sections. The stationary arc characteristic is derived from the quasi-stationary current sections, whereas the transient arc characteristic is

evaluated from the fast varying current sections.

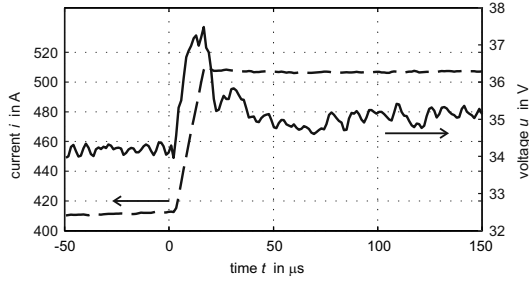


Fig. 1: Example voltage response of arc subject to current step.

An example arc voltage response (solid line) to a single current step (dashed line) is shown in figure 1 for a free burning arc between two horizontally arranged copper electrodes with $d = 4$ mm electrode separation. The arc shows in principle a stationary characteristic during the constant current sections, although arc voltage fluctuations are clearly visible as well. The arc voltage response to the current step is a spike occurring during the current step followed by an exponential decrease in the constant current phase toward the new stationary voltage. From the observed transients one can conclude that the arc characteristic is well described by the *Mayr-Schwarz equation* [6]. The model arc parameters $P(g)$ and $\tau(g)$ characterize the stationary cooling power and thermal inertia, respectively, and are free functions of the arc conductance g .

3. FLEXIBLE ARC CHAMBER

For the arc characterizations presented in this contribution, a flexible arc chamber was used (cf. figure 2). It consists of two vertically arranged electrodes; the lower one inside the pressure chamber is fixed, but the upper one is movable and driven with a slow pneumatic drive. The resulting maximum electrode separation distance is typically $L_{\text{tot}} = 100$ mm. The arc between the electrodes is constricted by a cylindrical nozzle with inner diameter d_T at its smallest cross section. The arrangement is flexible and the nozzle can be easily replaced. Thus, the influence of the nozzle constriction on the arc characteristic is studied by exchanging nozzles with varying inner diameter. The nozzle is made of acrylic glass (PMMA) to enable visual observation and high-speed imaging. At both ends, the nozzle widens with an angle of 45° . The lower electrode is fixed at a distance of $L_{\text{in}} = 10$ mm below the nozzle throat. The lower electrode is mounted inside a pressure volume of

1 liter. This pressure volume is fed from eight pressure bottles that are connected via fast acting valves. The blow gas is pre-stored in these bottles before the experiment. The resulting blow gas pressure in the volume is up to $p_H = 50$ bar. The gas outflow from the nozzle is into the ambient air of the laboratory. Thus, only environmental benign gases, like synthetic air, can be used.

The arc is blown by $p_h = 1.5$ bar synthetic air in PMMA nozzles of length $L_T = 50$ mm and varying cross section $d_T = 6, 8, 11$ mm.

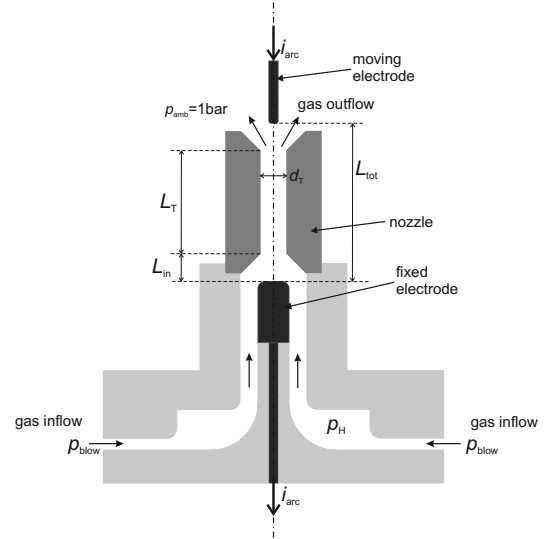


Fig. 2: Schematic representation of the flexible arc chamber used for arc characterization.

4. ARBITRARY CURRENT SOURCE

The basic concept of the novel arbitrary current source has been presented at GD 2010 [8]. The source is now completely set-up and fully operational. It consists of three parallel interleaved modules with a capability to provide a voltage of 3 kV and a current of 1 kA each and is equipped with a common controller. The load current i_{load} is the superposition of all three module currents i_n . The functional principle of the modules is similar to that of a buck-type converter (cf. figure 3). Nearly all current shapes with slopes up to $150 \text{ A}/\mu\text{s}$ can be created by combined or opposed operation of several modules with different current slopes.

Selected example current shapes are shown in figure 4. Constant current section can be created up to 3 kA, but a certain ripple is always present (cf. figure 4(a)). The ripple can be decreased with increased switching frequency of S_n and increased inductances L_n .

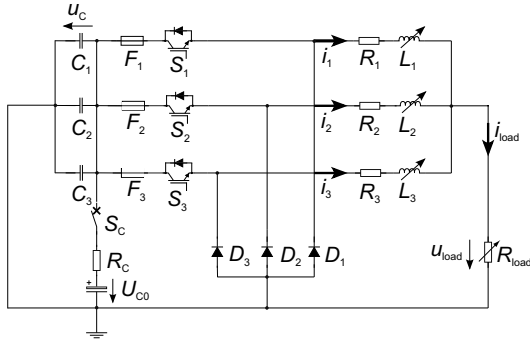


Fig. 3: Schematic representation of the pulsed current source.

Moreover, constant current sections can be preceded or followed by sections with constant positive or negative current gradients (cf. figure 4(b)). The steeper these current gradients shall be, the smaller the inductance L_n has to be selected. The theoretically optimal current shape [9] to characterize switching arcs is stair-like (cf. figure 4(c)). Here, the constant current sections are achieved by two opposite acting submodules and the stepped increase by two common acting submodules. As can be seen in subfigure (c), this is very difficult to achieve over a large current range for an arc with strongly varying arc voltage. Thus, the practically optimal current shape is a slowly varying (quasi-stationary) current, superimposed with sections of varying current with large slopes (cf. figure 4(d)). With this current shape, the stationary arc parameters can be derived from the slowly varying sections, and the transient response is evaluated from the section with steep current gradients. Current shapes similar to the one shown in subfigure (d) have been used for the analysis in this contribution.

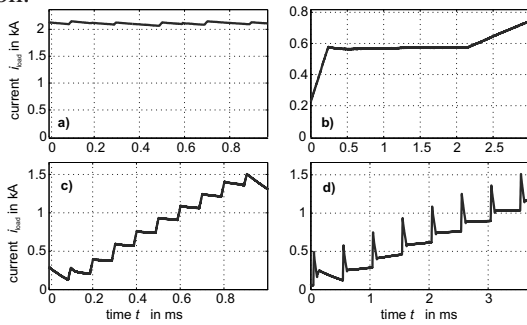


Fig. 4: Example current shapes possible to create with pulsed current source.

5. RESULTS

For the measured currents < 2 kA, the effect of nozzle diameter on the arc characteristics at low blow pressure ($p_H = 1.5$ bar) is shown in figure 5. Subfigure (a) shows the measured

stationary UI -curves, plotted in subfigures (b) and (c) are the evaluated arc cooling power $P(g)$ and the thermal time constants $\tau(g)$, respectively. Shown are results for three different inner nozzle diameters $d_T = 6, 8, 11$ mm. For small current amplitudes, the UI -characteristics show a negative dU/dI (“falling UI -curve”).

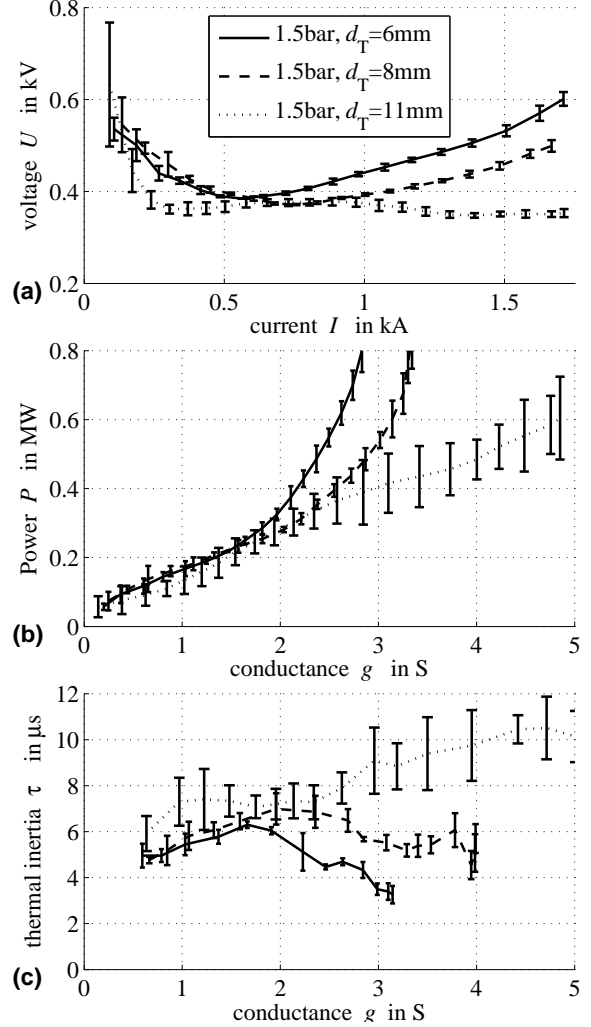


Fig. 5: Arc characteristics of an axial blown arc with different nozzle cross sections.

For the smallest nozzle diameter $d_T = 6$ mm, dU/dI becomes positive (“rising UI -curve”) for currents above $I_T > 550$ A (I_T being the ‘transition’ current). This effect is seen in the $P(g)$ -curve as an overproportional increase with conductance $g > 1.5$ S. The positive slope of the UI -curve decreases with increasing nozzle diameter. At $d_T = 8$ mm, dU/dI becomes positive only for larger currents $I_T > 750$ A and the arc voltage is generally lower compared to those burning in smaller nozzle diameters. For the largest nozzle diameter $d_T = 11$ mm, the arc voltage remains approximately constant for large currents and no increasing arc voltage up to the maximum test cur-

rent of $I_{\max} = 2 \text{ kA}$ has been observed. However, negative dU/dI is only observed for currents $I < 300 \text{ A}$. Here, the arc cooling power increases linearly with conductance over the entire measurement range.

The corresponding arc thermal time constant $\tau(g)$ is shown in figure 5(b). For all three nozzle diameters, an increase of τ with conductance g can be observed when dU/dI is not positive. For the largest nozzle diameter this is the case for the entire measurement range. Here, the maximum arc conductance at $I = 1.75 \text{ kA}$ is $g = 6.2 \text{ S}$, and the thermal inertia τ increases gradually and continuously from $\tau = 6 \mu\text{s}$ to $\tau = 12 \mu\text{s}$. The situation is different for arcs constricted in nozzles with smaller inner diameters. The thermal inertia increases up to the conductance value that corresponds to the transition currents I_T . For $d_T = 8 \text{ mm}$ this is $g = 2.2 \text{ S}$ and the maximum value of the arc thermal inertia is $\tau = 7 \mu\text{s}$. For the smallest nozzle diameter $d_T = 6 \text{ mm}$ the conductance with the highest inertia is $g = 1.7 \text{ S}$ with $\tau = 6 \mu\text{s}$. For higher conductances g the thermal inertia decreases and reaches its lowest value of $\tau = 3 \mu\text{s}$ for the maximum measured conductance $g = 3.2 \text{ S}$.

6. DISCUSSION & OUTLOOK

With the presented method it is possible to characterize arcs with high accuracy. Unfortunately, it is not possible to understand the physical mechanisms behind the characteristics with this method as well. However, from AC switching arc investigations it is well known that ablation causes a positive dU/dI [10]. The result from the present investigation are consistent with this and it is expected that the effect increases with decreasing nozzle diameter.

For the application of this type of arcs in HVDC CBs with passive resonance it is not possible to find an optimum configuration varying only the nozzle diameter. Arcs in small nozzle diameters show a positive dU/dI already at currents well below typical nominal currents in HVDC systems. This would lead to a damped oscillation and not result in an artificial CZ crossing. Although no positive dU/dI results from arcs in large diameter nozzles, the thermal arc time constant τ increases and limits the maximum current slopes, i.e. the maximum possible oscillation frequency. This in turn requires large L and C components in the par-

allel oscillation path.

It will thus be necessary to continue the search for optimum arc characteristics by investigating arcs with systematically varied nozzle length, nozzle material, blow gas pressure, and type of blow gas.

Acknowledgement

Discussions on the project with E. Panousis and M. Bujotzek are gratefully acknowledged. The project is financially supported by ABB Switzerland, Corporate Research.

REFERENCES

- [1] Cigre Report WG 13.01, "Applications of black box modeling to circuit breakers", *electra* **149**, 41 (1993).
- [2] R. Smeets and V. Kertsz, "Evaluation of high-voltage circuit breaker performance with a validated arc model", *Gen. Transm. Distrib.* **147**(2), 121 (2000).
- [3] B. Bachmann, et. al., "Development of a 500 kV airblast HVDC CB", *IEEE Trans. Power App. Syst.* **104**(9), 2460 (1985).
- [4] C. M. Franck, "HVDC circuit breakers: A review identifying future research needs", *IEEE. Trans. Power Del.* **26**(2), 998 (2011).
- [5] O. Mayr, "Beiträge zur Theorie des statischen und des dynamischen Lichtbogens", *Arch. f. El.-Tech.* **37**, 588 (1943).
- [6] J. Schwarz, "Berechnung von Schaltvorgängen mit einer zweifach modifizierten Mayr-Gleichung", *ETZ-A* **93**, 386 (1972).
- [7] M. M. Walter and C. M. Franck, "Improved method for direct black-box arc parameter determination and model validation", *IEEE Trans. Power Del.* **29** doi: 10.1109/TPWRD.2013.2283278 (2014).
- [8] M. M. Walter and C. M. Franck, "Flexible pulsed DC-source for investigations of HVDC circuit breaker arc resistance", *Proceedings of XVIII International Conference on Gas Discharges and Their Application*, Greifswald, Germany, p. 170 (2010).
- [9] M. M. Walter and C. M. Franck, "Optimal test current shape for accurate arc characteristic determination", *IEEE Trans. Power Del.* **29** (2014).
- [10] P. Kovitya and J. J. Lowke, "Theoretical predictions of ablation-stabilised arcs confined in cylindrical tubes", *J. Phys. D: Appl. Phys.* **17**, 1197 (1984).