Validation of a Non-invasive Measuring Method to Determine the Arc Position of an Axially Blown Switching Arc

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Today's research on circuit breaker concepts for alternative insulation and quenching gases is focused on the understanding of the physical processes during a switching process as well as the interaction of the blow gas flow and the switching arc. In order to determine these influences a non-invasive measuring method is established which allows the determination of the spatial arc resistance distribution of an axially blown switching arc to gain a deeper understanding of the cooling processes. In addition, this system is capable of detecting the position of the switching arc by means of trilateration with a measurement system consisting of multiple capacitive field probes. The measurement system is adapted to a laval nozzle geometry and investigations in nitrogen are performed. The results of these investigations are compared to basic optical investigations on switching arcs within this laval nozzle to validate the applicability of the assumptions made for the position determination.

Keywords: non-invasive diagnostics, arc position, arc resistance distribution, optical investigations

1 INTRODUCTION

The development and research on high voltage circuit breakers requires a deep understanding of the physical processes during a switching process. Especially the interaction of the quenching gas and the switching arc are of main interest. Most of today's circuit breaker concepts in the transmission and sub-transmission level ($U_s \geq 72.5$ kV) are based on sulphur hexafluoride (SF_6) as insulation and quenching gas. Because of its high global warming potential the demand for substitution of SF_6 with alternative quenching gases like carbon dioxide (CO_2) or nitrogen (N_2) is growing. The reduced dielectric properties and the changed gas characteristics compared to SF_6 require a detailed understanding of the physical processes and the interaction of the gas and the switching arc during a switching process to develop new breaker concepts.

In this contribution the applicability of a non-invasive measurement method for the determination of the spatial arc resistance distribution is validated by basic optical investigations. The non-invasive test setup is based on capacitive field probes and allows the determination of the spatial arc resistance distribution and the arc position. The reconstruction of the arc position requires mathematical assumptions which are validated with the results of basic optical investigations. Therefore both measuring methods are adapted to a laval nozzle geometry related to a reference case [1]. The analysis of the results yields a first approach for a verification of the applicability of the non-invasive measurement method for the position determination.

2 EXPERIMENTAL SETUP

For determining the arc behavior, a contactless measuring method has been developed [2]. This method uses capacitive field probes for measuring the dielectric displacement current caused by the electric field of the switching arc. By using multiple sensors around the arc and along the axis of symmetry of a circuit breaker model it is possible to calculate the spatial arc resistance distribution considering the potential drop along the arc and the arcing current. A first validation of the results for the spatial arc resistance distribution has shown that the system in principle is able to detect the influence of turbulent and laminar flow sections on the current interruption [3].

In continuation of the previous research work, the arc position can additionally be determined by means of trilateration from the signals of the 36 field probes (9 layers, each equipped with 4 sensors) (cf. Fig. 1).

In each single layer three sensors are shifted by $\alpha = 120°$ so that a localization can be real-ized using a trilateration method. The fourth

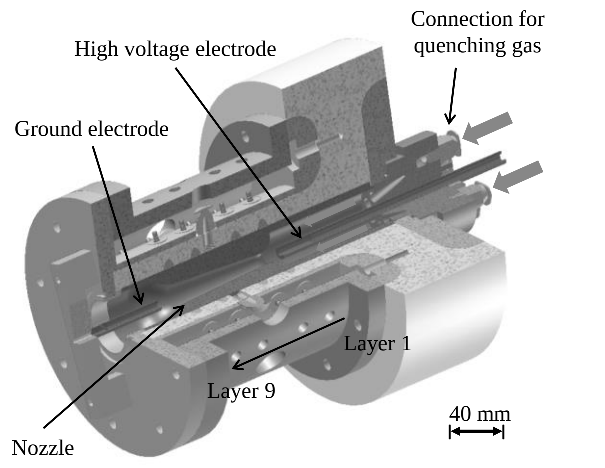

Fig. 1: Sketch of the circuit breaker model of the contactless measurement system

sensor will be used for a radius determination of the arc in future research work. In order to use this method within the diagnostics and research of circuit breakers assumptions are necessary to solve the mathematical problems related to the trilateration. Therefore a cylindrical symmetry of the arc is assumed. In addition, the arc radius is neglected.

For the validation of this newly implemented position determination approach, basic optical investigations are performed. Therefore a simplified circuit breaker model is developed based on the laval nozzle geometry from previous investigations [1,3] (cf. Fig. 2). The insulation nozzle is made of polytetrafluorethylene (PTFE) and covered by two acrylic glass plates yielding a flat viewing window for the optical recording system and preventing multiple refractions at the glass plate surfaces. The electrodes made of tungsten-copper are mounted corresponding to the experimental investigations performed with the non-invasive measurement system (cf. Fig. 2). A transition part at the circuit breaker model serves as quenching gas connection and is connected to an external heating volume. This transition part ensures laminar inflow conditions of the quenching gas at the inlet close to the ground electrode.

Two gas tanks are connected to the external heating volume and filled to an absolute pressure of $p = 4.5$ bar before the experiments. As power supply an *L*-*C*-oscillating circuit is used consisting of an inductivity of $L = 315$ µH and a capacitance of $C = 36$ mF.

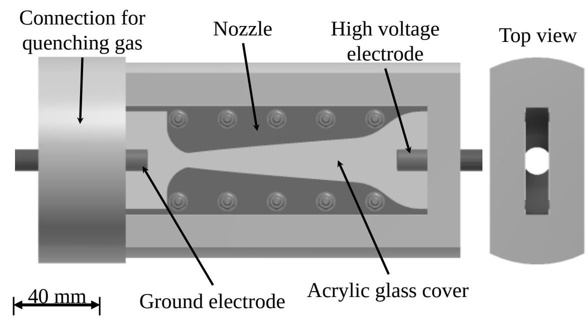

Fig. 2: Sketch of the optical circuit breaker model

The current is ignited at maximum pressure in the heating volume to guarantee a constant pressure profile during the switching process. Exemplary characteristics of the pressure and the current from the performed experiments are shown in Fig. 3.

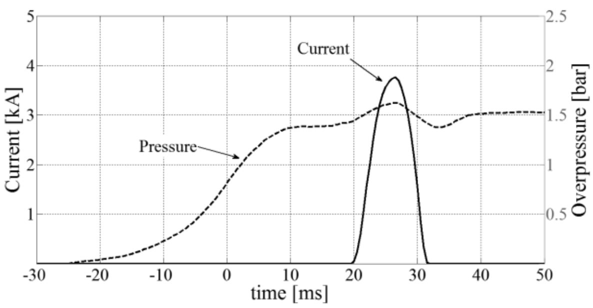

Fig. 3: Exemplary characteristics of the pressure in the heating volume and the current

The optical recording system consists of a high speed camera equipped with a neutral density filter. The exposure time is set to $t = 1.5$ µs. In order to gain a deeper understanding on the behavior of the arc, in a first approach single photographs are taken for a test current range of several 100 A to less than 20 A at the instant of the exposure. The focus of these investigations is the current zero region. A quenching gas pressure of $\Delta p = 1.5$ bar in the heating volume and a peak current of $I_{peak} = 3.5$ kA are achieved for all experiments. Table 1 depicts the instant of recording before current zero and the current.

Table 1: Parameters of the performed tests

Experiment No.	Time [µs]	Current [A]
1	-40	110
2	-20	31
3	-12	12.5
4	-7	6

3 RESULTS AND DISCUSSION

In contrast to the previously investigated reference case[1,3] compressed air is used as quenching gas in this investigation, so no extensive gas handling and no test vessel are required for the first experiments. In a first approximation air is used as quenching gas for deducing possible influencing factors on the capacitive measuring system as well as for investigating the applicability of the assumptions for the position determination. Therefore especially the general flow characteristic and its influence on the arc behavior are of interest. With regard on the generation of turbulences the Reynolds number is considered setting up the experimental parameters. According to the gas properties and the laval nozzle geometry the difference of the Reynolds number for air and nitrogen yields to less than 1 % considering the experimental setup as well as the gas velocity $v = 500$ m/s at the nozzle throat resulting from CFD simulations [4,5].

In agreement with the reference case [1] the nozzle geometry is divided in five sections a-e as depicted in Fig. 4. The arc shape at $t = -40$ µs is in good agreement with the results for the reference case [1]. In the laminar flow section a-b the arc is nearly centered and quenched to a cylindrical shape whereas in the transition section b-c the arc starts pending around the axis of symmetry. Additionally the arc core is surrounded by hot gas in these sections resulting in an increased diameter of the plasma channel. Moving along the axis of symmetry towards the nozzle diffusor the arc channel and the surrounding hot gas gets more and more diffuse leading to an accumulation zone of hot gas in front of the high voltage electrode. Approaching the current zero crossing the arc diameter reduces strongly with decreasing current amplitude and the transition zone from laminar to turbulent flow translates towards the grounded electrode (cf. recordings at -20 µs < t < -7 µs). Thus the turbulent cooling gets dominant which can be observed from the growing arc and hot gas eddies in the photographs. These results yield a general agreement with those of the reference cases [1,3] detecting the turbulent cooling mechanism as dominant effect during the interruption success.

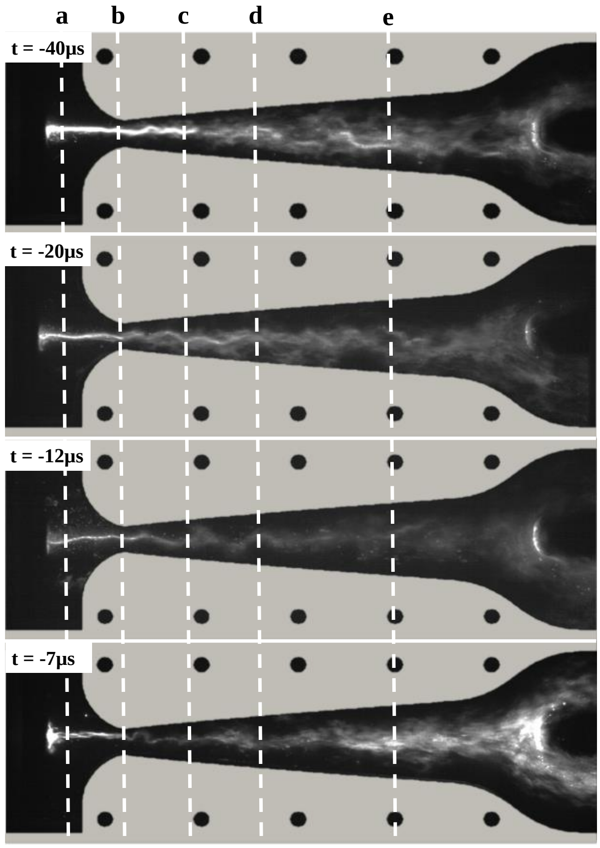

Fig. 4: Arc motion photography before current zero (nozzle sections a-e according to [1,3])

From the optical investigations, it can be concluded that the arc is controlled and centered by the blow gas flow in the vicinity of current zero. In contrast to this the position determined with the non-invasive measuring system yields a more asymmetrical arc behavior which is analyzed in the following. The exemplary behavior of the arc for one single layer for several experiments (Exp. 1 - 3) is shown in Fig. 5. In general it is observed that the radial position over time is in good agreement for different experiments. Therefore the average value for the radial position of the experiments is determined and the standard deviation serves as an indicator for the position change over time.

The resulting radial arc positions are depicted in Fig. 6. Here for each sensor layer the error bar represents the standard deviation of the arc position due to the arc movement during a time range of 40 µs before current zero.

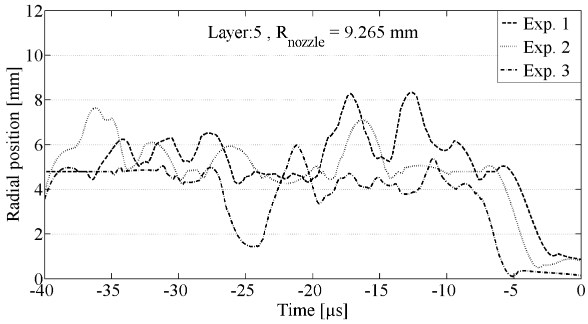

Fig. 5: Exemplary radial arc positions of three experiments before current zero

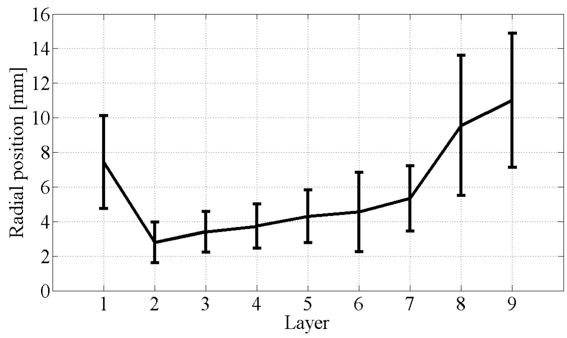

Fig. 6: Arc position for a time range of 40 µs before current zero (cf. Fig. 1)

Moving along the axis of symmetry towards layer nine (cf. Fig. 1) the arc seems to move more and more off-centered and also the oscillation of the arc position over time increases as can be seen in the high values of the standard deviation. This behavior indicates an influence of the hot gas surrounding the arc core on the measuring signal obtained by capacitive coupling. The conductivity of the hot gas leads to a stronger coupling to the capacitive field probes and the real arc position seems to be concealed. Therefore the assumption made in the trilateration process that the position of the arc core is directly determined is possibly not generally valid for all sections of the arc in the used nozzle geometry. Analyzing layers two and three the determined average position is indicated to be in good agreement with the results from the optical investigations (cf. section a-b in Fig. 4). Thus it is indicated by these first results that for sections a-b, respectively layer one to three, the assumptions made for the trilateration method are valid and the arc can be located because of its contracted shape. Thus it is necessary to gain additional knowledge about the arc and the surrounding hot gas for optimizing the arc position determination with the non-invasive measurement system.

4 CONCLUSION AND OUTLOOK

In this contribution it was shown in a first approach that the influencing factors on the capacitive arc resistance and position measuring system, e.g. hot gas surrounding the arc core, can be additionally analyzed by optical investigations. A further analysis of this hot gas surrounding the arc core for example using temperature measurements by spectroscopy can improve the insight on the interaction of the arc and the quenching gas. In combination with the results of the non-invasive measurement system those techniques can be used to develop a measuring system which may include both methods in one common setup for future investigations.

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