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Influence of the simulation model on the spatial arc resistance distribution of an axially blown switching arc

Matthias Hoffacker[1], Paul G. Nikolic[1], Daniel Eichhoff[1], Andreas Kurz[1]

[1] Institute for High Voltage Technology, RWTH Aachen University, Aachen, Germany
(Email: hoffacker@ifht.rwth-aachen.de)

Abstract: Circuit breakers are important elements of the electric power supply system. Due to the contact separation during the switch-off process an electric arc is ignited within the circuit breaker. A forced flow of the insulating quenching gas medium is used to cool the arc influencing its conductivity. Only if the power dissipation due to cooling exceeds the electrical power input by ohmic heating, the arc is extinguished and the current is successfully interrupted in its natural zero crossing (CZ). As the impact of the cooling by the quenching gas on the resistance of the arc is considered crucial for the success of the switch-off process, the spatial distribution of the resistance is of high importance for the assessment of a circuit breakers performance.
Research and development projects related to circuit breakers more and more often use computational fluid dynamics (CFD) simulations. The implemented simulation models have to be be verified by adequate experiments. This paper deals with the influence of the simulation model on the simulated spatial arc resistance distribution near current zero. Different approaches for modelling the chaotic and turbulent phenomena of the arc are introduced and their results are compared with values measured in experiments. Here the turbulence model is of main interest. On the one hand the investigations show a good agreement between simulative and experimental results for the total arcing voltage when using adequate models. On the other hand these turbulence models lead to differences in the calculated spatial arc resistance distributions – which cannot be verified by experiments so far.

Keywords: CFD-simulations, circuit breaker, high voltage, arc, arc resistance, spatial resistance distribution, chaotic modeling, turbulence, turbulence model

1 Introduction

Circuit breakers are important elements of the electric power supply system. They are necessary for the safe switching of rated currents and the interruption of short-circuit currents. Today's high voltage power supply system's predominantly make use of self blast circuit breakers using sulphur hexafluoride (SF_6) as insulating and quenching gas. The contact separation during the switch-off process creates an electric arc within the circuit breaker. By cooling with a forced flow of the insulation medium the energy is dissipated until the arc is extinguished. Simultaneously the resistance of the arc rises. The value of the

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resistance and its distribution along the arc is the crucial factor for the switch-off process to be successful [1].

Research and development projects related to circuit breakers increasingly use computational fluid dynamics (CFD) simulations as these simulations can reduce the number of cost-intensive reference experiments and allow the visualization of physical values which are not – or only very difficult – accessible in experimental investigations. Thus, they can also improve the understanding of the physical processes in the plasma of the electric arc during the switching operation of circuit breakers.

However, this paper deals with the influence of the simulation model on the calculated spatial arc resistance distribution near current zero. The arc resistance is mainly influenced by the convective and turbulent cooling of the quenching gas flow [2]. This leads to a non-linear arc resistance distribution near current zero. Hence, the simulation models need to consider both cooling mechanisms. Different approaches for modelling the turbulent phenomena of the arc are introduced and their results are compared with values measured in experiments.

Firstly experiments using a circuit breaker prototype are carried out. Here the arcing voltage close to the natural current zero (CZ) in the 50 Hz sinusoidal oscillation of the electric network is of main interest. Secondly CFD-simulations of the switching operation are performed using different turbulence models for the calculation. The results of these simulations are compared with the experimental ones.

2 Experimental investigations

For the experimental investigations the behaviour of a circuit breaker prototype is investigated in a synthetic test circuit.

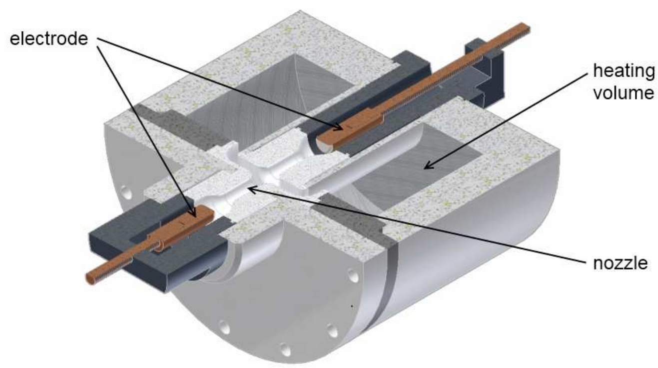

Fig. 1. Cross-sectional view of the circuit breaker model used in the experiments

A cross-section of the test breaker is given in figure 1. The arc is ignited between the electrodes by a thin copper wire which evaporates due to the high current flow of more than 10 kA. The formed electric arc is burning inside the nozzle which is made of polytetraflourethylene (PTFE) and evaporates material from the nozzle surface. This ablation and the heating by the arc lead to a pressure rise inside the nozzle which is relieved through the heating channel into the heating volume of the breaker.

As a consequence, the pressure in the heating volume rises accordingly. When the sinusoidal current and thus the power input by the arc decrease, the gas flow reverses and the quenching gas flow from the heating volume cools the arc inside the nozzle. If the cooling power of the quenching gas flow exceeds the power input of the arc the current can be interrupted during its natural current zero crossing.

For the experimental investigations in this paper a synthetic Weil-Dobke test circuit is used. The equivalent circuit diagram is shown in figure 2. The pre-charged capacitor C_T and the inductor L_T form a 50 Hz-resonance circuit together with the test breaker (TB). Closing the making switch (MS) and subsequently opening the auxiliary breaker (AB) one half period of a high current sinusoidal oscillation is precisely applied on the test breaker. The elements C_S and L_S form another resonance circuit, called injection circuit, with a frequency of approximately 950 Hz. This oscillation is triggered by the ignition spark gap (ISG) 500 µs before the end of the high current phase and causes a dielectric stress for the breaker after current interruption. The shape of this so-called transient recovery voltage is determined by the elements R_p and C_p. For the measurement of the currents a Rogowski-coil and a coaxial shunt are used. Details on the Weil-Dobke test circuit can be found in [3].

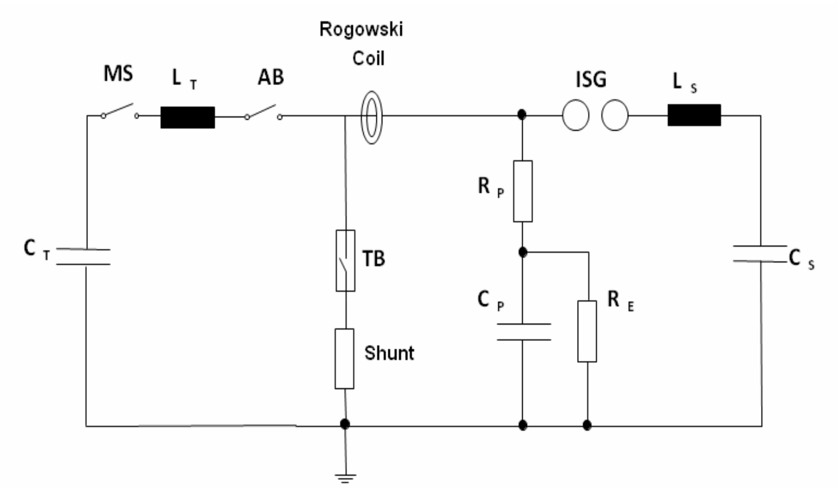

Fig. 2. Equivalent circuit diagram of a synthetic test circuit after Weil and Dobke used for the experimental testing

3 Simulations

Computational-Fluid-Dynamic (CFD) simulations are a state-of-the-art tool in the development of high voltage circuit breakers, reducing the amount of time consuming and cost intensive experimental investigations. Nevertheless the applied simulation models need to be verified as the results of the simulation of a switching operation are sensitive to small changes in the geometry or the used models. The considered circuit breaker prototype used in the experiments is simplified for the simulations. This simplified geometry is given in figure 3. The 3-dimensional breaker prototype is replaced by a 2-dimensional, axis-symmetric model which is reduced to the region of interest – the arcing zone. The heating volume of the breaker is substituted by an inlet with the corresponding gas temperature, pressure and composition. Due to the fact that solely a time period of some µs before current zero is simulated these values are quasi constant. They are derived from simulations of the full high current period of 10ms. The applied mesh has its highest resolution in the area of the highest gradients of the physical values, i.e. along the axis of symmetry.

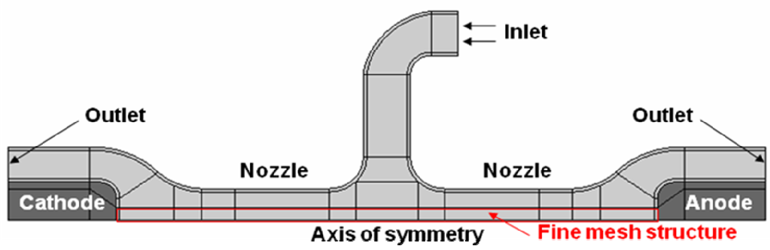

Fig. 3. Geometry for the CFD-simulations

During the switching operation of a circuit breaker different physical phenomena occur. These are for example supersonic gas flows, turbulence, dissociation of the gas, radiation and ablation of the PTFE nozzle surface. They have to be considered in the CFD-simulation by using different models. Here the influence of the model for the calculation of the turbulence effects is investigated. The dissociation of the gas is considered by using appropriate gas data from look-up-tables providing transport and thermodynamic properties of the gas for pressures up to 100 bar and temperatures up to 40000 K. The radiation is calculated according to the discrete ordinate method (DOM) [4] and the model published in [5] is used to describe the ablation of the nozzle surface.

For predicting the effect of turbulence two different methods can be employed. Both calculate the mean gas flow parameters by using the Navier-Stokes equations. The first turbulence calculation method is based on the Reynolds Averaged Navier-Stokes equations and uses time averaging to predict the

turbulence effects. The turbulent fluctuations are calculated by means of modelling the kinetic energy (k) and the kinetic energy dissipation rate (ε). Therefore different approaches exist [4].
The second turbulence calculation method is based on a large eddy simulation and uses a spatial averaging of the Navier-Stokes equations and thus extends them by sub grid scale stresses. For modelling these sub grid scale stresses different approaches exist [4].

The energy balance of an electric arc differentiates between different physical effects and can help to understand the cooling processes during the switching operation. The current driven through the plasma in the circuit breaker by the electrical network causes the ohmic heating. The heating power per volume (p_{ohm}) can be calculated by knowing the electric conductivity (σ) and the electric field (E):

$$p_{ohm} = \sigma \left| \vec{E} \right|^2$$

For the cooling of the arc by the gas flow from the heating volume different cooling mechanism are responsible. The three main effects are the cooling by radiation, by microscopic turbulence effects and the convective cooling. They can be calculated according to [6]:

$$p_{rad} = \sum_{n=1}^{N} \sum_{m=1}^{M} \nabla \cdot (I_n \; w_m \; \vec{s}_m \;)$$

$$p_{turb} = -\frac{\partial}{\partial x} (\lambda_t \frac{\partial T}{\partial x}) + \frac{1}{r} \frac{\partial}{\partial r} (r \; \lambda_t \frac{\partial T}{\partial r})$$

$$p_{conv} = \rho \; (u \frac{\partial h_0}{\partial x} + v \frac{\partial h_0}{\partial r})$$

It is known that the effectiveness of these cooling effects depends on position and time [6]. Thus it might occur that the radiative cooling dominates in one part of the arc while the turbulent cooling dominates in another part. These differences can be visualized in CFD-simulations. However it is not possible to separate between the different cooling mechanisms in experimental investigations. To be able to verify the results of the CFD-simulations by experiments anyhow, the spatial arc resistance distribution has to be determined. The arc resistance is depending on the temperature of the plasma and thus on the local power balance.

Hence the arc resistance distribution is an indication for the local cooling power. As the conductivity and the electric field are coupled by the electric current density (J) by

$$\sigma = \frac{J}{E},$$

the electric field can be used to visualize the spatial cooling power.

4 Results

Up to now experiments can only provide information on the total arcing voltage – not on their spatial distribution. Typical shapes of measured current and voltage are given in figure 4. The high current phase lasting until 11 ms is then superpositioned with the injection current. The region of interest ranges from the last increase of the arcing voltage at approximately 11.5 ms to the final extinction of the current flow. The typical arcing voltages at t = -1µs (CZ at t = 0) are in the range of U = 750...1300 V.

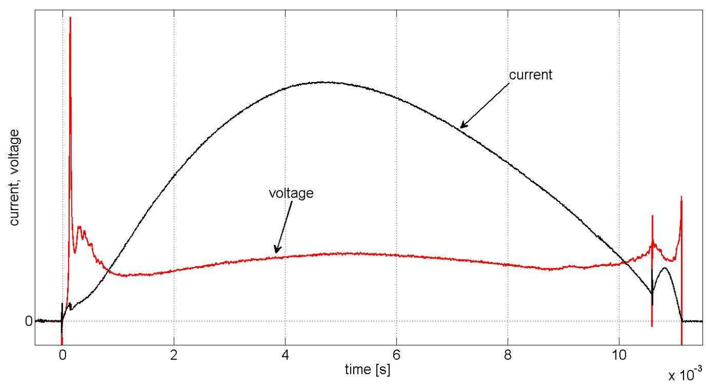

Fig. 4. Exemplary current (black) and voltage (red) shape for an experiment

To analyze the local cooling power of the quenching gas flow in the CFD-simulations the electric field along the axis of the arc – which is proportional to the local arc resistance – is plotted. The black curve in figure 5 shows the behaviour without any turbulence model. One can see that the cooling power is highest in the centre of the nozzle where a stagnation point occurs due to the radial symmetric gas flow. The red curves in the same figure show the electric field for simulations using the k-ε-turbulence model with three different parameters (P1-P3). This model predicts high turbulence in the outer parts of the nozzle. Thus an increased arc resistance and an increased electric field are observed. By using different parameters for the model the general shape remains constant while its height can be influenced. The total arcing voltage is derived by integration of the electric field along the axis of the arc and is given in the legend of figure 5.

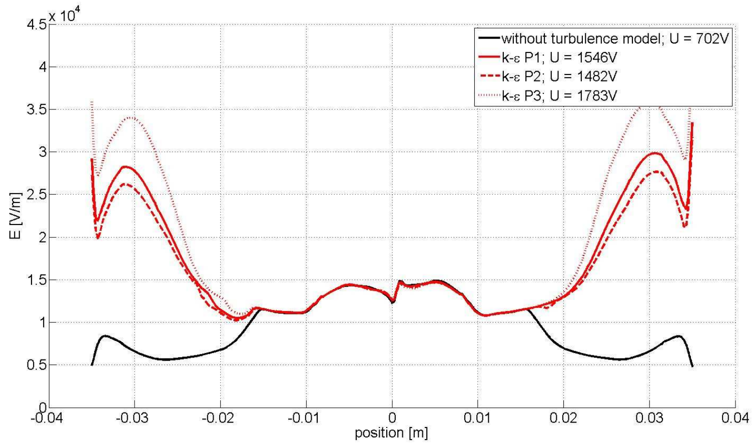

Fig. 5. Electric field along the axis of symmetry for simulations without turbulence model and simulations using the k-ε-turbulence model with different parameters at t=-1µs

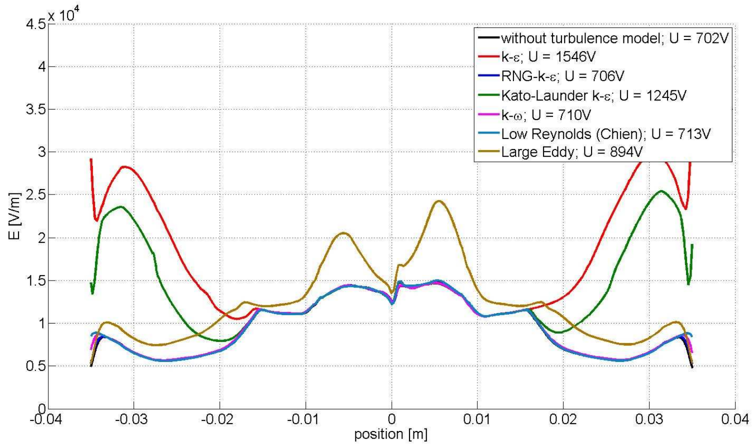

Fig. 6. Electric field along the axis of symmetry for simulations using different turbulence models at t=-1µs

In addition CFD-simulations are carried out using the following different turbulence models: RNG-k-ε, Kato-Launder k-ε, k-ω, Low Reynolds (Chien) and Large Eddy. Their results are plotted in figure 6. While the simulations using the RNG-k-ε and the k-ω turbulence models lead to results comparable to the simulation without turbulence model the result of the Kato-Launder k-ε model is comparable to the simulation using the standard k-ε model. The large eddy model predicts the highest cooling power in the region left and right of the stagnation point. Here the electric field strength is higher than in all other simulations.

5 Conclusions

In the experiments of this contribution the arcing voltage of a self blast circuit breaker prototype shortly before current zero has been investigated and compared to CFD-simulations using different turbulence models. The simulated total arcing voltage is within the variation of the experimental measured voltages at $t = -1\,\mu s$ before current zero. But depending on the applied turbulence model and its parameters the predicted arc resistance distributions – visualized by plotting the electric field – significantly differ.
Using state-of-the-art measurement technology the simulated resistance distribution cannot be verified in a real circuit breaker experimentally. Hence, future research aims for the development of a new measurement technology to determine the spatial arc resistance distribution from experiments providing a deeper insight into the physical cooling processes of blown switching arcs.

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