CFD-SIMULATION AS A TOOL FOR CIRCUIT BREAKER DIAGNOSTICS AND MAINTENANCE

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Abstract: Nowadays high voltage circuit breakers use the self-blast principle for generating the blow gas pressure to extinguish the arc. During each current interruption the nozzles and the contact system are stressed by the switching arc. The energy input into the system by the arc causes material ablation from the insulating nozzles and the contacts. As a result of this ablation the inner nozzle diameter increases with every current interruption especially in the case of short circuit interruption with current amplitudes in the range of some 10 kA. With increasing nozzle diameter the flow conditions inside the nozzle change. Therefore the maximum possible blow gas pressure available for arc quenching and therewith the switching capability of the circuit breaker decreases. This limits the lifetime of a circuit breaker. In this investigation the amount of nozzle and contact material ablated during a switching operation is determined from CFD-simulations. These simulations provide information on the spatial distribution of the amount of ablated material inside the nozzle. Furthermore a prediction of the pressure build-up in the heating volume and therewith of the remaining interruption capability is possible. Finally CFD-simulations allow a prediction of nozzle and contact wear from measured currents and therewith a lifetime prognosis.

1 INTRODUCTION

SF_6 circuit breakers are switching components used in energy transmission and distribution networks to switch nominal currents and to interrupt short circuit currents in case of network failures. State of the art research focuses on the improvement of the switching capability in combination with a reduction of manufacturing costs. Nowadays CFD-simulations (computational fluid dynamics) are widely used in circuit breaker development to emulate the physical processes inside a circuit breaker during current interruption. These processes are metrological not or only hardly accessible. Additionally those simulations help to save cost-intensive reference experiments. Subject of previous works are simulations of the high current and current zero phase during an interruption process as well as investigations of the influence of electrode vapor on the switching capability of a high voltage circuit breaker [1, 2, 3]. In general the comparison between experimental investigations and simulations serves to improve the understanding and modeling of the basic physical processes. For this purpose a system of partial differential equations, i.e. the Navier-Stokes equations for fluid mechanics, in combination with Maxwell's equations for the electromagnetic field is solved. Thereby a good agreement with experimental results is obtained. CFD-simulations deliver information on the amount of ablated nozzle material and on the electrode wear. Knowing the spatial distribution of the nozzle ablation rate from the simulations helps to identify weak spots in the nozzle system for example regions of critically reduced wall thickness. Therefore CFD-simulations as a non-invasive method to gain information on the conditions inside a circuit breaker can also be advantageous related to fault-prone manual maintenance. In contrast to previous investigations in this investigation the information on nozzle and contact wear resulting from the simulations are regarded in the context of everyday business. Here they are used for the improvement of maintenance processes. In addition to the prediction of the wear of the switching chamber a statement about the remaining pressure build-up capability in the heating volume is possible. From that a lifetime prognosis of the circuit breaker results which means that it might be possible to keep circuit breakers in operating state for a longer time than originally planned. This comes along with a cost advantage for the network operators and therefore leads to a reduction of the inhibition threshold for applying state oriented maintenance strategies. In the following section the influencing parameters on the lifetime of circuit breakers are presented. After that the basic setup of the CFD-simulations is explained, followed by a presentation of the investigation results. Finally the applicability of the results to maintenance processes is discussed.

2 LIFETIME OF CIRCUIT BREAKERS

The lifetime of a circuit breaker depends on several influencing parameters. In general the leak-tightness of the gas compartments and the mechanical stability of the operating mechanisms are of importance. The number of switching operations and the amplitudes of the interrupted currents which mainly affect the switching chamber are of special interest with regard to the remaining interruption capability and therefore regarded in the context of this paper.

$$\text{Lifetime} = f\,(\text{NSO}, I_{peak,ic}) \qquad (1)$$

where:

NSO = Number of Switching Operations
$I_{peak,ic}$ = Peak value of interrupted current

During the interruption of short circuit currents material ablates from the insulating nozzles which causes an increased inner nozzle diameter. This increase in diameter leads to changes concerning the flow conditions inside the nozzle system resulting in a reduced pressure build-up Δp inside the heating volume. The interruption capability depending on this pressure build-up Δp decreases with increasing nozzle cross sectional area A_n.

$$\text{Interruption Capability} = f\,(\Delta p) = f\,(A_n) \qquad (2)$$

where:

Δp = pressure build-up in heating volume
A_n = nozzle cross sectional area

Additionally material is ablated from the arcing contacts during the interruption process. Depending on the amount of ablated contact material this can also influence the interruption capability of the circuit breaker [2, 3]. While gas density and for example the state of the hydraulic drive are monitored during operation, no monitoring systems are applied for an observation of the nozzle and contact system. Therefore in the following simulation approaches for determining the nozzle and contact ablation are presented which could make the control of nozzle and contact wear possible in combination with an appropriate protection system.

3 CFD-SIMULATION SETUP

The CFD-simulations performed in the context of this paper use the discrete ordinate method (DOM) to model the arc radiation corresponding to the simulation setup presented in [3]. Accordingly the ablated mass of PTFE per unit time is given by [3, 4]:

$$\dot{m}_{PTFE} = q \cdot (h_v + \delta h)^{-1} \qquad (3)$$

where:

q = radiation flux density impinging on the nozzle surface
h_v = vaporization enthalpy
δh = enthalpy required to heat up the PTFE vapour from 1000 K to 3500 K

Additionally the calculation of the amount of ablated electrode material is possible using the following equation [3]:

$$\dot{m}_{WCu} = \Delta U_{electrode} \cdot |I_{arc}| \cdot h_{vap}^{-1} - 0.5 \cdot C \cdot A \cdot (h_{vap} \cdot \sqrt{t})^{-1} \qquad (4)$$

where:

$\Delta U_{electrode}$ = electrode fall voltage
I_{arc} = arc current
h_{vap} = $4.6 \cdot 10^6$ J/kg
C = $1.035 \cdot 10^7$ $Ws^{0.5}/m^2$
A = electrode cross section

Based on these equations nozzle and contact wear are implemented. The principle simulation setup for the determination of the position dependent nozzle ablation in a simplified cylindrical arrangement is presented in Figure 1. As the investigated arrangement is rotationally symmetric the model is built up in a two dimensional plane. For the simulations gas flow, heat transfer, radiation electrical potential and grid deformation for modelling the nozzle widening are taken into account.

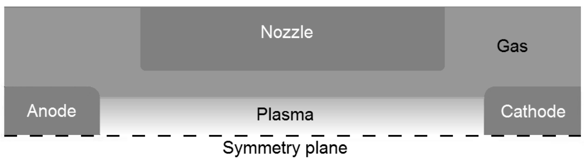

Figure 1: CFD-simulation geometry

Simulations are performed concerning different nozzle diameters and length. An additional simulation model with a diffuser geometry, this means with a cone shaped increase of the nozzle diameter near the electrodes is investigated. Furthermore the influence of an increased nozzle area cross section on the pressure build-up inside the heating volume of a circuit breaker model is analyzed by means of CFD-simulations. The results of these investigations are presented in the next section.

4 SIMULATION RESULTS

The specific mass loss and the nozzle widening of a cylindrical shaped nozzle result from the evaluation of the CFD-simulations described above as depicted in Figures 2 and 3. From the comparison of Figure 2 and Figure 3 it can be seen that nozzle widening and specific mass ablation are proportional to each other. Therefore only the specific mass loss of a nozzle with diffuser geometry is depicted in Figure 4. For both cases the highest specific ablation is observed in the center region of the nozzle. The specific ablation of the diffuser nozzle decreases starting with the cone shaped widening of the nozzle. One possible explication for this effect is a reduction of the current density coming along with the increased nozzle area cross section. In addition to the simulative results presented above, experiments and CFD-simulations were performed using a sliced nozzle which is constructed of eight segments which makes a comparison of the simulated and experimentally determined amount of ablated nozzle material possible. The ablation profile is investigated regarding the inner six segments. As those experiments serve to validate the corresponding simulations a comparison is drawn in the following section.

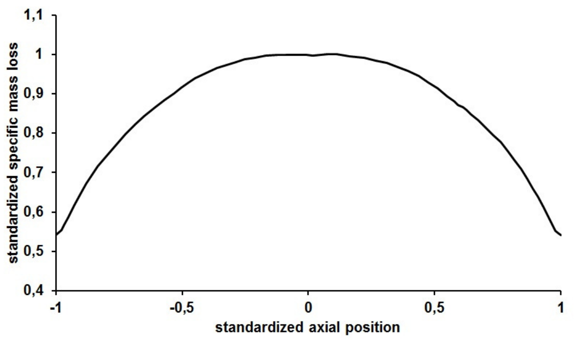

Figure 2: Simulated specific mass loss for cylindrical nozzle arrangement

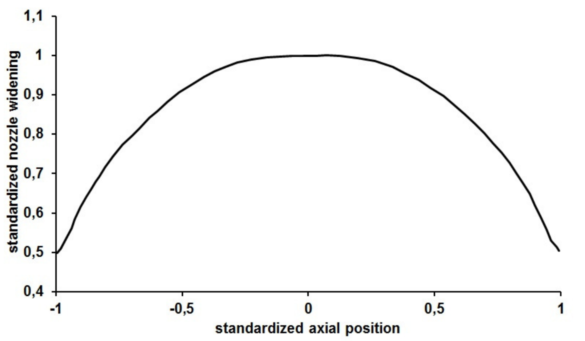

Figure 3: Simulated nozzle widening for cylindrical nozzle arrangement

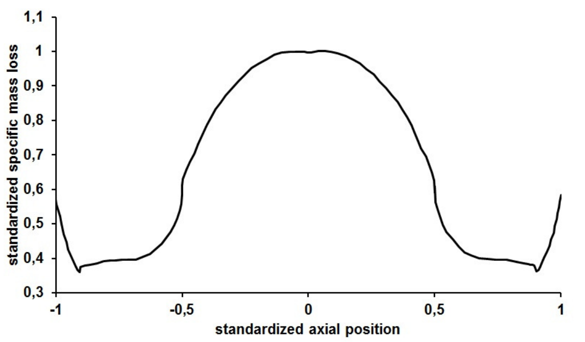

Figure 4: Simulated specific mass loss for diffuser nozzle

Furthermore a reduction of the thermal interruption capability of circuit breakers caused by the influence of tungsten/copper contamination of the quenching gas is observed in previous investigations [3]. This is due to an increase in the conductivity of the arc plasma coming along with an increase of the tungsten/copper concentration.

5 DISCUSSION

A comparison between the results of the CFD-simulations and the experimental investigations for the sliced nozzle test series is depicted in Figure 5. Considering the scattering of the experiments, the simulations are in good agreement with the measured specific ablation, except of the value for slice number 5.

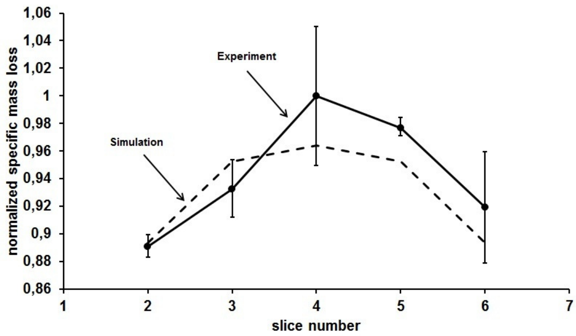

Figure 5: Comparison of simulation results and experimental investigations

From that it can be concluded that the position dependent prediction of the amount of ablated nozzle material is possible using CFD-simulations. Two applications of the simulation results are distinguished in the following. On the one hand regions with high ablation rates are of special interest for the evaluation of the wear of the circuit breaker. For example a nozzle which has weak points due to high ablation could be mechanically destroyed during switching operation. This could lead to an internal fault arc and to the destruction of the circuit breaker. Leakages inside the nozzle system could also cause an uncontrolled gas flow inside the breaker. On the other hand a prognosis on the future behavior of a circuit breaker is possible based on the results of the CFD-simulations. A component specific model of the wear can be derived knowing the previous current interruptions of a circuit breaker characterized by the current characteristics and the instant of contact separation. The subsequent simulative prediction of the pressure build-up in the heating volume of a circuit breaker leads to a statement on the maximum achievable blow gas pressure during the next current interruption. In Figure 6 the dependency between the nozzle area cross section and the decrease of the maximum pressure build-up in the heating volume of a circuit breaker model is depicted. These results are obtained from CFD-simulations of a breaker model with heating volume applying a constant current amplitude. For the pressure decrease, the following scaling law is derived:

$$\Delta p \sim A_n^{-b} \quad (5)$$

where:

Δp = pressure build-up in heating volume
A_n = nozzle cross sectional area
b = scaling factor

As it can be seen from the figure, an increase of the nozzle cross sectional area of 44% causes a reduction of the pressure build-up by 32%. Additionally the thermal interruption capability di/dt_{limit} as depicted in Figure 7 can be calculated from the blow gas pressure p at current zero [1].

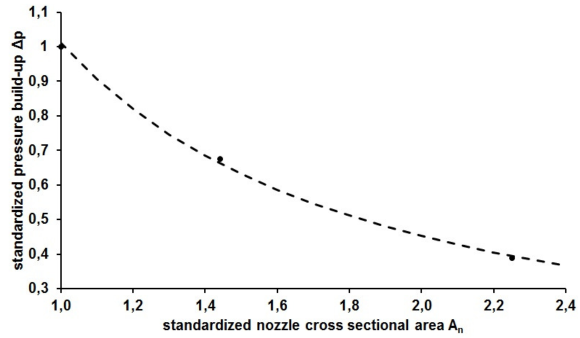

Figure 6: Dependency of the pressure build-up in the heating volume on the nozzle cross sectional area

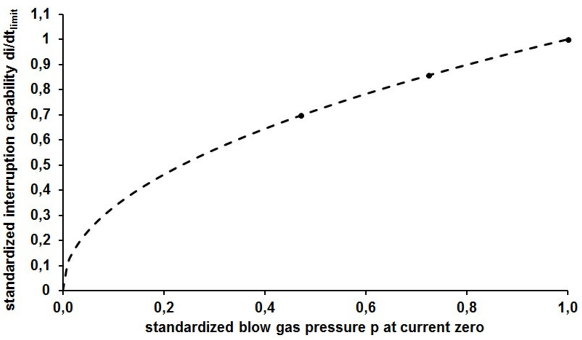

Figure 7: Dependency of the interruption capability on the blow gas pressure at current zero

Based on the simulation results presented above, a decision can be taken, if a fault-prone manual maintenance is necessary or if the circuit breaker can remain in operation without maintenance. The decision process which considers the found scaling law for the pressure build-up in the heating volume is depicted in Figure 8. Additionally a combination of the CFD-based switching chamber maintenance with other diagnostic methods like acoustic diagnostics is imaginable in order to detect mechanical failures for example of the operating mechanisms.

6 CONCLUSIONS

It can be concluded, that CFD-simulations could serve as a means for non-invasive circuit breaker diagnostics taking into account the improvement of simulation technologies during the last decade. On the one hand they allow a circuit breaker specific maintenance coming along with a reduction of the error potential, e.g. during reassembly. On the other hand a simulation-based lifetime prognosis can lead to extended maintenance intervals which are aimed for by many network operators.

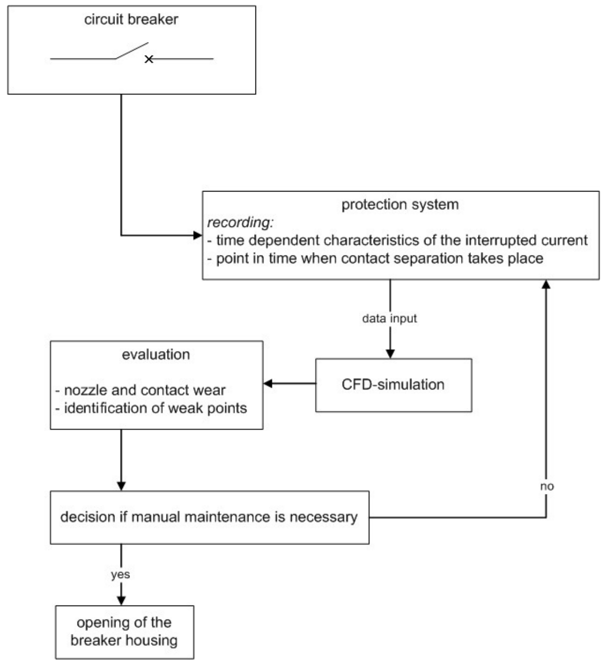

Figure 8: CFD-based maintenance strategy

7 ACKNOWLEDGEMENTS

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