INTERRUPTION CAPABILITY OF AN AUTO-EXPANSION CIRCUIT BREAKER WITH DIFFERENT ARC DURATIONS

Y PEI [1] AND J D YAN[2]

Department of Electrical Engineering and Electronics, The University of Liverpool, UK
[1]yuqing@liv.ac.uk, [2]yaneee@liv.ac.uk

ABSTRACT

A computational study of the thermal interruption process of an auto-expansion circuit breaker with different arc durations (12.25 ms, 15.25 ms and 18.62 ms) has been carried out. While the pressure rise in the expansion volume depends mainly on the final half-cycle of the current, the thermal interruption capability, in terms of its critical rate of rise of recovery voltage (RRRV), is severely affected by the contact separation at current zero, thus the effective flow cross sectional area of the main nozzle. The short arc duration case has the lowest RRRV.

1. INTRODUCTION

Different arc durations implies different axial positions of the live contact of a circuit breaker at current zero, determining two important factors for the thermal interruption process. One is that the relevant position of the live contact tip in the main PTFE nozzle will determine the nozzle surface area that is exposed to arc radiation around the current peak(s) and subsequently the amount of PTFE vapour produced in the high current phase for pressurisation of the expansion volume. The other is that the position of the live contact tip may affect the effective gas flow area through the main nozzle and thus the development of flow field around the arc column at current zero, directly affecting the interruption capability of the breaker. A well designed circuit breaker should ensure that the arc is always successfully quenched with the live contact at all possible positions between the shortest and longest arc durations.

This paper presents a comparative study of the arcing process in a commercial 145 kV auto-expansion circuit breaker with different arc durations by using a newly developed automated simulation platform, the Integrated Simulation and Evaluation Environment (ISEE) [1]. A sinusoidal short circuit current waveform and an identical contact travel curve are used for all cases. Important details of the arc model are given in Section 2 and results presented and analysed in Section 3. Conclusions are drawn in Section 4.

2. THE ARC MODEL

The arc together with its surrounding gas flow is assumed to be axis-symmetric and in local thermodynamic equilibrium (LTE) state. The problem can be mathematically described in a 2D cylindrical coordinate system by time-averaged Navier-Stokes equations taking account of Ohmic heating, electromagnetic effect (Lorenz force), nozzle ablation, radiation loss and turbulence enhanced mass, momentum and energy transport. The general conservation equations and boundary conditions have been described and discussed in [2, 3] and will not be repeated. The electric power input is calculated by solving the current continuity equation, and radiation transport with the approximate model of Zhang et al [4] but modified to cope with non-monotonic radial temperature profiles in real circuit breakers. The effect of nozzle ablation is considered by solving a mass concentration equation for PTFE vapour. The equation of state and the thermodynamic and transport properties of SF_6-PTFE gas mixtures are given in [3]. The use of transparent contacts and arc roots was explained in [2].

Prantl mixing length model is used. The turbulent viscosity is given by

$$\mu_t = \rho {l_m}^2 \sqrt{\left(\frac{\partial \omega}{\partial r}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \qquad (1)$$

The length scale for tubulent momentum transport is expressed by the product of the arc thermal radius and a tubulence parameter.

$$l_m = c \cdot \mathrm{R}_{arc} \qquad (2)$$

where R_{arc} is defined as the radius of 5,000 K isotherm in the high current phase and 3,000 K isotherm in the current zero phase (from 15 kA in the last half loop to the final current zero point). The coefficient c is set to be 0.05 for the high current phase, and linearly changed with the magnitude of current between 0.05 and 0.3 in the current zero phase. For post arc calculations c is fixed at 0.3. The choice of 0.3 is reasonable, because it is calibrated by satisfying the results from two tests for the circuit breaker under consideration, one of them successfully interrupted, while the otherfailed. The simulation conditions match the real test conditions including the current, travel and recovery voltage.

3. RESULTS AND DISCUSSIONS

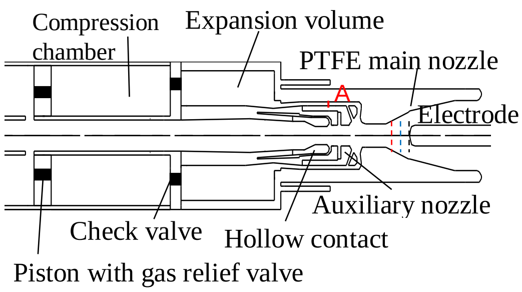

Fig.1. Simplified geometry of the 145 kV auto-expansion circuit breaker under investigation. The final position of the live contact is shown by the three dash lines near the live contact for different arc durations.

The circuit breaker (Fig.1) is rated at 145 kV and 40 kA with a power frequency of 60Hz. The filling pressure of SF_6 is 6 bar at an initial temperature of 300 K. The arc is initiated when the contacts separate at a distance of 8mm at 12.72 ms. The initial current is set to 3 kA and ramps up in 0.3 ms to the instantaneous value to start the arc.

3.1 ARCS AT HIGH CURRENT

The long arc duration cases has a higher pressure rise in the expansion volume at the initial stage up to 19 ms, because the current is approaching its peak after arc initialization which result in a earliest enthalpy flux increase (Fig.3). However, the enthalpy flux increase keeps a short duration, which stops at 20.7 ms and the current decays to 16 kA. The evidence is that the enthalpy flow rate towards the expansion volume decreases to zero. Before 20.7 ms, the live contact just enters the flat section of the main nozzle, thus the radiation from the arc core to the ablation surface is limited, which explains the lower enthalpy flow rate (-5 MJ/s) in comparison with the second half cycle of the long arc duration case (-15MJ/s). From 20.7 ms to 22.8 ms, the current decreases from 30 kA to 3 kA and there is virtually little ablation generated though more PTFE surface is exposed to the arc column. As a result, the temporary reverse occurs during this time period. After that, the current goes through its peak of 56 kA, generating a much higher enthalpy flow rate (-15 MJ/s) into the expansion volume. The pressure in the expansion volume also increases from 15 bar to over 40 bar in 5 ms (from 24 ms to 29 ms, Fig.2) before it drops to 38 bar at current zero.

For medium arc duration, the enthalpy flow rate also increases after 16.5ms, but lasts for a very short time (less than 0.5 ms), and then drops because the current is rapidly approaching zero. After the current pass its first zero point, the enthalpy rate begins to rise again. In addition, from 19.5 to 23 ms (current peak), the live contact travels through the full length of the flat throat of the main nozzle. Due to the high current during this period, PTFE is effectively ablated which significantly increases the enthalpy flow rate to -18 MJ/s. Therefore, the pressure rapidly increases to the peak of 41bar at 3 ms after current peak because of the pressure propagation and inertia effect of arcing gas.

As expected, the enthalpy flow rate in the short arc duration case experiences a delayed rise between 17 ms and 18 ms in comparison with the long arc duration case because of the lower currents. The final position of the live contact tip is just out of the main nozzle throat exit (Fig.1). Since the main nozzle is blocked by the live contact and ablation in the auxiliary nozzle creates a stagnant region in the high current phase, vapour compression in the main nozzle rapidly established a high pressure zone and develops a high enthalpy flux (-17 MJ/s) towards the expansion volume (Fig.3).

For the geometry under investigation which is representative of modern auto-expansion circuit breakers, the final half-cycle of the current is mainly responsible for the pressurization in the expansion volume. In particular in the long arc duration case, the final half-cycle produces 77% of the total pressure rise in the expansion volume. While the fluctuation on the pressure curve is due to change in arc column size generating pressure waves propagating towards the expansion volume, the overall delay is caused by the development of the high pressure zone in the contact space and the motion of hot vapour across the length of the heating channel into the expansion volume.

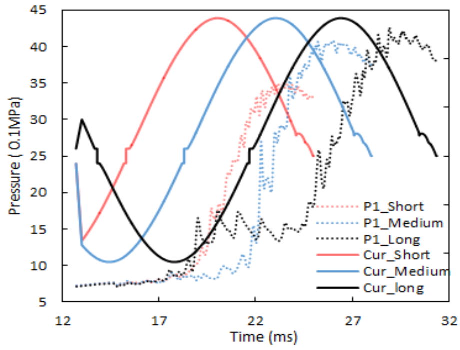

Fig.2. Predicted pressure rise in the expansion volume

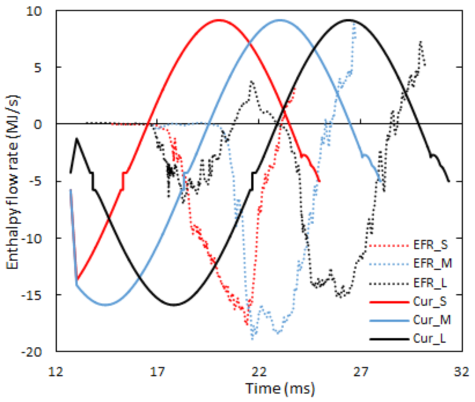

Fig.3. Enthalpy flow rate at location A in Fig.1 in the flow guild channel at high current phase

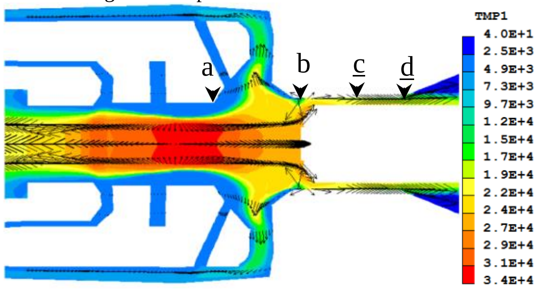

Fig.4. Velocity field at current peak for short arc duration, the time instant for live contact position (a) 16.5ms (b)19.5ms (as figure shows) (c)21.3ms (d) 23.5ms.

3.2 ARC DYNAMICS BEFORE CURRENT ZERO

From Fig.5, the region around an axial position of 0.56 m (left end of flat nozzle throat) and the region near the tip of the auxiliary nozzle (0.54 m) take up a considerable part of the recovery voltage. Energy balance is performed at the critical region to identify the dominant energy transport mechanisms at several key instants before current zero in Fig.6. For the short arc length at its peak current, convection dominates the transport process. This is because in front of the live contact, energy is convected into the domain in the axial direction and convected out in the radial direction (Fig.4). For both medium and long arc duration cases, the live contact at peak currents has cleared the nozzle throat and strong axial flow has been established and Ohmic heating and radiation dominate the energy transport process (Fig.6b and 6c). Approaching current zero, turbulence plays an increasingly important role. At 12kA, the arc changes from radiation dominated to turbulent cooling dominated. At 500 A (30 us before current zero) turbulent cooling has become the dominant mechanism for energy removal (Fig.6d).

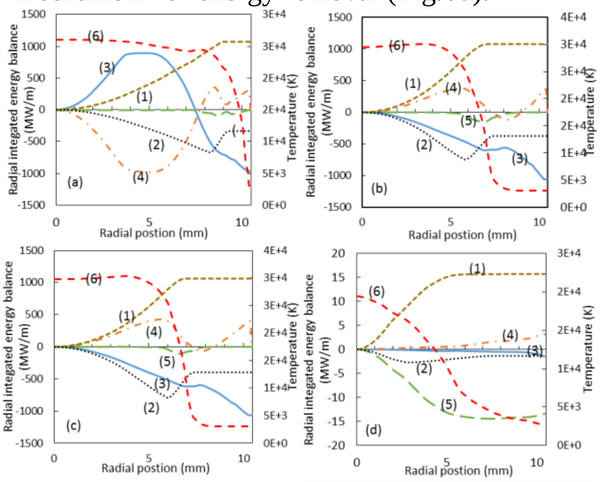

Fig.5. Radial integrated energy balance of critical cross section with axial position 0.56 m at final current peak for (a) short (b) medium, and (c) long arc duration. (d) Radial integrated energy balance at 500A for short arc duration. The curves present (1) Ohmic heating: $\int \sigma E^2 2\pi r dr$ (2) radiation loss: $-\int q 2\pi r dr$ (3) axial convection: $-\int \frac{\partial}{\partial z}(\rho \omega h) 2\pi r dr$ (4) radial convection: $-\int \frac{1}{r}\frac{\partial}{\partial r}(r\rho v h) 2\pi r dr$ (5) radial thermal and turbulence conduction: $-\int \frac{1}{r}\frac{\partial}{\partial r}(-r\frac{k}{C_p}\frac{\partial h}{\partial r}) 2\pi r dr$ (6) radial temperature profile

3.3 THEMRAL INTERRUPTION PERFORMANCE

The hot spot (Fig. 7) before the live contact for short arc duration case is caused by the arc flow hitting the contact and causing a stagnation region with reverse flow. Arc temperature on the axis has two valleys, one near the tip of the auxiliary nozzle and the other near the entrance of flat throat of the main nozzle (Fig.7). Results in Fig.5 clearly shows that the gas in the auxiliary nozzle region takes a significant part of voltage. Arc in the main nozzle is more rapidly cooled down to take an increased share of the recovery voltage after current zero. In the short arc duration case the auxiliary nozzle region plays a more important role in comparison with the other two cases.

For a 40 kA and 60 Hz system, the value of dV/dt for short line fault (SLF) is around 9 kV/us, which is much higher than terminal fault [5]. To investigate the differences in interruption capability, the critical rate of rise of recovery voltage (RRRV) is calculated for different arc durations after current zero. The computational uncertainty is less than 0.5 kV/us.

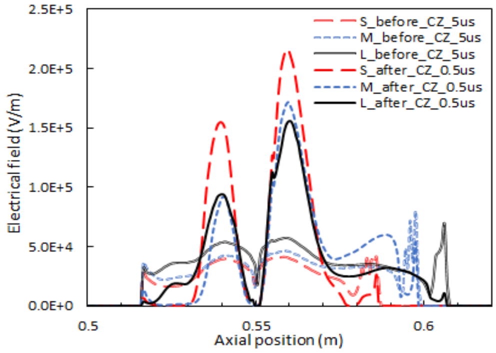

Fig.6. Axis Electrical field 5us before current zero and 0.5us after current zero under dV/dt of 8kV/us

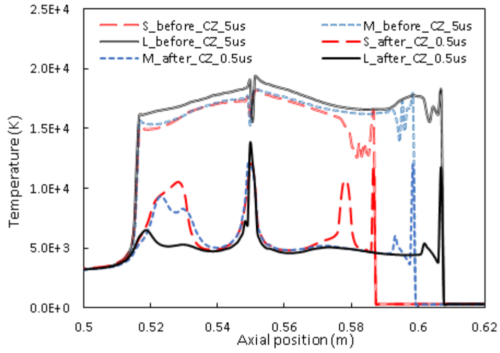

Fig.7. Axis temperature 5us before current zero with the current of 98 A and 0.5us after current zero under dV/dt of 8kV/us

At 5us before current zero, the arc has a higher axis temperature in the long arc duration case (Fig.7). However, the temperature drops more rapidly after current zero leading to lowest axis temperature at 0.5 us after current zero. Its critical RRRV is expected to be the highest. For the circuit breaker under investigation, all test duties have passed. The predicted critical RRRV for short arc duration is 10.0 kV/us, higher than the applied RRRV of 9.0 kV/us in type test. The critical RRRV for the medium and long arc duration cases are both higher than 12 kV/us. The lower RRRV of the short arc duration case is in fact caused by the slower gas flow around the arc column because the main nozzle in this case is still partially locked by the live contact.

3. CONCLUSIONS

The behavior of a 145 kV, 60 Hz auto-expansion circuit breaker with different arc durations and symmetrical short circuit current waveforms is computationally studied. The results clearly shows:

a) The final half-cycle of the current is mainly responsible for the pressure rise in the expansion volume.

b) When the current falls from its final peak toward the zero point the arc evolves from radiation and convection dominated cooling into a turbulent cooling dominated regime. The transition takes place at 12kA.

c) After current zero the system recovery voltage is shared by two sections of the contact gap divided by the flow stagnation point. The arc in the auxiliary nozzle region takes about 46% of the recovery voltage in the short arc duration case, which is the most difficult interruption duty of the three cases studied. The auxiliary nozzle as a key component should be designed carefully.

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