

Analysis of SLF Interruption Performance of Self-Blast Circuit Breaker by Means of CFD Calculation

Hong-Kyu Kim[†], Jin-Kyo Chong* and Se-Hee Lee**

Abstract – This paper presents the performance analysis results of a short line fault interruption of a gas circuit breaker, particularly a self-blast type breaker. Hot gas flow analysis was carried out using a CFD calculation combined with the arc model and nozzle ablation model. To evaluate the interruption performance, the index function was defined using the pressure in the heating chamber and the density above the arc region. The simulation and test results showed that the gas flow field and suitable choice of an interruption performance index can be used to predict the interruption characteristics and provide guidelines for designing self-blast breakers with a higher interruption capability.

Keywords: Gas circuit breaker, Short line fault, Performance index, Arc model, CFD calculation

1. Introduction

Owing to the low mechanical driving energy, self-blast type gas circuit breakers (GCBs) have been studied extensively and developed over the last few decades. The required pressure rise for a large current interruption is achieved by the arc energy itself and nozzle ablation. For a successful interruption, high pressure build-up is needed in the heating chamber (HC). On the other hand, the gas temperature in the HC is much higher than that of a conventional puffer type GCB because a pressure build-up is achieved by the thermal energy and ablated mass flow from the arc region. The high temperature gas can reduce the dielectric withstanding capability considerably. For the successful interruption of a large fault current, two flow conditions must be satisfied: sufficient pressure build-up in the HC to acquire strong arc cooling power, and a high density (i.e. low temperature) gas flow from the HC to the arc region to ensure dielectric recovery after current zero (CZ). Considering these points, the interruption performance index was defined with the pressure in the HC and the density above the arc region. The performance index was compared with the interruption test results, and the feasibility of it was demonstrated. The results showed that the defined index function represents the measured arc conductance characteristics well according to successful or failed interruption tests.

2. Simulation of Gas Flow Field

The arc plasma in a GCB can be treated as being in local thermodynamic equilibrium. Therefore, the classical conservation equations for mass, momentum and energy can be used to analyze the hot gas flow considering the interactions with the arc plasma. Many physical phenomena need to be considered when simulating the interaction between the gas flow and arc plasma, such as moving geometry, compressible flow, joule heating, radiative heat transfer, wall ablation etc.. In this study, the two zone arc model [1] was used to calculate the arc voltage, arc temperature, arc radius, and the ablation rate of nozzle material. The arc voltage was obtained after calculating the arc temperature and arc radius. The ablation rate of the nozzle material can be calculated using (1):

$$dm/dt = \delta U_a I_a \quad (1)$$

where, δ is the specific ablation factor [1], and U_a and I_a are the arc voltage and arc current, respectively.

The pressure rise in a self-blast GCB is strongly affected by nozzle ablation. δ was adjusted by comparing the calculated and measured pressure in the HC. The ablated nozzle material by (1) was treated as a mass source term in the mass conservation equation. The arc was treated as an energy source term and the flow equations were solved by the Finite Volume Fluid in Cell method as a computational fluid dynamics (CFD) scheme [2].

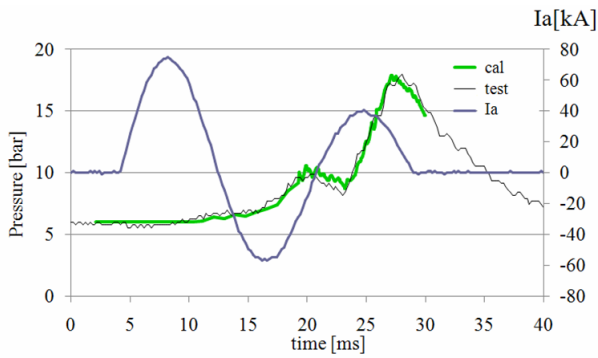
The calculated and measured pressure rise in the HC was compared to validate the CFD computation, as shown in Fig. 1 (a). As shown in the figure, the calculated pressure profile followed the measured one quite well and there was a time delay between the current peak and pressure peak instant. Fig. 1 (b) shows the density distribution at the high current phase. Although the pressure in the HC was almost

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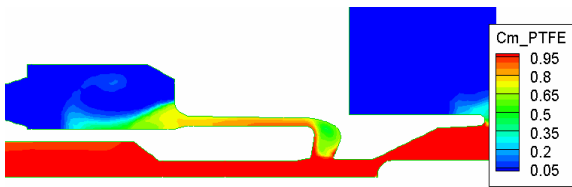
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(a) Comparison of pressure rise in HC



(b) Density distribution



(c) Nozzle vapor concentration distribution

Fig. 1. Results of gas flow computation.

even, the density pattern was irregular. Owing to the compression of the gas caused by back flow from the arc region to the HC, the density of the left side in the HC was high. Fig. 1 (c) shows the mass concentration of the ablated nozzle material. During the high current phase, the arc region was filled with the ablated nozzle material. The ablated nozzle vapors flowed into the HC, and carried high thermal energy. This thermal energy is the main cause of the pressure increase in a self-blast GCB.

3. SLF Interruption Performance Index

A self-blast GCB makes use of the arc energy itself and nozzle ablation to obtain the required pressure build-up for arc quenching and successful interruption. That is, the high thermal energy of the arc plasma and ablated nozzle vapors are transferred to the HC, which causes an increase in pressure in the HC. To examine the required pressure rise for the 145kV model GCB, the pressure in the HC was measured and the success or failure of an interruption for the various fault current conditions was observed. Fig. 2 shows the measured pressure profile in the HC for the 4 test cases. Table 1 shows the test conditions for each case. In all cases, the dv/dt and di/dt conditions were the same according to the IEC standard for the 90% SLF interruption.

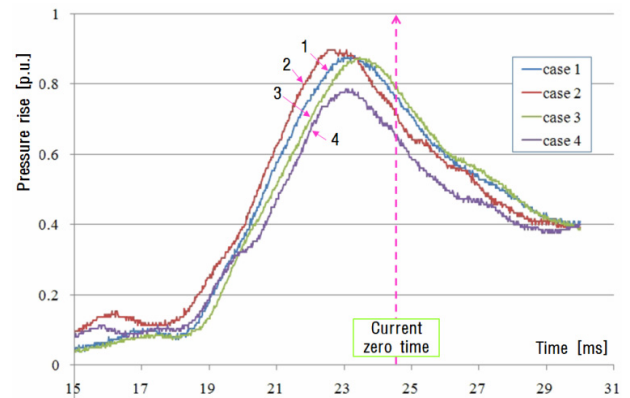


Fig. 2. Measured pressure profile for each test case.

Table 1. Test condition and interruption test result.

Model	I_{peak} [kA]	Arcing time [ms]	P_{HC} at CZ [p.u.]	Interruption
Case 1	31	11.8	0.82	O
Case 2	31	12.4	0.77	×
Case 3	34	11.6	0.85	×
Case 4	31	11.8	0.71	×

I_{peak} : peak current [kA]

P_{HC} at CZ: pressure rise in HC at current zero

Interruption: O - successful interruption

×

For case 1, the pressure at CZ was 0.82 [pu] and the interruption test result was a success. For case 2, although the maximum pressure rise was higher than that of case 1, the pressure at CZ was lower than that of case 2. The interruption test result was a failure, possibly due to the low pressure in the HC at CZ. The pressure of case 3 at CZ was slightly higher than that of case 1. On the other hand, the test result was a failure. The current peak of case 3 was 10% higher than that of case 1. Therefore, the temperature in the HC is higher than that of case 1, which reduces the interruption ability.

After several interruption tests, the diameter of the nozzle surface became wider than that of an initial nozzle due to nozzle ablation. This can explain why the pressure increase in case 4 was lower than that of case 1. For case 4, a failed interruption was observed due to the low pressure at CZ.

The interruption tests and pressure measurement data suggest that for the successful interruption, the pressure increase in the HC at CZ should be high enough and the gas temperature in the upstream region should be low enough to secure the thermal and dielectric interruption capability [3].

For a conventional puffer type breaker, the SLF interruption performance can be described by the following Eq. [4]:

$$\frac{dv}{dt} = kP^\alpha \left(\frac{di}{dt}\right)^{-\beta} \quad (2)$$

where dv/dt is the critical rate of the rise of the recovery

voltage (RRRV), di/dt is the current slope at the CZ, P is the pressure at the compression chamber at the CZ, k , α , and β are the coefficients that depend mainly on the interrupter geometry and gas type, which should be determined by testing. For a conventional puffer type GCB, $\alpha = 1.4 \sim 1.6$ and $\beta = 2.2 \sim 2.4$ are used.

This equation can also be applied to a self-blast type GCB. On the other hand, for self-blast GCB analysis and design, density (or temperature) in the upstream region should also be considered.

Fig. 3 shows the pressure and density monitoring positions to examine the relationship between the gas flow field and interruption performance. Fig. 4 shows the calculated density at point “Up” by the CFD calculation. The density ρ_{Up} at point “Up” for models 3 and 4 was lower than that of model 1 and the low gas density reduced the interruption ability. Consequently, the SLF interruption performance index can be defined as the pressure P_{HC} in the HC and density ρ_{Up} in the upstream region of the arc zone as:

$$\text{Interruption performance index} = k P_{HC}^{\gamma} \rho_{Up}, \quad (3)$$

where k is a constant to normalize the index.

In (2), only the pressure rise in the upstream chamber is considered. On the other hand, for a self-blast GCB, the density is also an important parameter to be considered, which was considered in the proposed index (3).

The exponent γ in (3) determines which parameter has a more important effect on the performance index between the pressure and density. To obtain the optimal γ , the experimental data and CFD analysis results are required. γ can be used in similar GCB models.

The arc conductance $G(-200\text{ns})$, which is taken at 200ns immediately before current zero, was measured to verify the proposed SLF interruption performance index. This conductance is a direct indicator of the success or failure of

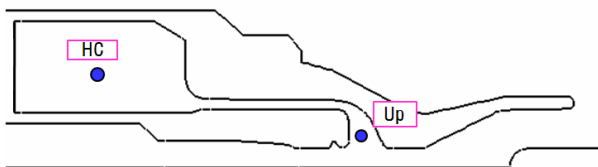


Fig. 3 Pressure and density monitoring position.

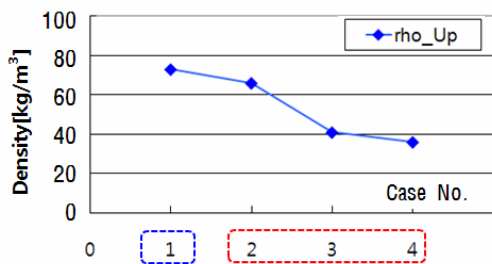


Fig. 4 Comparison of the calculated density for the 4 cases.

the SLF interruption [5-7]. The $G(-200\text{ns})$ is low when the interruption is successful and high in the case of a failed interruption. Fig. 5 compares the calculated performance index and measured $G(-200\text{ns})$. The G index is the normalized value $G_0/G(-200\text{ns})$ using the G_0 , which is the $G(-200\text{ns})$ value for the successful interruption case 1. Therefore, the higher G index means a higher interruption capability. The SLF interruption performance index is normalized by the value of case 1. As shown in the figure, the performance index represented the measured SFL interruption characteristics (i.e. G index) quite well.

The proposed performance index was applied to the different interrupter geometries. The dimensions and shape were different for both GCB models, as shown in Fig. 6. Fig. 6 shows the density distribution at current zero calculated by CFD code. The pressure rise at current zero for both models was similar, but the density immediately above the arc region showed a considerable difference. Failed interruption for model 1 and successful interruption

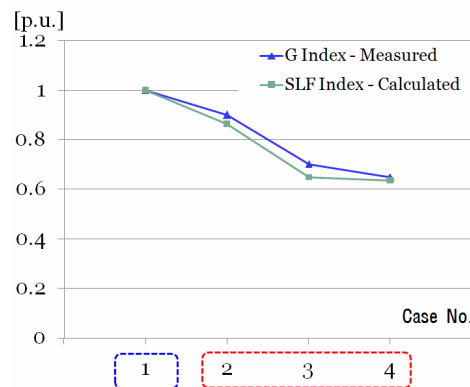
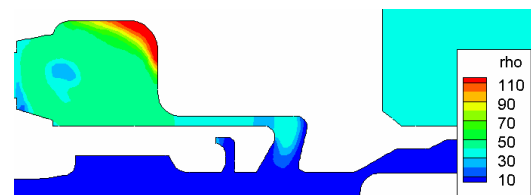
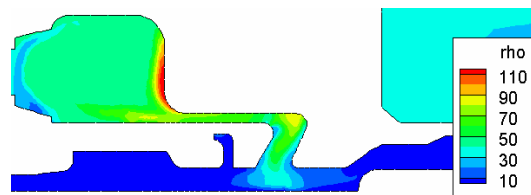


Fig. 5. Comparison of the measured arc conductance and interruption index ($G \text{ Index} = G_0/G(-200\text{ns})$, $G_0 : G(-200\text{ns})$ of case 1).



(a) Model 1 (HC volume 900cc, nozzle throat length 22mm)



(b) Model 2 (HC volume 1,000cc, nozzle throat length 20mm)

Fig. 6. Comparison of the density distribution between two different interrupters

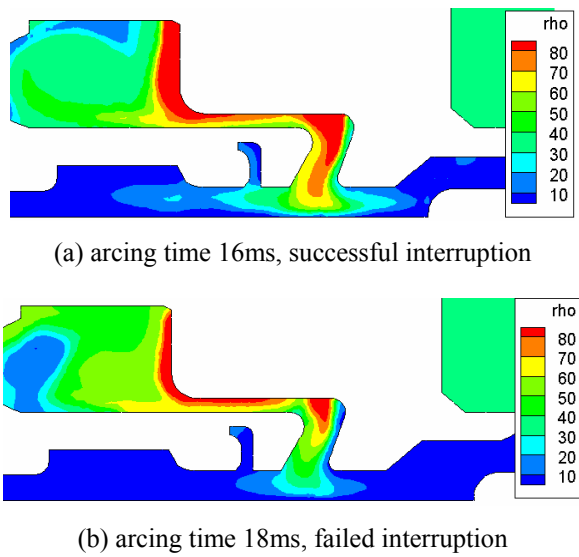


Fig. 7. Comparison of the density distribution between two different arcing times.

for model 2 were observed in the test. This suggests that although the pressure rise was similar, the interruption ability can be distinguished by the proposed performance index.

To examine the effect of the arcing time, the SLF index was applied to the same GCB geometry for different arcing times. The rating of GCB was 145kV and 40kA. Fig.7 shows the density distribution for the arcing time, 16ms and 18ms, respectively. The pressure rise at current zero for case (a) was lower than that of case (b). On the other hand, density of case (a) in the arc region is higher than that of case (b). If Eq. (2) is used, case (b) has higher interruption performance. In contrast, in the test, case (a) was successful and case (b) failed.

The same γ value was used as the previous example to predict the interruption performance. The calculated index for case (a) was higher than that of case (b).

G(-200ns) is a direct interruption performance indicator. However, the calculation is time consuming with huge computational cost. For optimal design of the interrupter chamber, many iterative analyses are needed for the changed interrupter geometries. In that case, if the performance index defined in this paper is used as an objective function, the optimal solution can be found within the tolerable computation time. The performance index calculated by the CFD calculation is a good design tool for simulating and verifying the SLF interruption performance.

4. Conclusion

High pressure build-up in an interrupter chamber is a necessary condition, but is not a sufficient condition for the successful interruption. Successful interruption requires

high density gas flow from the upstream chamber to the arc zone. Considering these points, this paper proposed the SLF interruption performance index using the pressure in the HC and the density above the arc zone, and compared it with the measured interruption characteristics (G index). The index derived in this paper is a useful objective function in designing and optimizing the interrupters with a higher interruption capability. Future research will examine the optimal coefficient γ of various GCB models, as well as the different rating voltages and interruption currents.

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