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Investigation of SLF Interruption Capability of Gas Circuit Breaker with CFD and a Mathematical Arc Model

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Abstract – This paper discusses the analysis of arc conductance in a gas circuit breaker (GCB) during current interruption process and the investigation method of the interruption capability. There are some limitations in the application of the computational fluid dynamics (CFD) for the implementation of an arc model around the current zero, despite the fact that it gives good results for the high-current phase arc. In this study, we improved the accuracy in the analysis of the interruption performance by attempting the method using CFD and a mathematical arc model. The arc conductance at 200 ns before current zero (G-200ns) is selected as the indicator to predict the current interruption of the Short Line Fault (SLF). Finally, the proposed method is verified by applying to the actual circuit breakers which have different interruption performances.

Keywords: Gas circuit breaker, CFD, Mayr arc model, SLF, Arc conductance, G_{-200ns}

1. Introduction

The phenomena observed in the interruption of current in the gas circuit breaker contain arc radiation, nozzle ablation, movement of contact point accompanied with electric field and magnetic field, transfer of momentum and energy by turbulence and thus are very complicated. During the last decades, computational fluid dynamics tools have been developed to obtain a better understanding of the physical processes, and they are considered as powerful methods because of their rapid and cost-effective properties for the design of GCBs [1, 2]. Recently, the advanced measuring technology is accelerating the accuracy improvements of the CFD analysis by providing the verification data [3]. In contrast, there are some difficulties to be overcome especially near current zero. In the current zero phase, the hot gas channel becomes extremely thin as shown in Fig. 1, so the energy dissipation by turbulence is particularly critical and deviations from equilibrium are shown [4-7]. Additionally, the axial symmetry shape of arc starts to be shaken by the ambient flow, as the current is attenuated. Therefore, a number of cells must be allocated around the arc axis in the low-current phase to solve this problem and accurate turbulence model suitable for the diminished arc must be applied [8]. In addition, the 3-dimensional arc simulation is also required to simulate the fluctuating arc.

On the other hand, the mathematical arc models also have been developed for describing the dynamic arc behavior for a long time, and there have been numerous applications and improvements made to arc models. However, they have some difficulties in handling the effects of movement of contact and heat flow. In addition, several parameters must be determined to implement the mathematical arc model, requiring precisely measured waveforms of arc voltage and current [9]. The method of extracting the arc parameters from the experimental data is also not general.

This study suggests a practical and efficient method to overcome the weakness of CFD analysis around the current zero and determine parameters without requiring test data in setting of the mathematical arc model parameters. During the high-current phase CFD simulation is performed to calculate temperature and pressure of hot gas within the GCB. Immediately after that, the parameters required for the mathematical arc model are obtained on the base of the CFD simulation results and the arc conductance is calculated up to the current zero.

We use the arc conductance at 200 ns before current zero to evaluate the interruption performance of the SLF interruption. The suggested data by KEMA shows that the interruption performance of SLF is directly connected to the arc conductance at 200 ns before current zero,

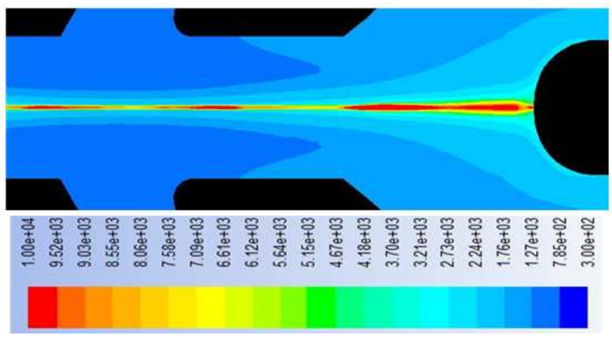

Fig. 1. Arc temperature at current zero

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regardless of the types and ratings of GCBs from the analysis of experimental data [10].

2. Arc Model

2.1 CFD analysis

If interrupting current conducts through the gas between contacts, the arc of high temperature and high pressure generates through Joule heating, and most of thermal energies are transferred by radiation. Most of thermal energies out of the center of the arc by radiation are absorbed again in the boundary layer of the arc and some portion of them arrive to the surface of the nozzle wall consisted of the polytetrafluoroethylene (PTFE) and filling materials. The vaporized nozzle substances from the wall are mixed with SF_6 gas and moved to the thermal expansion room along with flow causing increase of pressure which is used for extinguishing arc between contacts in the time of current zero. The modeling for the circuit breaker analysis was implemented by the User-Defined function (UDF) in a commercial code (FLUENT) on the Navier-Stokes' equation considering that a shape of circuit breaker is axial symmetry. Equation required for this analysis is as follows:

$$\frac{\partial(\rho\phi)}{\partial t}+\nabla\cdot(\rho\phi\vec{V})-\nabla\cdot(\Gamma_\phi\nabla\phi)=S_\phi \quad (1)$$

where, ϕ is the dependable variable, Γ_ϕ is the diffusion coefficient, S_ϕ is the source term (See Table 1).

Material of nozzle and the mass fraction rate of SF_6 gas is defined as follows:

$$c_m=\frac{n_{PTFE}M_{PTFE}}{n_{PTFE}M_{PTFE}+n_{SF_6}M_{SF_6}} \quad (2)$$

Table 1.

Equation	ϕ	Γ_ϕ	S_ϕ
continuity	1	0	0
r-momentum	v	$\mu_l+\mu_t$	$-\partial P/\partial r$ +viscous terms
z-momentum	w	$\mu_l+\mu_t$	$-\partial P/\partial z$ +viscous terms
enthalpy	h	$(k_l+k_t)/c_p$	$\sigma E^2-q+dP/dt$ +viscous terms
PTFE mass concentration	c_m	$\rho(D_l+D_t)$	0

ρ = *density*, v = radial velocity, w = axial velocity, h = enthalpy, c_p = specific heat at constant pressure, c_m = PTFE mass concentration, μ = viscosity, D = Diffusion coefficient, P = pressure, J = current density, E = electric field, σ = electrical conductance, q = radiation loss. Subscript l and t represent laminar and turbulent terms, respectively.

where, n represents the number of mol, M represents the quantity of substance.

The current density and the electric field are calculated by solving the current continuity equation, which is expressed in terms of electrical potential.

$$\nabla\cdot(\sigma\nabla\varphi)=0 \quad (3)$$

where φ is the electrical potential and σ is the electrical conductance. The Lorentz force is ignored.

A k-epsilon model was applied for the turbulence model, and the Discrete Ordinate Method (DOM) was applied for arc radiation energy transfer. The spectrum of SF_6 is divided into five bands and the average absorption coefficients are calculated as a function of temperature for each band. These averaged absorption coefficients can be used to solve five DO equations, one for each band [11, 12].

2.2 Mathematical arc model

Typical models among the mathematical arc models are Mayr arc model and Cassie arc model [13, 14]. It is known that the Mayr arc model shows good results around current zero and the Cassie arc model for the high-current arc. The KEMA arc model combining the Mayr model and Cassie model is also used for the arc analysis including low-current and high-current phases [15].

Since the result of the CFD analysis is used in the high-current phase and the mathematical arc model is subsequently applied up to the current zero in this paper, the Mayr arc model showing good results for the low-current phase arc is adopted.

Formula of the Mayr arc model is as follows:

$$\frac{1}{g}\frac{dg}{dt}=\frac{1}{\tau}\left(\frac{ui}{P}-1\right) \quad (4)$$

where g, u, i, τ, and P are, respectively, arc conductance, arc voltage, arc current, time constant, and cooling power.

On the other hand, the partially modified arc models have been suggested to increase the accuracy around the current zero as compared with the original Mayr arc model. This study finally adopted the modified Mayr arc model of which cooling power is expressed as a function of input arc energy [16].

Related formula is as follows:

$$\frac{1}{g}\frac{dg}{dt}=\frac{1}{\tau}\left(\frac{ui}{P_0+P_1 ui}-1\right) \quad (5)$$

The procedures of completing the mathematical arc

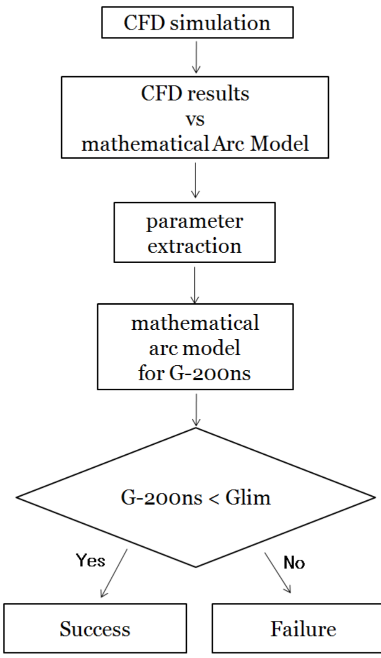
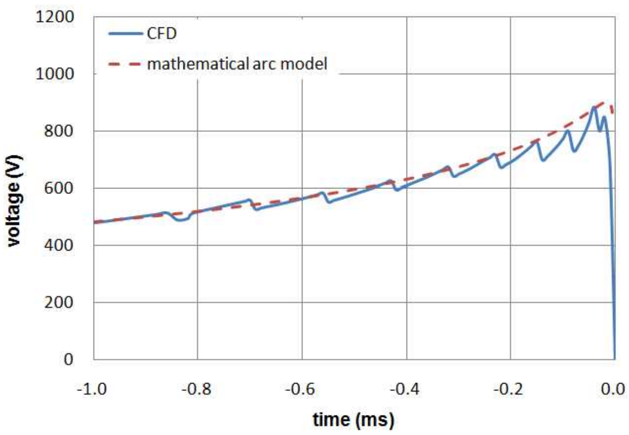
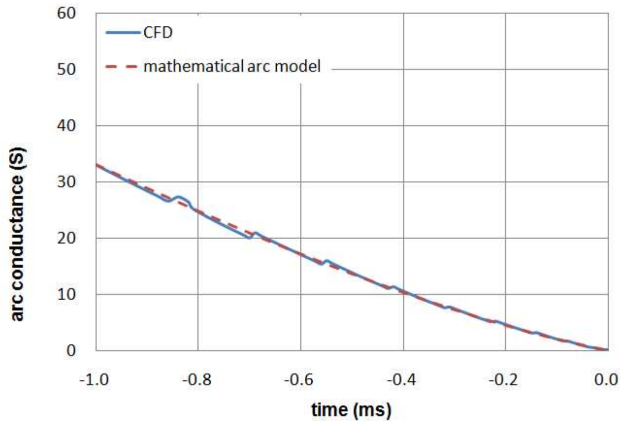


Fig. 2. Flow chart for evaluation of the interruption performance of GCBs



(a) arc voltage



(b) arc conductance

Fig. 3. The extraction of parameters for the mathematical arc model

model are expressed with a flowchart in Fig.2. First, the analysis of heat transfer and fluid flow including arc is performed in the high-current phase up to near current zero. After that, the arc parameters (τ, P_0, P_1) required for the analysis of the modified Mayr arc model are determined by using the result of the CFD analysis. As shown in Fig.3, the optimal arc parameters are calculated by minimizing the least root mean square error between the conductance of the CFD analysis and the modified Mayr arc model. In this procedure, it is needed to arrange the comparing period and the ranges of the parameter values. As the comparing period can considerably affect the decision of parameter values, the start and end time should be set carefully in order to satisfy the overall trend of arc voltage as shown in Fig. 3 (a).

In this study, the start time is about 1ms before current zero and the comparing period is up to current zero. The suitable free parameter ranges to be investigated for the GCB models in this study are set widely (τ: 0.1~2 μs, P_0: 5~30 kW, P_1: 0.999~1).

For this procedure the optimization program searching optimal parameter values comparing the result of the CFD analysis with the result of the mathematical arc model is implemented, which gradually increases the values respectively within specific ranges and searches the optimal values. The optimal parameter values decided by the program for both models are as follows.

Model-0 τ: 0.6 μs, P_0:9 kW, P_1: 0.9997
Model-1 τ: 0.7 μs, P_0:12 kW, P_1: 0.9997

The mathematical arc model is subsequently calculated by 200 ns before the current zero by applying so determined parameter values to obtain the arc conductance. The critical conductance to determine the thermal interruption performance of the circuit breaker suggested by KEMA is between 0.81 and 3mS and the larger value than the critical value means failure of the interruption, and the smaller value than it means success of the interruption.

3. Application to Design of Circuit Breakers

Analysis tools suggested in this study were used for the design of the self-blast type breaker of 145kV 40kA and 60Hz. The interruption performance of the model-0 was insufficient for arc time of 18 ms, so the analysis method was applied for improvement of the interruption performance. Since the performance of the interruption must be guaranteed over the whole arc time range as well as arc time of 18ms, the analysis was also performed at the same time for the short arc time and the long arc time with changing the design parameters. Fig.4 shows the result of arc conductance at 200 ns before the current zero point by using the methods suggested in this study. As seen in Fig. 4, the G_{-200ns} value of model-0 at the arc time of 18ms

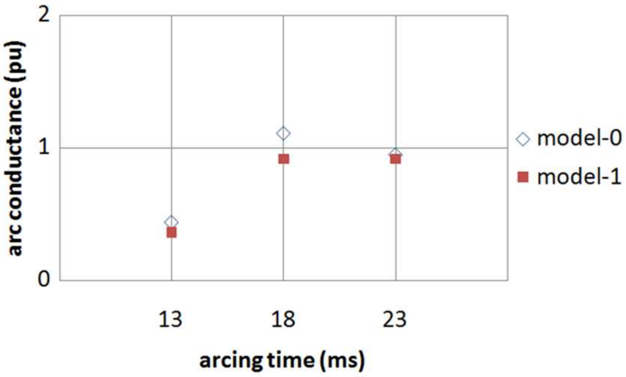
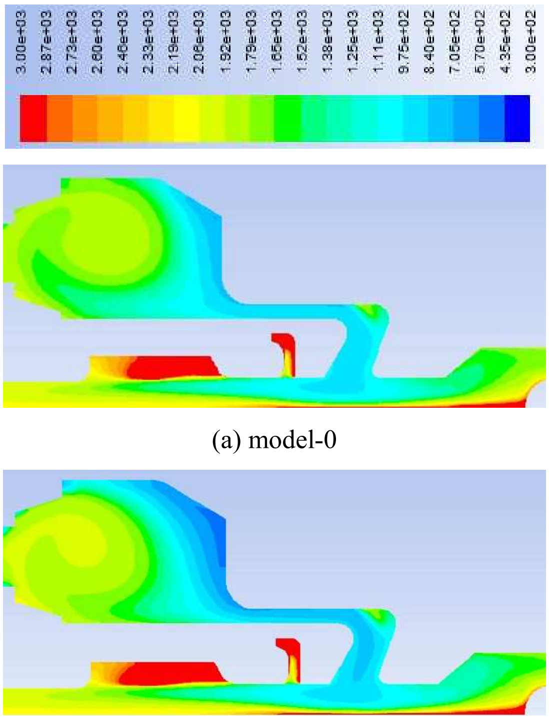


Fig. 4. Arc conductance at 200 ns before current zero



(a) model-0

(b) model-1

Fig. 5. Temperature distribution at current zero

appears slightly higher than the critical arc conductance value (1pu) as the interruption test result is failure.

The critical arc conductance value is obtained through analyses and experiments for the various models of gas circuit breakers. They are somewhat higher than the G_{-200ns} value suggested by KEMA based on a lot of experiments. It may be caused by the effect of accuracy degree of the result of the CFD analysis and assuming arc parameters as constant in spite of time varying property up to the current zero. To improve model-0, the length of nozzle neck is reduced by 5mm and the overlapped length of contacts is lengthened by 10mm. When analysis was performed for a new model (model-1), it can be found that the performance of the interruption is improved since the G_{-200ns} values generally become lower than the critical value over the

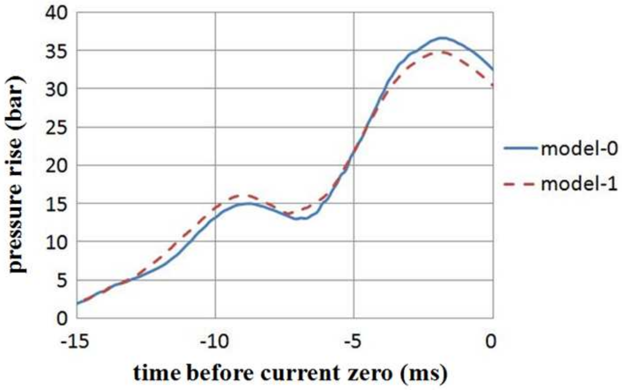


Fig. 6. The averaged pressure rise in the thermal expansion room (t_{arc}=18 ms)

whole arc time range. The improved model (model-1) was fabricated using the design parameters obtained by the analysis and success of the interruption was also found in the interruption tests. Fig. 5 and Fig. 6 show the result of CFD analysis of the arc time of 18ms for both models at the current zero point. Though the performance of the interruption is classified into success and failure, the distribution of temperature within the GCB at the current zero point appears no significant difference. The averaged pressure rise of the thermal expansion room appears lower by about 1bar for the model-1.

From the CFD results, we can also understand the reason why the model-1 shows the better thermal interruption performance than model-0. Though model-0 has a sufficient pressure rise of the thermal expansion chamber for interruption, the temperature of thermal gas blowing out from the thermal expansion chamber to the arc is higher than the critical temperature needed to extinguish the arc. In the case of model-1, the lengthened overlapped contacts affects the increase of the initial averaged density of thermal expansion chamber and the shortened nozzle neck causes the lowering blowing gas temperature near current zero by reducing the nozzle ablation. These effects are regarded as the main reason for improvement of the thermal interruption performance of model-1 [17].

4. Conclusions

A new attempt to combine the CFD analysis and the mathematical arc model analysis was performed for evaluation of the interruption performance of the gas circuit breakers in this study. The physical and chemical phenomena of the arc generated in the high-current interruption were studied through the CFD analysis and the parameter values of the mathematical arc model were extracted through the CFD result. Arc conductance at 200 ns before the current zero was obtained by applying these values, and the interruption performance of a breaker can be evaluated through comparison with arc conductance values. When using the methods suggested in this study, it makes it possible to overcome the CFD limitations due to very complicated physical and chemical phenomena in the low-current phase, which can reduce the computation time and the effort in the CFD simulation. Especially, more accurate evaluation of the interruption performance is possible when applying these methods for the cases in which no significant difference of temperature and pressure rise appears in the thermal expansion room at current zero through the result of CFD analysis as for the model-0 and the model-1.

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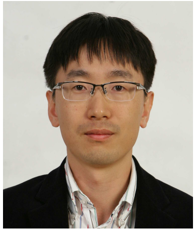

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