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FEM을 이용한 가스차단기의 아크해석

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Arc Simulation of GCB Interrupter Using FEM

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Abstract

An arc model based on the N-S equations modified by adding an energy source term to take account of the arc is developed and solved using Taylor-Garlerkin FEM in the present paper. The numerical method is applied to the simulation of the opening procedure of a puffer type GCB. Moving boundary conditions of the arc chamber during operation is taken into account. Numerical predictions of the temperature profiles at different strokes are presented.

Keywords: arc simulation, finite element method, gas circuit breaker

1. Introduction

Considerable efforts have been made on the computer simulation of arc dynamics in the interrupter of SF6 GCB in recent years. Two main categories can be identified among them. One is the application of commercial CFD package, the majority of which is based on the finite volume method such as PHOENICS[1]. The other is the use of self-programmed code, which adopt finite volume method[2], FLIC[3] or any other finite difference methods.

An arc model based on the Navier-stokes equations for compressible flow including an energy source term which takes into account the ohmic heating and radiation is developed in the presented paper. The numerical method adopts the Taylor-Garlerkin finite element method (FEM). The main feature of this numerical method is that, in time domain it adopts finite difference method and in spatial domain Garlerkin FEM is applied. The advantage of Taylor-Garlerkin method lies on the fact that less computer memory is needed in this method, which makes it possible to solve time evolution problems using FEM with an ordinary PC.

The numerical method is applied on the simulation of the contact separation procedure of a 72.5kV, 25kA puffer type GCB. The moving boundary condition for a puffer type interrupter is taken into account by subdividing the stroke into 10 steps. The stroke curve is obtained from the experiment. The numerical predictions of temperature profiles at different instant, that is different strokes, are presented.

2. Governing Equations

The governing equations are based on Navier-Stokes equations with an energy source term to take into account the arcing effect. The axisymmetric N-S equations are given by

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial r} + H = S \qquad (1)$$

where

$$U = [\rho, \rho u, \rho v, \rho e]^T$$

$$F = [\rho u, \rho uu + p - \tau_{xx}, \rho uv - \tau_{xr}, u(\rho e + p - \tau_{xx}) - v\tau_{xr} - k\partial T/\partial x]^T$$

$$G = [\rho u, \rho u v - \tau_{rx}, \rho vv + p - \tau_{rr}, v(\rho e + p - \tau_{rr}) - u\tau_{xr} - k(\partial T/\partial r)]^T$$

$$H = 1/r[\rho v, \rho uv - \tau_{rx}, \rho vv - 2\mu(\partial v/\partial r - v/r), v(\rho e + p - \tau_{rr}) - u\tau_{xr} - k\partial T/\partial r]^T$$

$$S = [0,0,0,Q]^T$$

in which ρ is the gas density, u and v the axial and radial fluid velocity, p the pressure, T the temperature, μ the viscous coefficient, k is the coefficient of the heat transfer.

$$\tau_{xx} = \frac{2}{3}\mu(2\frac{\partial u}{\partial x} - \frac{\partial v}{\partial r} - \frac{v}{r})$$

$$\tau_{rr} = \frac{2}{3}\mu(2\frac{\partial v}{\partial r} - \frac{\partial u}{\partial x} - \frac{v}{r})$$

$$\tau_{xr} = \tau_{rx} = \mu(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x})$$

e is the internal energy, which is given by

$$e = cvT + \frac{1}{2}(u^2 + v^2) \qquad (2)$$

All the thermodynamic and physical properties of equilibrium SF6 are taken from Frost and Liebermann [4].

Source term

$$Q = \sigma E^2 - U_{net} \qquad (3)$$

Where is the electrical conductivity of the plasma, E the potential gradient of the arc column and U_{net} is the net emission from the arc core. U_{net} can be expressed as a function of arc radius R, temperature T and pressure P, which can be obtained from Ref[5].

To enclose the equations we should add Ohms Law

$$E = \frac{I}{\int_0^\infty 2\pi r \sigma dr} \qquad (4)$$

and the equation of state

$$p = p(\rho, T) \qquad (5)$$

In the present calculation, the temperature may reach a much high level, in which SF6 can no longer be regarded as ideal gas. This equation of state is a revised one[4].

3. Numerical Method

The above governing equations are solved using Taylor-Garlerkin FEM[6]. In the time domain it adopts finite difference scheme, but in the spatial domain Garlerkin FEM is applied.

(1) Time discretization

Two-step Taylor series is applied to the time discretization.

Step 1: $$U^{n+1/2} = U^n + \frac{\Delta t}{2}\frac{\partial U}{\partial t}\bigg|^n \qquad (6)$$

Step2 : $$U^{n+1} = U^n + \Delta t\frac{\partial U}{\partial t}\bigg|^{n+1/2} \qquad (7)$$

(2) Garlerkin finite element approximation

The spatial discretization is also for two steps, corresponding to the two-step time discretization.

Step 1: Partial average interpolation function is applied

$$\int_{\Omega_e} P_e U_e^{n+1/2} d\Omega = \int_{\Omega_e} P_e U_e^n d\Omega + \frac{\Delta t}{2}\int_{\Omega_e} P_e \frac{\partial U_e}{\partial t}\bigg|^n d\Omega \qquad (8)$$

where $U_e^{n+1/2}$ is the average of U for the half step in the element of Ω_e, P_e is the partial average interpolation function.

Step 2 : According to the Garlerkin finite element method, let the inner product of the residual and the weight function to be zero, yield

$$\int_{\Omega_e} N_i^e (\Delta U^{n+1} - \Delta t\frac{\partial U}{\partial t})\bigg|^{n+1/2} d\Omega = 0 \qquad (9)$$

where $\Delta U^{n+1} = U^{n+1} - U^n$

By applying the Gauss-Green theorem, we get

$$\int_{\Omega_e} N_i^e \Delta U^{n+1} rdrdx = \Delta t \int_{\Omega_e} (F\frac{\partial N_i^e}{\partial x} + G\frac{\partial N_i^e}{\partial r})\bigg|^{n+1/2} rdrdx$$

$$+ \Delta t \int_{\Omega_e} (G - rH)|^{n+1/2} N_i^e \, drdx$$

$$- \Delta t \int_{\Omega_e} (\vec{h}_x F + \vec{h}_r G)|^{n+1/2} N_i^e r \cdot d\vec{\Gamma} \qquad (10)$$

where Γ_e is the boundary of Ω_e, $\vec{h}_x$ and $\vec{h}_r$ is the unit normal and tangential vector respectively.

4. Results and Discussions

The numerical method is applied to the simulation of the contact separation procedure of a 72.5kV, 25kA puffer type GCB.

During the contact separation of a puffer type GCB, the moving contact and the cylinder on which the nozzle is fixed on are driven by the operating mechanism. The geometry of the arc chamber changes all the time. That means the calculation domain changes at the meanwhile. The treatment of moving boundary is simplified by making the moving contact fixed and moving the stationary contact and piston in a reverse direction. The opening stroke is divided into 10 steps. At each step the boundary is regarded as fixed and the speed of the piston is constant.

The computed result of the former step is interpolated to the domain of the next step as an initial condition. The computation begins from the pre-compression stage which is before the separation of the contacts. In this case, temperature of 300K and pressure of 0.6MPa is assumed everywhere of the arc chamber as the initial condition for the first step of cold gas flow. At the very beginning of the step just after the separation of the contacts, a temperature which is just above the ionized temperature of SF6 plasma, for example 4000-5000K, is imposed at the elements on the axis between the contacts to simulate the ignition of the arc.

The stroke curve is obtained from the experiment. In the present computation, the interrupting current is 25kA, arcing time 16.67ms(1 cycle).

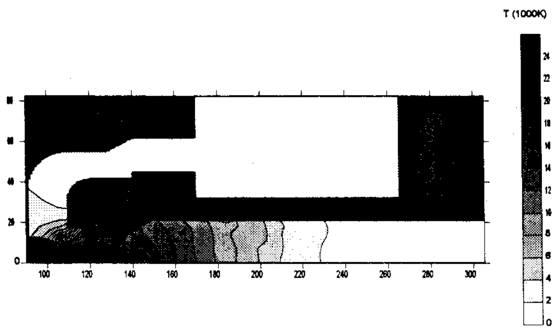

Figure1 Temperature distribution ($\varphi = 0.5\pi$)

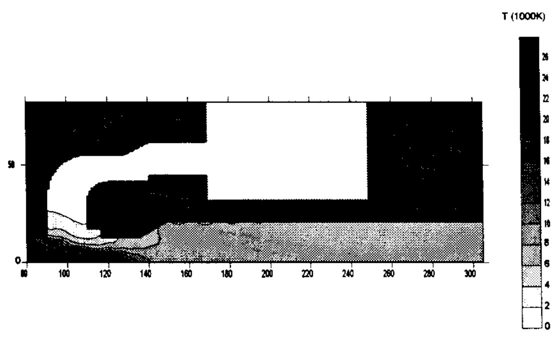

Figure2 Temperature distribution ($\phi = 0.8\pi$)

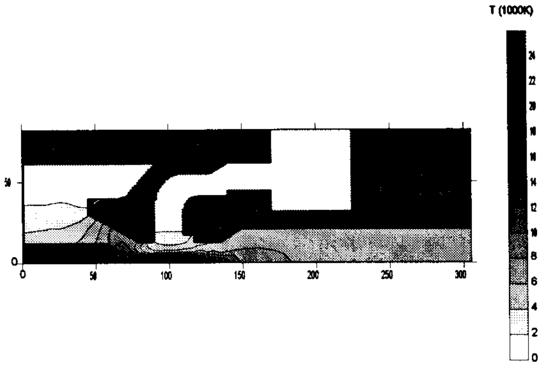

Figure3 Temperature distribution ($\phi = 1.2\pi$)

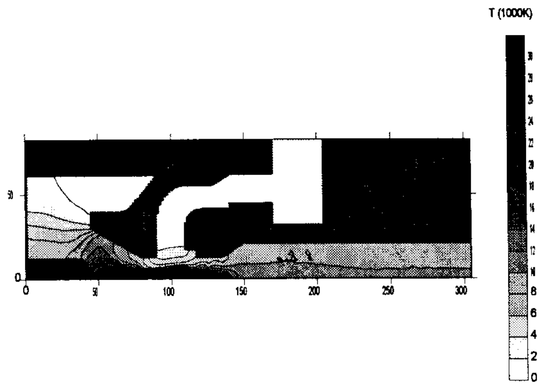

Figure4 Temperature distribution ($\phi = 1.5\pi$)

Figure 1 to figure 6 are the time evolution of the temperature profiles in the arc chamber during the contact separation.

In the period of the first half cycle of current, the nozzle is blocked by the stationary contact. Hot gas exhausts from the moving contact pipe. The temperature of the arc core reaches more than 24000K, as shown in figure 1 and 2. After the stationary contact moves out of the nozzle throat (figure 3 and 4), one can find that the nozzle is clogged by hot gas with temperatures above 6000K, during the most time of the second half cycle of current. This is known as arc clogging, which is usually utilized to elevate the pressure of the puffer chamber.

One of the important purposes to simulate the arc in the large current phase is to provide accurate initial conditions for the study of the phenomena in the post arc period. Figure 5 illustrates the temperature distribution at the current zero.

From the data of Frost and Liebermann[4], the SF6 is nonconductive below the temperature of 4000K.

Figure 6 shows that at the current zero there is a very slender current conducting channel (the column enclosed by the isothermo line of 4000K) at the axis between the two arcing contacts. The conducting channel has the thinnest diameter and lowest temperature at the throat of the nozzle, which indicates that this region plays an important role in the thermal recovery of the SF6 interrupter.

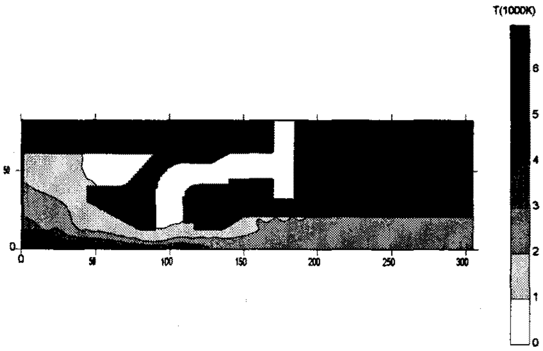

Figure5 Temperature distribution (ψ =2.0 π)

5. Conclusions

1. The arc model based on the N-S equation of gas dynamics was solved using Taylor-Garlerkin FEM. The numerical method was applied to the simulation of the operation of a puffer type GCB.
2. The numerical solutions show that arc clogging takes effect at the most time of the large current phase.
3. The present work provides an accurate initial condition for the further study of the post arc phenomena.

6. References

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