COMPUTER SIMULATION OF ARC INTERRUPTION USING FEM FOR SF_6 GAS CIRCUIT BREAKERS

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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-Galerkin FEM. The numerical method is applied to the simulation of the interruption process of a puffer type GCB. Moving boundary conditions of the arc chamber during operation is taken into account. The thermal interruption capability of an actual puffer type GCB will be predicted and compared with that of the measured result.

1. INTRODUCTION

Considerable efforts have been made on the computer simulation of arc dynamics for the interrupter of SF_6 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 adopts 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-Galerkin 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 Galerkin FEM is applied. The advantage of Taylor-Galerkin 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. Arbitrary quadrilateral elements are used for the mesh generation, which makes it easy to deal with the complicated geometry of the arc chamber.

The numerical method is applied to the simulation of the arc interruption 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 numerical predictions of the temperature and pressure distributions as well as the arc voltage are presented. Some of them are compared with the experiments. Finally, the thermal interruption capability is predicted and compared with the experimental results.

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

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

where

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

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

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

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

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

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

e is the internal energy, which is given by

$$e=c_V T+\frac{1}{2}(u^2+v^2) \quad (2)$$

The coefficient of viscosity and thermal conductivity can be expressed

$$\mu=\mu_l+\mu_t$$

$$k=k_l+k_t$$

as

μ_l and k_l are laminar viscosity and thermal conductivity, respectively. μ_t and k_t are related turbulent values calculated from Prandtl's mixture length model[4]

$$\mu_t=\rho\varepsilon$$

$$k_t=2\rho c_p\varepsilon$$

with

$$\varepsilon=\alpha\delta|v_z|$$

where α is an adjustable turbulence parameter and δ is the characteristic length of the arc radius.

All the thermodynamic and physical properties of equilibrium SF_6 are taken from Frost and Liebermann[5].

Source term

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

Where σ 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[6].

To close the equations we should add Ohm's Law

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

and the equation of state

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

In the present calculation, the temperature may reach such a high level that the SF_6 can no longer be regarded as ideal gas. This equation of state is a revised one[5].

3. NUMERICAL METHOD

The above governing equations are solved using Taylor-Galerkin FEM[7]. In the time domain it adopts finite difference scheme, but in the spatial domain Galerkin FEM is applied.

(1) Time discretization

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

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

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

(2) Galerkin finite element approximation

The spatial discretization also adopts two-step procedure, corresponding to the two-step time discretization.

Step 1: Partial average interpolation function is applied

$$\int_{\Omega e} P_e U_e^{n+1/2} d\Omega = \int_{\Omega e} P_e U_e^{n} d\Omega + \frac{\Delta t}{2}\int_{\Omega e} P_e \frac{\partial U_e}{\partial t} d\Omega \quad (8)$$

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 Galerkin finite element method, let the inner product of the residual and the weight function to be zero, yield

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

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

By applying the Gauss-Green theorem, we get

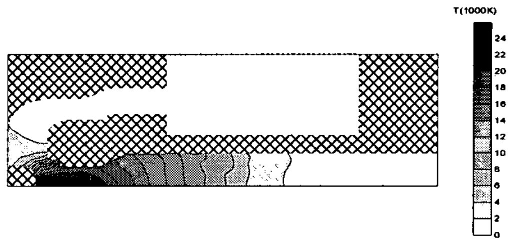
$$\int_{\Omega e} N_i^e \Delta U^{n+1} r dr dx = \Delta t \int_{\Omega e} (F\frac{\partial N_i^e}{\partial x} + G\frac{\partial N_i^e}{\partial r})\Big|^{n+1/2} r dr dx$$
$$+ \Delta t \int_{\Omega_e} (G - rH)\Big|^{n+1/2} N_i^e dr dx$$
$$- \Delta t \oint_{\Gamma e} (\vec{n}_x F + \vec{n}_r G)\Big|^{n+1/2} N_i^e r \cdot d\vec{\Gamma} \quad (10)$$

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

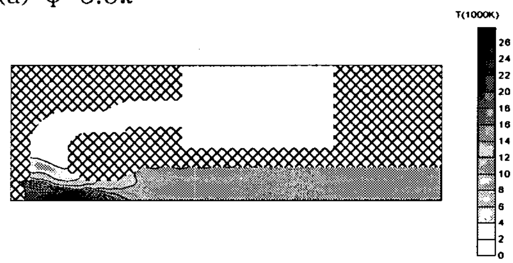
4. RESULTS AND DISCUSSIONS

The numerical method is applied to the simulation of the arc interruption process of a 72.5kV, 25kA puffer type GCB.

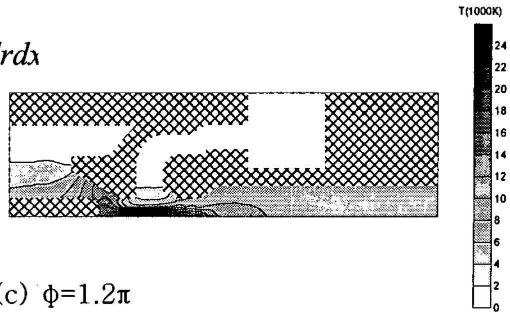
During the contact separation of a puffer type GCB, the moving contact and the cylinder on which the nozzle is fixed are driven by the operating mechanism. The geometry of the arc chamber changes all the time. That means the calculation domain changes in the meanwhile. The treatment of moving boundary is simplified by making the



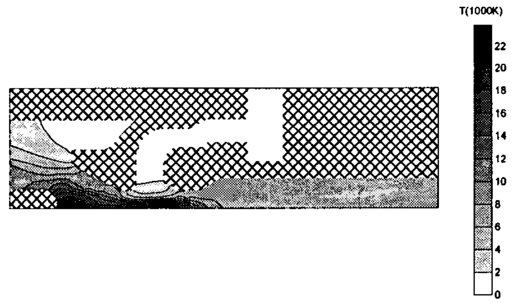
(a) Φ=0.5π



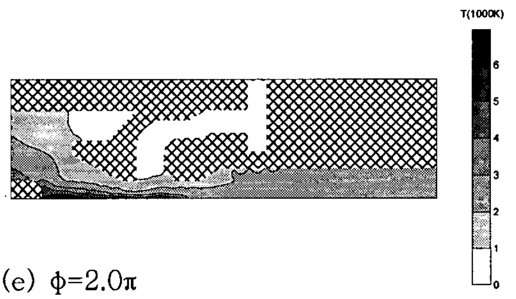
(b) Φ=0.8π



(c) Φ=1.2π



(d) ϕ=1.7π



(e) ϕ=2.0π

Figure 1 Temperature Evolutions

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 are assumed everywhere in the arc chamber as the initial condition. At the very beginning of the step just after the separation of the contacts, a temperature which is just above the ionized temperature of SF_6 plasma, for example 4000-5000K, is imposed on the elements on the axis between the contacts to simulate the ignition of the arc. 0.065 of α is used for the adjustable turbulence parameter.

Fig. 1 is 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 is exhausted from the moving contact pipe. The temperature of the arc core reaches more than 24000K, as shown in Fig. 1 (a) and (b). After the stationary contact moves out of the nozzle throat (Fig. 1 (c) and (d)), 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.

Fig. 1 (e) illustrates the temperature distribution at the current zero.

Both the calculated and measured pressure rise on the surface of the puffer piston during operation are shown in Fig. 2. The calculated values show the same trend with the experimental results.

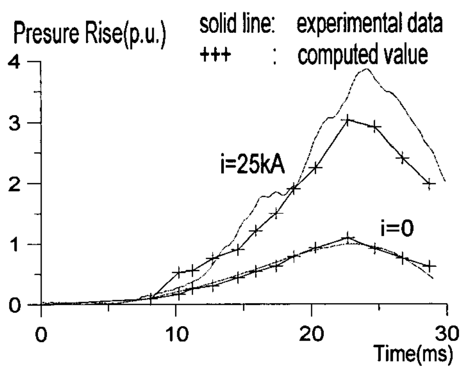


Figure 2 Pressure Rise of Puffer Chamber

The computed pressure distribution of the arc chamber at the instant of current zero is shown in Fig. 3, from which it may be observed that the highest pressure exists inside the puffer chamber and a stagnation region occurs on the axis between the movable contact and the nozzle throat.

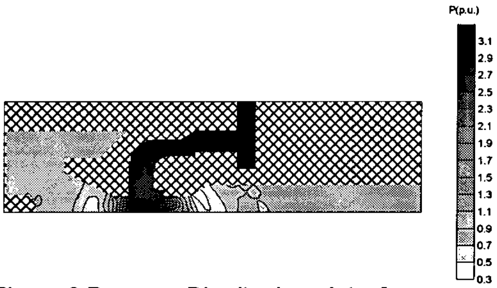


Figure 3 Pressure Distribution of the Interrupter

The numerical result of the arc voltage agrees well with that of the experiment except in the vicinity of the first current zero, as shown in Fig. 4. The arc voltage is given by

$$u = \int_0^L E \cdot dl \qquad (11)$$

in which L is the arc length. E can be obtained from the equation (4).

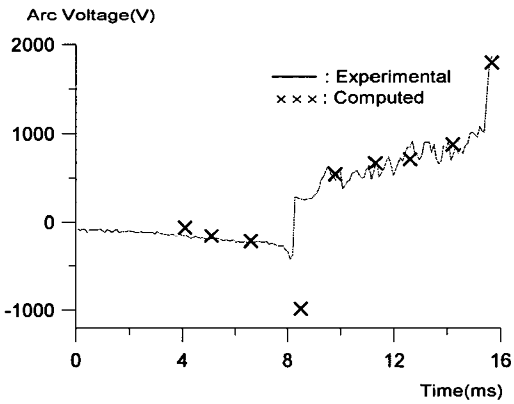


Figure 4 Arc Voltage (i=25kA)

Experiment was carried out to find out the critical RRRV for the circuit breaker. The experimental results are shown in Fig. 5, which reveals that the critical RRRV is between 6.1 and 6.3kV/μs for the interrupting current of 22.5kA (90% of the rated interrupting current) with an arcing time of 9ms. Under the same conditions, the computed post arc current under different du/dt is presented in Fig. 6, from which one can find that the critical RRRV is between 6.3 and 6.5kV/μs.

5. CONCLUSIONS

The arc model based on the N-S equations of gas dynamics was solved using Taylor-Galerkin FEM. The numerical method was applied to the simulation of the interruption for a puffer type GCB.

The numerical predictions agree well with those of the experiments for pressure rise, arc voltage and critical

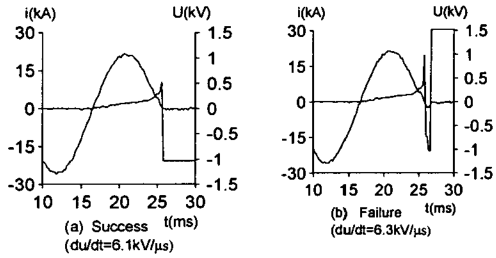


Figure 5 Experimental Results for Critical RRRV

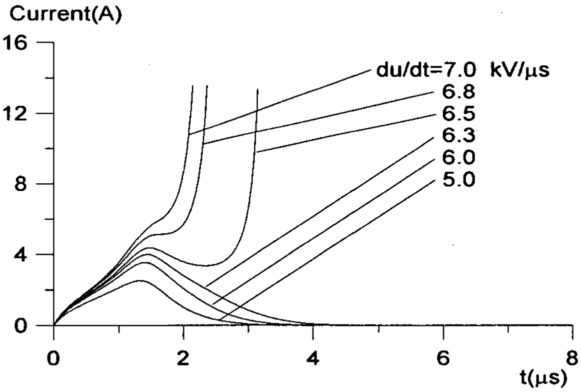


Figure 6 Calculated Post Arc Current (i=22.5kA, arcing time=9ms)

RRRV, which proves the validation of the present computer simulation method.

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