NUMERICAL SIMULATION OF A PRESSURE WAVE INTERACTING WITH A PROTECTION FILTER DURING AN INTERNAL ARC FAULT IN A MEDIUM VOLTAGE CELL

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Abstract – **We present a two-dimensional mathematical model and a specific numerical method to study the interaction of a pressure shock wave, due to an internal arc fault, with a protection filter in a medium voltage cell. The model is based on Euler equations in porous medium taking into account the porosity variation. Calculation results are compared to experimental measurements of the pressure performed on apparatus specially adapted for tests.**

Keywords: *medium voltage cell, internal arc fault, porous filter, finite volume method.*

1. INTRODUCTION

Internal arc fault testing on Medium Voltage (MV) cell has been a focused area [1,2] where experimental tests have been carried out to set the switchgear in conformity with IEC standards [3]. The MV cell is a compact unit combining all MV functional units to enable connection, supply and protection of a transformer. The switchgear and busbars are enclosed in a gas-tight chamber filled with SF6 and sealed for life by a safety valve located at the bottom of the metal enclosure. In order to limit the internal arc effects, a new protection filter constituted of a porous medium is used allowing better performances compared to traditional filter technologies.

Internal arc fault is an extremely rare phenomenon characterized by a powerful non controlled electric arc due to a dysfunction. The MV cell is presented in figure 1. The cell is constituted of a metal enclosure sealed by a safety valve, a buffer area, a protection filter composed of a porous medium and a gas exhaust area.

The process can be summarized as follow:

- Pressure rises in the metal enclosure initially sealed due to the internal arc apparition.
- To avoid the metal enclosure explosion containing the gas insulating, a safety valve bursts when the pressure reaches a critical pressure gauged at $P_c = 0.28\,MPa$.
- The hot gas flow is ejected toward the buffer area and penetrates into the porous filter.
- The porous filter role is to absorb the shock wave generated at the bursting valve and to cool the hot gas flow by heat exchange with the grains composing the protection filter.

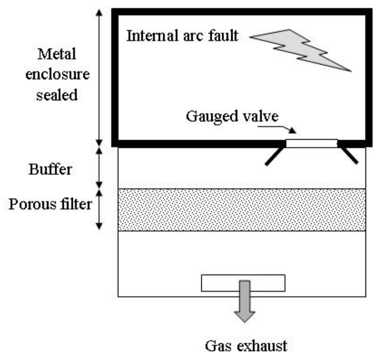

Figure 1: Schematic description of the MV cell.

The protection filter is used to obtain a gaseous outflow from the cell which is not harmful for the equipment and the people located near the cell during an internal arc fault.

In order to study the filter effects on the gas flow, a two-dimensional mathematical model in porous medium is used. To solve the system, we use the numerical scheme developed in [4] taking into account the non conservative term $P\nabla\phi$.

2. MATHEMATICAL MODEL

In order to evaluate the filter effects on the gas flow characteristics, we have developed a two-dimensional gas flow model in porous medium. The model is obtained by the homogenization process which results in describing the gas behavior at a macroscopic scale [5]. For the porous filter, we assume a set of simplifying assumptions:

- The porous medium is an underformable porous matrix.
- The Brinkman term is negligible.
- The porous medium is composed of spherical particles.
- The porosity is variable.

The mechanical interaction between the gas and the filter is described by behavioral laws (Darcy and Forchheimer laws) which contain the gas characteristics and the geometrical parameters of the porous medium. The thermal exchanges between the hot gas and the filter are described by a Newton law, where we evaluate the convective heat transfer coefficient which depends on the Nusselt, Reynolds and Prandlt numbers.
To describe the internal arc fault, we use a simplified model because there is limited literature about internal arc characteristics. We assume that the energy and the mass ablated are linearly dependent on the time, we inject $E_{inj} = 10MJ$ with a mass ablated rate $m = 20\mu g.J^{-1}$. The radiation losses are evaluated by the net emission coefficient [6]. The two-dimensional governing equations for a gas flow in variable porosity medium are based on the Euler equations. Since the porosity is not constant, a non conservative term appears in the impulsion equations during the homogenization process and the equations write:

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} + \frac{\partial G(U)}{\partial y} = NCT(U) + S(U),$$

with the notation:

$$U = \begin{pmatrix} \phi \\ \rho\phi \\ \rho\phi u \\ \rho\phi v \\ E\phi \end{pmatrix}, \; F(U) = \begin{pmatrix} 0 \\ \rho\phi u \\ \rho\phi u^2 + \phi P \\ \rho\phi uv \\ \phi u(E+P) \end{pmatrix}, \; G(U) = \begin{pmatrix} 0 \\ \rho\phi v \\ \rho\phi uv \\ \rho\phi v^2 + \phi P \\ \phi v(E+P) \end{pmatrix},$$

$$NCT(U) = \begin{pmatrix} 0 \\ 0 \\ P(\partial\phi/\partial x) \\ P(\partial\phi/\partial y) \\ 0 \end{pmatrix}, \; S(U) = \begin{pmatrix} 0 \\ r \\ -\phi^2 \frac{\mu}{k} u - \phi^3 \beta\rho |V| u \\ -\phi^2 \frac{\mu}{k} v - \phi^3 \beta\rho |V| v \\ P_{Elec} - P_{Rad} - h_{sf} A(T - T_{filtre}) \end{pmatrix}.$$

where ρ is the gas density, (u,v) is the velocity components, P is the pressure, ϕ is the variable porosity and E is the total energy per unit volume given by:

$$E = \rho\left(\frac{1}{2}V^2 + e\right),$$

with e the specific internal energy and $V = \sqrt{u^2 + v^2}$ the norm velocity field. In addition to close the system, we use the ideal gas equation of state $P = (\gamma - 1)\rho e$.

3. NUMERICAL METHOD

To deal with the numerical approximation, we introduce the following notations. $\mathcal{T}_h$ is a discretization of a two-dimensional polygonal bounded domain Ω with triangles S_i, $i = 1,\ldots,I$, where I is the number of mesh elements. For a given I, $\nu(i)$ represents the index set of the common edge elements $S_j \in T_h,\, j \in \nu(i)$, where $L_{i,j} = \overline{S_j} \cap \overline{S_i}$ stands for the common side. In the sequel, $|L_{i,j}|$ stands for the length of the side whereas $|S_i|$ is the area of the cell i. For a given side $L_{i,j}$, $\mathbf{n}_{i,j}$ represents the outwards normal of S_i pointing to S_j and $\mathbf{n}_{i,j} = -\mathbf{n}_{j,i}$. The sequence $(t^n)_n$ defines a time discretization of [0,T] with $t^{n+1} = t^n + \Delta t$ and U_i^n stands for an approximation of the mean value of U at time t^n on the element S_i.

We consider a general finite volume scheme described in [7]:

$$U_i^{n+1} = U_i^n - \frac{\Delta t}{|S_i|} \sum_{j \in \nu(i)} |L_{i,j}| \mathcal{F}(U_i, U_j, \mathbf{n}_{i,j}) + \Delta t\, S(U_i^n),$$

where $\mathcal{F}$ is the numerical flux on the corresponding cell boundary.
To evaluate the numerical fluxes, the technique consists in a linearization of the Riemann problem at each interface $L_{i,j}$ [4]. The particular point is that the numerical flux has to be non-conservative to take into account the term $P\nabla\phi$ into account i.e.

$$\mathcal{F}(U_i, U_j, \mathbf{n}_{i,j}) \neq \mathcal{F}(U_j, U_i, \mathbf{n}_{j,i}).$$

To solve the source terms, we use the Runge-Kutta method.

4. NUMERICAL RESULTS

The computational domain is discretized with triangle elements for a domain length $L = 1m$ and height $H = 1.5m$ and divided into four areas (see figure 2).

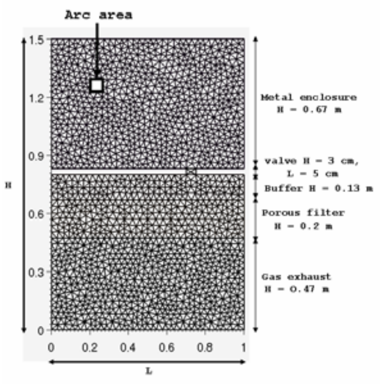

Figure 2: MV cell mesh.

In order to improve the understanding of the phenomenon, we have realized a simulation on the first $0.2s$ of the process. At initial time $t = 0s$, the whole domain contains air gas at atmospheric pressure, ambient temperature at rest. The porous filter is composed of spherical particles of $d_p = 25mm$ diameter. We inject the energy and the mass in the area represented by a square in the metal enclosure in figure 2.

Figure 3 shows the pressure distribution in the cell just after the valve bursting, a shock wave is generated in the buffer area propagating in the porous filter. A transmitted and a reflected wave appear during the interaction with the filter boundary due to the discontinuity of the porosity. An acceptable overpressure is observed in the buffer area.

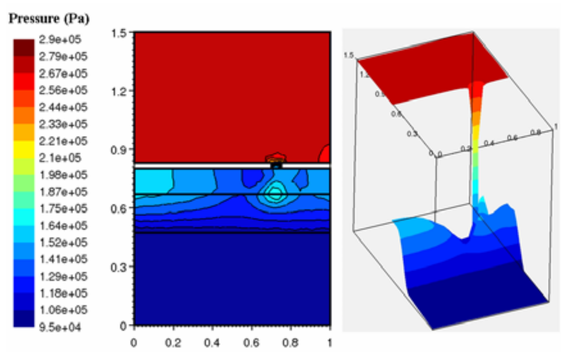

Figure 3: Pressure distribution in the MV cell just after the valve bursting.

In order to compare with the numerical simulation, physical measurements were acquired during standardized internal arc fault tests performed in a high power test laboratory on real electrical apparatus [2,8]. A 3-phases arc current of 20 kA RMS is maintained during one second in the metal enclosure filled with air for environmental protection.

Figure 4 presents the temporal evolution of the pressure in the metal enclosure of the MV cell obtained by simulation and measurements. Due to the injected energy and the ablated mass in the metal enclosure, the pressure increases until reaching a critical pressure of $2.8 \times 10^5 \, Pa$, the gauged safety valve bursts, the gas release takes place in the first $0.2s$.

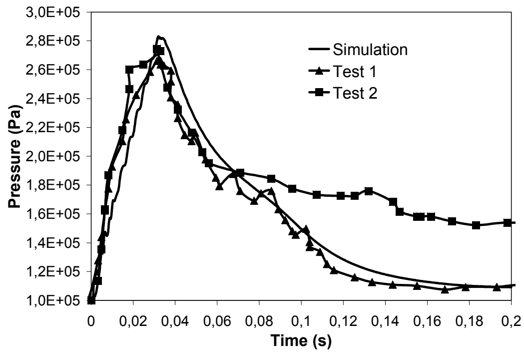

Figure 4: Pressure evolution in the metal enclosure obtained by experiment and simulation.

Figure 5 presents the temporal evolution of the pressure in the buffer area located under the safety valve obtained by simulation and experiments. The valve bursting occurs around $0.03s$ after the arcing fault. The compression peak obtained by simulation and measurements are in good agreement.

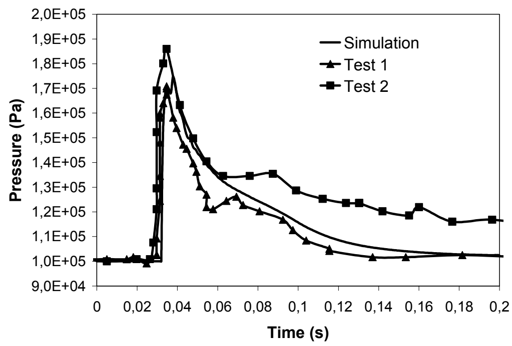

Figure 5: Pressure evolution in the buffer area obtained by experiment and simulation.

5. CONCLUSIONS

We have developed a two-dimensional homogenized model of gas flow in porous medium with porosity variation. We show that during the safety valve bursting a shock wave is generated interacting with the filter, transmitted and reflected waves are produced. The model gives a good agreement between the simulated pressure and the experimental recording of the pressure.

Acknowledgments

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