Two-dimensional modelling of internal arc effects in a enclosed MV cell provided with a protection porous filter

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Abstract. Medium voltage (MV) cells have to respect standards (for example IEC ones [1]) that define security levels against the internal arc fault which is an accidental electrical arc occurring in the apparatus. New protection filters based on porous materials are developed that provide better energy absorption properties and a higher protection level for people. To study the filter behavior during a major electrical accident, a two-dimensional model is proposed. The main point is the use of a dedicated numerical scheme for non conservative hyperbolic problem. We present a numerical simulation of the process during the first 0.2 second where occurs the safety valve bursting and we compare the numerical results with tests carried out in a high power test laboratory on real electrical apparatus.
1. Introduction

Internal arc fault on Medium Voltage (MV) cell has been a focused area [2, 5, 6, 7] where experimental tests have been carried out to set the switchgear in conformity with IEC standards [1]. The MV cell is a compact system 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 [2] is recently used providing 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 simplified geometry of the MV cell is presented in figure 1. The cell is constituted of a metal enclosure sealed by a safety valve containing the busbars and the insulating gas SF6, a buffer area, a protection filter composed of a porous medium to attenuate the internal arc effects and a gas exhaust area.

![Internal arc fault in enclosed MV cell](image)

**Figure 1.** Schematic description of the MV cell.

The arcing fault process can be chronologically summarized as follows:

- An internal arc fault involves the pressure rise in the metal enclosure initially sealed due to the increase of the temperature and the vaporized mass (plastic and metal vapours).
- To avoid the metal enclosure explosion containing the insulating gas, a safety valve located at the bottom of the metal enclosure bursts when the pressure reaches a critical value gauged at $2.8 \times 10^5 \text{ Pa}$. 
• After the valve bursting, the gas releases and a shock wave is generated: the hot gas flow is ejected toward the buffer area then penetrates into the porous filter.

• The porous medium role is to absorb the shock wave generated at the valve opening and to cool the hot gas flow by heat exchange with the grains composing the protection filter. The goal is to obtain a gaseous outflow which is not harmful for the equipment and the people located in the MV cell vicinity.

In order to simulate the process and to enhance the protection technology, several investigations on the arcing fault in MV cell have been carried out [5, 7, 8]. In [8], numerical simulations using a one-dimensional model of the MV cell have been carried out. The major point is the specific numerical schemes employed to take into account the porous discontinuity at the interface of the filter. The authors have shown that the non-conservative term $P\nabla \phi$ has a major impact on the repartition between the transmitted and reflected waves at the filter interface. In the present article, we propose an extension of the model for the two-dimensional situation. To solve correctly the non-conservative contribution, we use a dedicated numerical scheme described in [4] based on a VFRoe solver.

As we highlight in [4], the non-conservative term can not be treated as a simple right hand side term (see also [9]) and specific numerical schemes for non-conservative hyperbolic system are recently the subject of intensive investigations [10, 11, 4]. We have adapted the original numerical scheme of [4] to the MV cell problem to capture and compute the waves generating by the filter interface.

The paper is organized as follows: in section 2, we describe the complete model giving the system of governing equations. A brief description of the numerical method is given in section 3. Section 4 is devoted to the description of the MV cell computational domain and numerical results are presented and compared with experimental tests in sections 5 and 6.

2. Mathematical modelling

To model the internal arc fault in a MV cell equiped with a protection porous filter, we use a unique system of equations valid for the whole domain. The model is based on the compressible gas equations and the key idea is to introduce the porosity $\phi$ as a new variable. In the metal enclosure, the buffer area and the gas exhaust, the porosity variable is assigned to $\phi = 1$ in order to represent a pure gaseous phase. On the contrary, the filter area is characterized by a porosity function with respect to the spatial variables. The two-dimensional governing equations for a gas flow with a variable porosity medium are derived from the Euler equations adding a non-conservative term and augmented by the source terms.

To model the filter interactions, we assume a set of simplifying assumptions:

• The porous medium is an underformable porous matrix.

• The porous medium is composed of spherical particles.
• The brinkman term is neglected.
• The porous medium in the filter is homogeneous of porosity $\phi = 0.5$.
• The permeability $k$ and the Forchheimer coefficient $\beta$ are deduced by the Carman-Kozeny correlations [12].
• The heat transfer coefficient is evaluated by the Wakao and Kaguei correlations [13].
• The porous medium temperature is assumed constant: $T_s = 300 \, K$.

The right hand side member is constituted of three major terms. A first source term is dedicated to the electric arc effect. We introduce a very basic model of the mass and power injection since the measured data in experimental cell only provides a global power injection $E_{\text{inj}} = 10 \, MJ$ and an evaluation of the ablated mass rate $m = 20 \, \mu g.J^{-1}$ in the whole cell. In our simulation, we inject the mass and the energy in a specific area inside the MV cell which roughly represents the arc location and we add the radiation losses using the net emission method [14].

A second class of source term concerns the modelling of the mechanical and thermal interactions. We use the Darcy and Forchheimer laws given in function of the gas characteristics and the geometrical parameters of the porous medium and the thermal exchanges between the hot gas flow and the filter are described by a Newton law where the heat transfer coefficient between phases is evaluated by the Wakao-Kaguei correlations [13].

The last term, named the non conservative term, models the porosity variation effects on the gas dynamic.

The two-dimensional governing 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

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

$$NCT(U) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ P \frac{\partial \phi}{\partial x} \\ P \frac{\partial \phi}{\partial y} \end{pmatrix}, \quad S(U) = \begin{pmatrix} 0 \\ \frac{r_{\text{abl}}}{k} \phi^2 \mu - \phi^3 \beta \rho u |V| \\ -\phi^2 \frac{\mu}{k} v - \phi^3 \beta \rho v |V| \\ P_{\text{inj}} - 2\pi \epsilon_n - h_v(T - T_s) \end{pmatrix},$$
where $U$ represents the vector of the conservative variables, $F(U)$ and $G(U)$ are the flux vectors, $\rho$ is the gas density, $(u, v)$ the velocity components, $P$ the pressure, $\phi$ the 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 $P(\rho, e) = (\gamma - 1)\rho e$ where $\gamma$ denotes the ratio of specific heats and the gas temperature $T$ is obtained by a function $T = T(e)$.

The vector $S(U)$ represents:

(i) the internal arc fault characterized by a mass source term $r_{abl}$ responsible of the pressure rise due to the erosion of the copper busbars and the wall material and a volumic power source term $P_{inj}$ deduced respectively of $m_{abl}$ and $E_{inj}$ and the radiation losses where $\epsilon$ is the net coefficient emission [14].

(ii) the porous medium interaction: the mechanical interaction between the gas and the filter is given by the Darcy force $F_D$ corrected by a non linear term: the Forchheimer force $F_F$:

$$F_D = \phi^3\frac{\mu}{k}u, F_F = -\beta\phi^3\rho u|V|,$$

where $\mu = \mu(T)$ is the gas viscosity and $k$, $\beta$ are geometrical coefficients depending on the porous medium (see Table 1). On the other hand, the thermal interaction between the gas and the solid grains governed by an empirical law [14] which depends on the convective heat transfer coefficient

$$h_v = \frac{6(1 - \phi)}{d_p} \frac{k}{d_p} (2 + 1.1Re^{0.6}Pr^{1/3})$$

with $d_p$ the particle diameter, $Re = \rho \phi |V| d_p / \mu$ and $Pr = \mu c_p / k$ are respectively the Reynolds and Prandtl numbers, $k = k(T)$ is the gas thermal conductivity and $T_s$ is the grain temperature.

At least, the term $NCT(U)$ represents the non conservative term $P \nabla \phi$ taking the porosity jump into account which occurs at the buffer-filter interface and at the filter-exhaust interface.

3. The 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 $\Omega$ 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 $S_j \in \mathcal{T}_h$ and $L_{i,j} = S_j \cap S_i$ 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. For a given side $L_{i,j}$, $\mathbf{n}_{i,j}$ represents the outwards normal of $S_i$ pointing
to $S_j$ and $n_{j,i} = -n_{i,j}$. The sequence $(t^n)_n$ defines a time discretization of $[0,T]$ with $t^{n+1} = t^n + \Delta t$ and $U^n_i$ 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 [15] in the context of the Euler equations:

$$U^{n+1}_i = U^n_i - \frac{\Delta t}{|S_i|} \sum_{j \in \Omega(i)} |L_{i,j}| \mathcal{F}(U_i, U_j, n_{i,j}) + \Delta t S(U^n_i),$$

where $\mathcal{F}$ is the numerical flux crossing the edge $L_{i,j}$ from $S_i$ to $S_j$.

To solve numerically the non conservative problem, we use the method proposed in [4] which is designed specifically for non conservative problems. Particularly, the numerical flux has to be non conservative to take the term $P \nabla \phi$ into account i.e.

$$\mathcal{F}(U_i, U_j, n_{i,j}) \neq \mathcal{F}(U_j, U_i, n_{j,i}).$$

To solve the source terms, we use the Runge-Kutta method, a detailed description of the method can be found in [4] and [8].

4. MV Cell geometry and computational conditions

The computational domain is a MV cell of length $L = 1 \ m$ and height $H = 1.5 \ m$ (see figure 2), the domain is divided into five characteristic areas:

- the metal enclosure of height $H_1 = 0.67 \ m$,
- the safety valve of length $L_2 = 0.05 \ m$ and height $H_2 = 0.03 \ m$ gauged at a critical pressure $P_c = 2.8 \times 10^5 \ Pa$,
- the buffer area of height $H_3 = 0.13 \ m$,
- the porous filter of height $H_4 = 0.2 \ m$ composed of $d_p = 0.025 \ m$ diameter particles,
- the gas exhaust of height $H_5 = 0.47 \ m$.

The domain is discretized into 3406 triangle elements and at the initial time $t = 0 \ s$ the MV cell contains air at atmospheric pressure, ambient temperature and the gas is at rest. All the boundary conditions are reflected conditions excepted at the bottom of the cell where ejection conditions are prescribed [15].

We have realized a simulation of the first 0.2 s of the process, using the physical parameters given in table 1, where we inject the energy and the mass in the domain represented by a square in the metal enclosure as shown in figure 2.
Figure 2. Unstructured Mesh of the MV cell with five characteristic areas.

Table 1. Physical parameters used in the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Air</td>
</tr>
<tr>
<td>Filter length</td>
<td>$H_4 = 0.2 \text{ m}$</td>
</tr>
<tr>
<td>Particle diameter</td>
<td>$d_p = 0.025 \text{ m}$</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\phi = 0.5$</td>
</tr>
<tr>
<td>Permeability</td>
<td>$k = \frac{d_p^2 \phi^3}{180(1 - \phi)^2} = 1.74 \times 10^{-6} \text{ m}^2$</td>
</tr>
<tr>
<td>Forchheimer coefficient</td>
<td>$\beta = \frac{1.8(1 - \phi)}{d_p \phi^3} = 288.0 \text{ m}^{-1}$</td>
</tr>
<tr>
<td>Injected energy</td>
<td>$E_{\text{inj}} = 10 \text{ MJ}$</td>
</tr>
<tr>
<td>Rate of ablated mass</td>
<td>$m = 20 \mu g \cdot J^{-1}$</td>
</tr>
<tr>
<td>Gauged pressure</td>
<td>$P_c = 2.8 \times 10^5 \text{ Pa}$</td>
</tr>
</tbody>
</table>
5. Numerical simulation

Figure 3 shows the pressure distribution in the MV cell just after the safety valve bursts around \( t = 0.035 \text{s} \). The energy and mass sources generate a pressure rise in the metal enclosure initially sealed and when the pressure reaches the critical pressure \( P_c = 2.8 \times 10^5 \text{Pa} \), the valve opens avoiding the mechanical rupture of the metal enclosure. This phenomenon induces a pressure discontinuity between the metal enclosure and the buffer leading to a strong wave propagating toward the filter. The porosity jump characterizing the buffer-filter interface generates the creation of a transmitted wave and a reflected wave which respectively travel in the porous filter and in the buffer area. A peak of compression appears at the interface of the filter under the valve which is an important criterion for the design of the porous filter (see figure 3).

![Pressure distribution in the MV cell just after the valve bursting](image)

**Figure 3.** Pressure distribution in the MV cell just after the valve bursting (\( t = 0.035 \text{s} \)).

Figure 4 represents the temperature distribution in the MV cell after time \( t = 0.2 \text{s} \). Just before the valve opens, the electric arc modeled by the energy and mass injection increases the gas temperature in the metal enclosure. After the valve bursting, the gas flow is ejected across the valve constriction and penetrates in the buffer area where the gas temperature is rapidly homogenized and decreases in the filter: the porous filter drastically cools the gas flow by heat exchange with the grains of the porous medium. On the 3D elevation of the temperature, the porous influence is very remarkable.
Velocity norm in the MV cell just after the safety valve opening is plotted in figure 5. During the depressurization of the metal enclosure, the gas is strongly accelerated in the vicinity of the valve throttling inducing high gas velocity. The gas reaches the filter and the normal velocity turns into a tangential velocity which results in a strong pressure on the porous medium. A part of the gas crosses the filter and the velocity is reduced by the Darcy and Forchheimer forces [16].
Figure 6 represents the pressure at $x = 0.72 \, m$ (corresponding to the valve center) in function of the height $y$. Some few milliseconds before the valve bursting, the pressure is practically homogeneous in the metal enclosure and when the valve opens, a shock wave is generated and interacts with the filter boundary leading to a reflected wave travelling backward while a transmitted wave propagates into the filter. During the transition across the porous discontinuity, several physical quantities must be conserved as mass flow rate, entropy and total enthalpy [10]. These conditions involve a compression peak at the buffer-filter interface which mainly depends on the filter porosity (see [4]) and a gas velocity discontinuity on both sides of the interface.

![Pressure distribution graph](image)

**Figure 6.** Pressure distribution following the $y$-direction at $x = 0.72 \, m$ for the time $t = 0.035 \, s$.

Temperature distribution following the $y$-coordinate at $x = 0.72 \, m$ and $t = 0.2 \, s$ is given in figure 7. During the process the gas temperature in the metal enclosure is not homogeneous unlike the pressure. The important fact deriving from the figure 7 is the gas temperature difference between the buffer and the outlet. Indeed, the gas temperature inlet the buffer is around 4000 $K$ while the outlet gas temperature is roughly 1000 $K$. We note a regular decrease (quasi-linear) of the gas temperature in the filter due to the heat exchange with the porous medium.
Figure 7. Temperature distribution following the $y$-direction at $x = 0.72\ m$ for the time $t = 0.2\ s$.

Figure 8 gives the temperature histories at three characteristic locations of the MV cell: the buffer, the filter and the exhaust during the process ($x = 0.72\ m$ and $y = 0.74\ m$, $y = 0.57\ m$, $y = 0.05\ m$ respectively).

- In the buffer, just after the valve rupture the gas temperature is initially fixed at the ambient temperature 300 $K$. When the valve bursts ($t = 0.035\ s$), the shock wave created at the valve transports the hot gas across the buffer where the temperature reaches 1300 $K$. Then the contact discontinuity wave, which physically represents the boundary between the hot gas and cold gas, occurs and the gas temperature increases during the process.

- At the filter, the shock wave gets to the interface with a delay. After the shock passed, the gas flow is drastically slowed down and the heat transfer is more important because it depends on the Reynolds number.

- At the outlet, we first note the initial shock wave arrives with 0.02 s of delay and has been smoothed. The outflow temperature is around 1000 $K$ which is too high for safety consideration.
Figure 8. Temperature distribution following at x-coordinate $x = 0.72 \, m$ in the buffer (solid line) in the filter middle (dashed line) and at the exhaust (dotted line) during the first $0.2 \, s$ of the process.

6. Comparison with experimental data

Experimental tests have been performed during standardized internal arc fault in a high power test laboratory on real electrical apparatus. A 3-phases arc current of $20 \, kA \, RMS$ is maintained during one second in the metal enclosure filled with air for environmental protection. The device is instrumented with pressure sensors in the metal enclosure and in the buffer. Figure 9 presents the temporal evolution of the pressure in the metal enclosure of the MV cell obtained by simulation and measurements. The experimental results show a good reliability in spite of the phenomenon complexity and we note a good agreement with simulation results. During the arcing fault, the pressure linearly increases in the metal enclosure, initially sealed, for both simulation and experiments and the pressure reaches a maximum corresponding to the critical pressure involving the valve bursting. Next the pressure regularly decreases and after $0.2 \, s$ the pressure is around the atmospheric pressure. In experiment 2, the pressure decrease is different probably due to a more important ablated mass. The arc position was not the same like in the first experimental test.

Figure 10 gives the temporal evolution of the pressure in the buffer area, located under
Figure 9. Pressure evolution in the metal enclosure obtained by two experiments and simulation.

the safety valve, obtained by simulation and two experiments. The valve opens at $t = 0.035 \, s$ after the arcing fault. The pressure suddenly increases and regularly decreases. The pressure reaches a maximum between the metal enclosure and the buffer around $1.8 \times 10^5 \, Pa$ for both the simulation and the two experiments. The difference observed between the experiment tests in the metal enclosure finds back in the buffer area.

Figure 10. Pressure evolution in the buffer area obtained by two experiments and simulation.
7. Conclusion

We have presented a two-dimensional mathematical model of gas flow in variable porous medium completed with a simplified internal arc model in order to simulate an electrical accident in a MV cell. A specific numerical scheme for non conservative Euler system is employed to obtain a numerical solution of the physical magnitudes (pressure, temperature...) in the cell during the time. A numerical simulation using experimental data has been performed and we present the main results about the wave interaction with the filter. Comparison with experimental tests show a good adequation of the model and the numerical method despite the succint arc model. We intend to improve both the model and the numerical method. A more precise model of the arc is crucial to obtain a better prediction of the energy and mass source. From a numerical point of view, a second order scheme using an adapted MUSCL method is required to perform better numerical results. At least, some mesh adaptative technique (we use an unstructured mesh) will give a more precise approximation especially near the valve, the arc area and the filter interface.

References

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