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ELECTROMAGNETIC PLASMA MODELING IN CIRCUIT BREAKER WITHIN THE FINITE VOLUME METHOD

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Abstract. In order to ensure the galvanic isolation of an electrical system following a manual operation or a default strike, current limitation properties of the electric arc are used, forcing a fast decrease to zero current. Modeling this process reveals complex, since it involves a large amount of physical phenomena (radiation, phase transitions, electromagnetism, fluid dynamics, plasma physics). In order to get a robust solving, enhancing strongly coupled resolution and time constants compatibility, the Finite Volume Method has been chosen. This method was first implemented on intrinsic electromagnetism problems (current flow, magnetostatics including non-linear materials, and magnetodynamics). Once validated, the models have been successfully used in the Schneider's current-interruption dedicated software, thus allowing a significantly improved simulation of Schneider Electric circuit breakers.

1 INTRODUCTION

Various multiphysic modeling, and more particularly the arc interruption modeling, requires fluid dynamics and electromagnetic models [1]. Whereas conventional Finite Volume Method (FVM) usually dedicated to Computational Fluid Dynamics enforces the local conservation of mass, momentum and energy [2], low-frequency electromagnetic software minimizes global energy functionals within the Finite Elements Method (FEM) [3]. Hence, magnetohydrodynamics problems are currently resolved by using either:

- a FE-CFD code, which is not suitable for circuit breaker applications because the method is unable to model the shock waves during the interruption process; or
- an hybrid method combining a FVM and a FEM, thereby sacrificing the high level of integration and the accuracy achieved with a single mesh [4].

Thus, the search for a common, effective and integrated model and important hydrodynamic constraints call for a single numerical method for the two phenomena. In this work, an electromagnetic model based on the FVM is adopted.

2 ELECTROMAGNETISM WITHIN FINITE VOLUME METHOD

2.1 Finite Volume Method (FVM)

The Finite Volume Method is based on the local conservation (Fig. 1). Expressing the balance in any elementary volume between the dissipative term (RHS) and the variation over time and the flux exchanged at its boundary (LHS), it reads:

$$\underbrace{\frac{\partial \gamma}{\partial t}}_{\substack{\text{Triansent}\\\text{term}}} + \underbrace{\operatorname{div}\left(-k\,\mathbf{grad}\,\gamma + \mathbf{v}\gamma\right)}_{\substack{\text{diffusive and convective flux}\\\text{term}}} = \underbrace{S}_{\substack{\text{source}\\\text{term}}} \tag{1}$$

where γ denotes the transported physical quantity, k is the diffusion coefficient of the transported quantity and $\mathbf{v}$ its velocity.

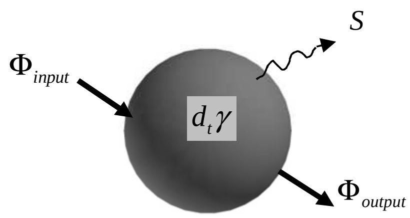

Figure 1: Local balance of the flow Φ: $d_t\gamma$ is the local variation and S denotes the source term.

In FEM the unknowns are associated to the nodes or edges of the mesh and the integral approximation is made by an approximation of the solution. In contrast, the unknowns are on the cell-centroid and the integral approximation is made by an operator approximation in FVM. Hence, the diffusive flux D_f, across a face f of a scalar V is given by:

$$D_f = \iiint_\Omega \operatorname{div}\left(-k\,\mathbf{grad}\,V\right)\mathrm{d}\Omega = \underbrace{-k\frac{V_1 - V_0}{ds}\frac{\mathbf{A}\cdot\mathbf{A}}{\mathbf{A}\cdot\mathbf{es}}}_{\text{Primary flux (implicit term)}} + \underbrace{k\,\mathbf{grad}\,V\cdot\left(\mathbf{A} - \mathbf{es}\frac{\mathbf{A}\cdot\mathbf{A}}{\mathbf{A}\cdot\mathbf{es}}\right)}_{\text{Secondary flux (explicit term)}} \tag{2}$$

where k is the diffusion coefficient at the face, V_0 and V_1 the scalar value in the cell c_0 and c_1, **A** the area normal vector of face directed from cell c_0 to c_1, ds the distance between the cell centroids, and **es** the unit normal vector in this direction.

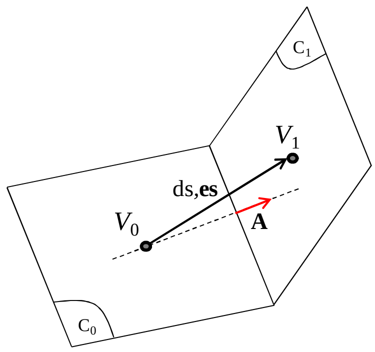

Figure 2: Diffusive flux approximation for non-orthogonal meshes

While the first term of D_f on the right hand side represents the primary gradient directed along the vector **es**, the second term represents the cross diffusion term directed along the vector $\mathbf{es}^{\perp}$. Notice that the former is an implicit term whereas the latter is explicit and allows correcting fluxes for non-orthogonal meshes (Fig. 2).

The previous description was adapted successfully to solve linear magnetostatic problem within the so-called $\mathbf{T}_0$-ϕ formulation [5]. This formulation is known to require a lower number of degree of freedom than the magnetic potential vector formulation [6]. Unfortunately, no extension to non-linear case was given, preventing to compute the inclusion of the electric arc in the splitter plates. In order to make feasible the whole arc inerruption process – including its vanishing by the inclusion in the splitter plates –, a specific formulation should be developed to take non-linear magnetostatic properties into account.

2.2 Non linear Magnetostatics (3D)

Within the 3D magnetostatic $\mathbf{T}_0$-ϕ formulation, the magnetic field reads $\mathbf{H} = \mathbf{T}_0 - \mathbf{grad}\phi$. Hence, the magnetic flux density divergence-free is expressed as a diffusion equation with a source term resulting from the field $\mathbf{T}_0$ obtained in vacuum:

$$\underbrace{\mathrm{div}(-\mu_r \nabla\phi)}_{\substack{\text{diffusive}\\ \text{term}}} = \underbrace{\mathrm{div}(-\mu_r \mathbf{T}_0)}_{\substack{\text{source}\\ \text{term}}} \tag{4}$$

where μ_r is the non-linear magnetic permeability. Notice that $-\mathbf{grad}\phi$ is nothing but the demagnetizing field if $\mathbf{T}_0$ is given by the Biot and Savart's law.

Among the various choices to describe the non-linearity [7], a two-parameter $\tan^{-1}$ law is used to fit the anhysteretic curve. After an initial magnetostatic resolution in vacuum to compute $\mathbf{T}_0$ and the set-up of the relative magnetic permeability μ_r – typically the half-value of the relative magnetic permeability at the origin μ_{r_init} –, the computation is performed iteratively thanks to an update of μ_r. To avoid the oscillation around the solution, an over-relaxation on μ_r is used. The inspection of the flux density conservation provides a criterion to check the convergence (Fig. 3).

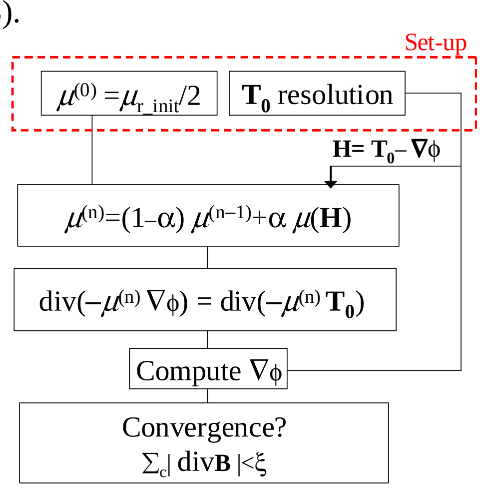

Figure 3: Flow chart algorithm for the resolution of a non-linear magnetostatic problem.

The previous developments are used in a 2D case where two steady and opposite currents flow in circular conductors to magnetize a non-linear ferromagnetic plate (Fig. 4).

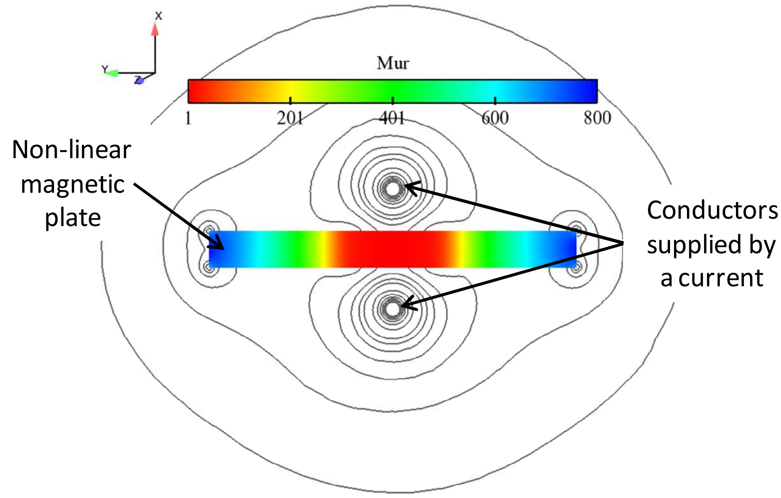

Figure 4: Refraction of the H-lines around a non-linear ferromagnetic plate magnetized by two conductors supplied by opposite currents: The level of saturation of the plate may be followed by the permeability value μ_r.

The saturation is observed qualitatively and the numerical comparison with finite element computations – achieved with Flux2D® software – show that the relative error in energy deviates less than 5% (Fig. 5). Hence, the extension of the **T**-ϕ formulation in 3D is quite straightforward [8].

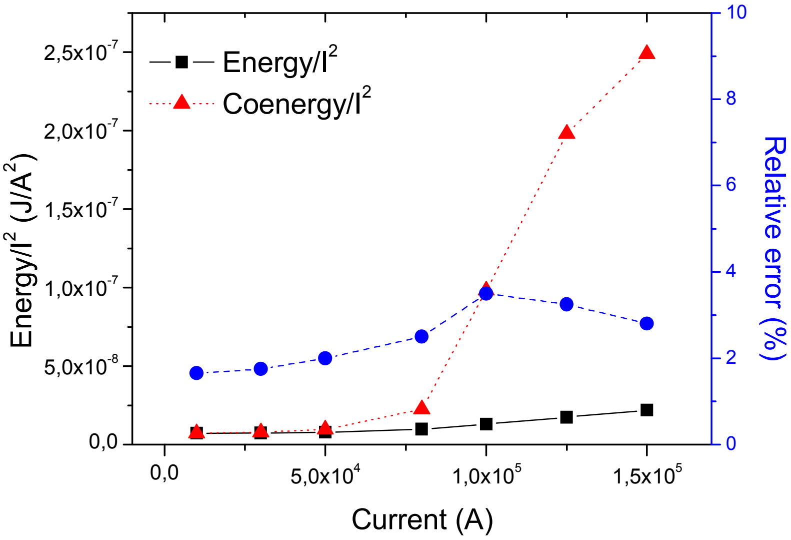

Figure 5: Energy and co-energy curves reduced by squared current (left) and the maximum relative error computed with FEM (right) vs. supplied current.

3 CIRCUIT BREAKER MODELING

In the interruption process, the magneto-dynamic effects (eddy currents) can be neglected both in feeders and splitter plates (often called arc chutes) [9]. Therefore it is possible to model the process within the previous FV electromagnetic developments.

3.1 The framework of the resolution procedure

The resolution procedure follows the chart represented in Fig.6 where one iteration is represented. The previous formulation was implemented within the plasma physics-dedicated Schneider Electric software. This code already included:

- a real gas model,
- a radiation model,
- a table of electrical properties,
- an arc root model.

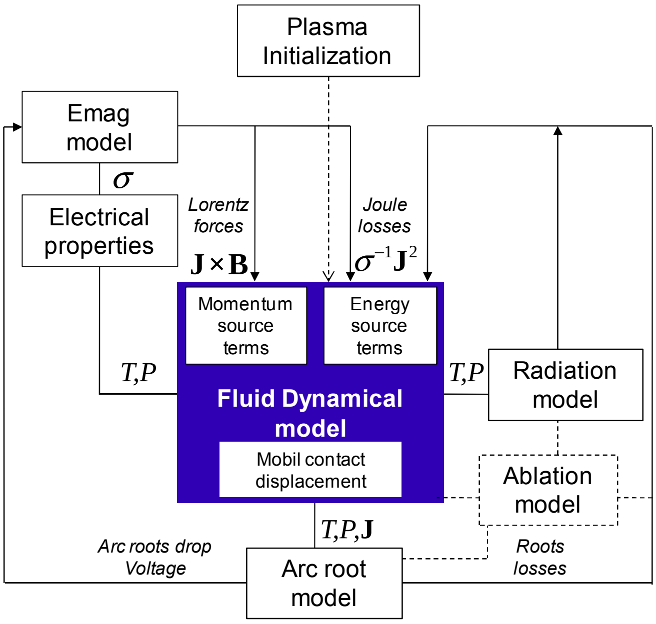

Figure 6: Resolution procedure chart for the interruption process modeling (T is the temperature, P the pressure, and σ denotes the electrical conductivity).

All the models (real gas, radiation, root model and electromagnetism) are driven by the fluid dynamical based core [10]. These models are the inputs of source terms in energy and momentum. In the case of electromagnetism, the Lorentz forces and the Joule losses are introduced in fluid dynamical solver (Fig. 5).

This resolution code is achieved within the CFD Fluent® code thanks to the explicit solver, which use a Gauss-Seidel method with a multi-grid resolution.

2.2 Circuit breaker modeling

The Fig. 7 shows a LV arc chamber currently designed in Schneider Electric. After modeling of the whole interruption process occurring therein thanks to the non-linear developments derived above, comparison with experiments is provided in Fig. 8. Agreement is quite encouraging on both current and voltage drop.

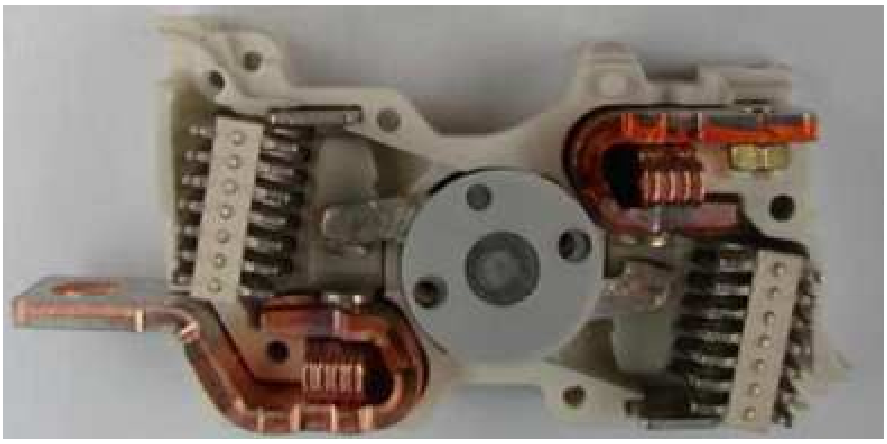

Figure 7: Typical circuit breaker arc chamber: While two electric arcs are initiated by the rotation of the moving conductor (center), their displacement towards the splitter plates (right and left) is enhanced both by the loop effect (provided by the feeders shape) and the switching reluctance effect (provided by the ferromagnetic parts).

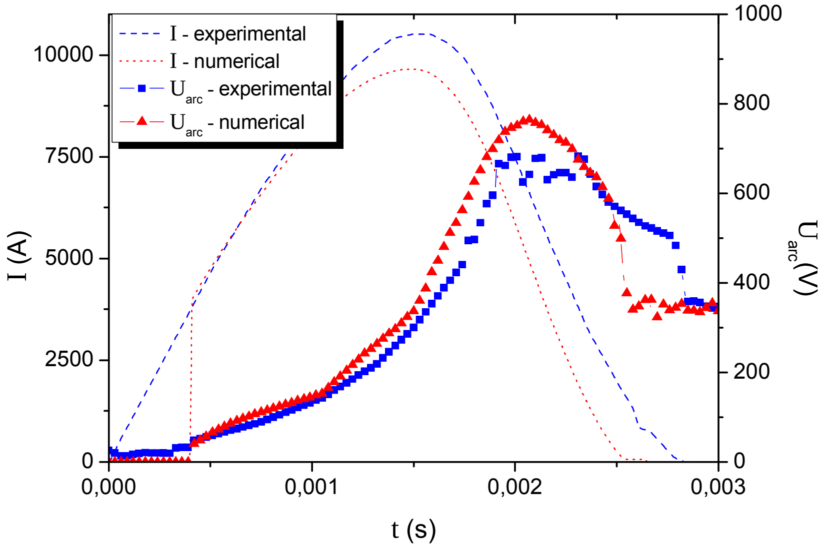

Figure 8: Comparison of numerical and experimental results on current and voltage drop during an interruption process.

Hence, further investigations on local behaviors occurring during the interruption process could be considered to enhance the arc chamber design. This kind of investigation was performed on an experimental mock-up, composed of two feeders, three ferromagnetic splitters plates, and a far pressure outlet (Fig. 9). The mesh has 400,000 cells and the unknown solving are (ρ,$\mathbf{v}$,H,V,$\mathbf{T}_0$,ϕ), respectively density, velocity, Gibbs' energy, electrical potential, field in the vacuum and magnetic scalar potential. The computational time for an arc interruption process modeling is about 3 weeks on Pentium Xeon single core 2 GHz -2Gb RAM, each time step running for 10ns.

The Fig. 9 also provides three iso-values of the current density during the whole arc interruption process, and especially when the arc is getting into the ferromagnetic splitter plates (also called arc chutes). As a result, the saturation of the splitter plates is effective during the breaking process, showing that a non-linear treatment of the field is required to avoid an over-estimation of the driving force acting on the electric arc [6].

Furthermore, such investigations are necessary to enhance current limitation and subsequently thermal and electrodynamical damages of the electrical installation.

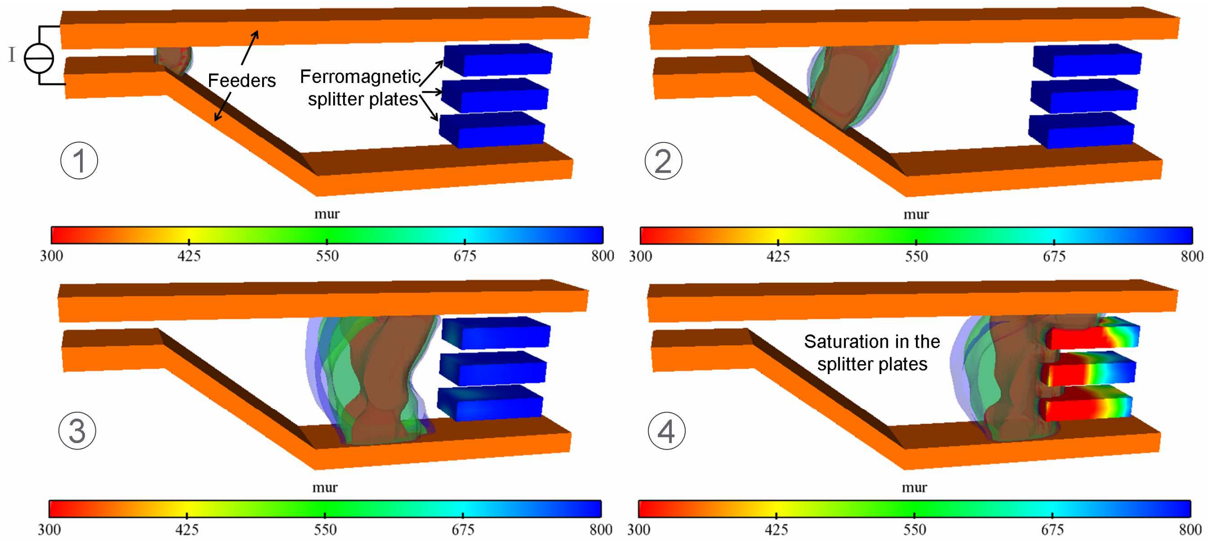

Figure 9: Modeling of the arc interruption process: While the electric arc is displayed with three iso-values of the current density ($1.5{\cdot}10^7$; $8.0{\cdot}10^6$; $5{\cdot}10^6$ $A{\cdot}m^{-2}$), the saturation of the splitter plates is effective and represented with the relative magnetic permeability μ_r.

CONCLUSION

Within sight of the results obtained thanks to non-linear magnetostatic developments, the Finite Volume Method seems suitable to model efficiently electromagnetism. This method does not have any ambition to compete with Finite Element Method but simply to allow a stronger coupling between the fluid dynamical and electromagnetism in the specific case of arc interruption. These electromagnetic developments allow already modeling the interruption process with ferromagnetic materials. The comparison with the experimental data is not easy but is under progress. Nevertheless, although non-linear ferromagnetic material modeling is already efficient, CPU-time remains too huge to be used for the modeling of the whole arc interruption process at a design center level. Subsequent improvements and productivity in the design of arc interruption products (Medium- and Low-Voltage circuit-breaker) are expected.

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