Coupled Simulations of Electric Arcs for Switching Devices with MpCCI and ANSYS

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1 Introduction

Electric arcs occur in various industrial applications from melting, welding, and lighting to switching devices. The discharge phenomenon is governed by the magneto-hydrodynamic (MHD) equations, considering the Lorentz forces, Ohmic heating and radiation transport. The resulting arc is coupled with the dynamics of the compressible flow of the gas. In order to model this phenomenon, we employ the multiphysics framework MpCCI CouplingEnvironment to subdivide the complex problem in a fluid flow model solved with ANSYS Fluent and in an electromagnetic model solved with ANSYS EMAG. In the scope of this work, the MpCCI ArcLib has been developed in order to provide the capability to model electric arcs using a unique coupling scheme adapted to switching device simulation.

2 Simulation Model and Co-Simulation Procedure

In this work we have considered a switching device based on two blocks: a contact block filled with a gas and an electromagnetic block which is controlling the contact block state ON/OFF. The simulation will focus on the breaking stage of the switching device.

2.1 Magneto-Hydrodynamics Models for Electric Arcs

Simulations of electrical arcs are challenging for a number of reasons. The physical model has to consider a very hot and highly compressible gas flow, which has to be simulated using real gas properties to account for the dissociation of the gas at high temperatures and other changes in its chemical composition.
This work applies the standard approximations for arc modelling used in industry. The material properties, such as electric conductivity, thermal conductivity, viscosity, density, etc., are computed using the LTE approximation, i.e. assumed local thermal equilibrium in each cell. This means that all the thermodynamic and transport properties only depend on the pressure and the temperature and can be computed in advance. When mixtures are involved, such as the mixture of gas and metal vapour, the quantities depend on pressure, temperature, and a concentration, e.g. the density is given by $\rho=\rho(p,T,C)$, where C is the mass ratio of metal vapour, p is the pressure and T is the temperature. LTE properties of standard gases are available in the literature [1] and from various research groups like Brno University of Technology, Czech Republic.

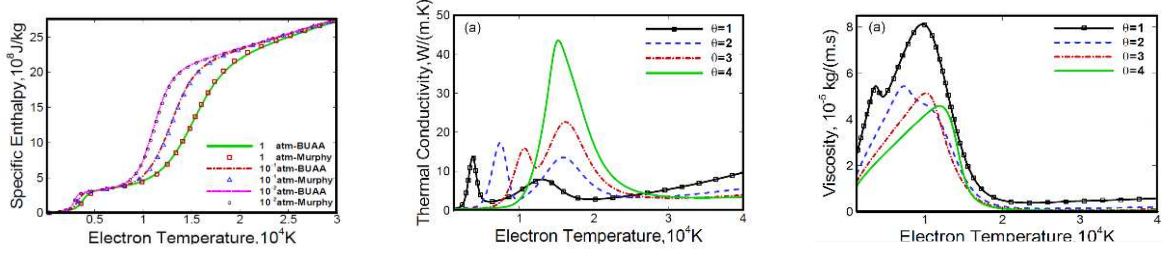

Fig. 1 Hydrogen material properties for Specific Enthalpy, Thermal Conductivity, Viscosity at $T=10^4$K for different pressure values

The heat transfer by radiation plays an important role in an absorbing medium in order to obtain the correct arc shape. Due to the very high temperatures, radiation is the main mechanism of heat transfer inside and outside the arc. The radiation is modelled using the standard models implemented in flow solver, e.g. the P1-model or the discrete ordinate model (DOM). The challenge here is to find and to implement the correct absorption coefficients. The frequency dependence of the absorption spectrum can be taken into account using a multi-band model [2]. For technical reasons, one is limited to a multi-band model with a fairly small number of absorption bands.

We use the magnetostatic approximation for the electromagnetic fields, meaning that the magnetic field has no history and can be computed directly from the momentary value of the current distribution.
The interaction of the arc with the electrodes (arc roots) is implemented as sources for mass and energy, where the mass current is proportional to the current density. This allows to consider the production and transport of metal vapour.

2.2 Moving Contact Models

The modelling of the movable contact has been considered in the CFD model as well as in the EMAG model. ANSYS Fluent provides several methods to model the movement of the movable contact based on the "Dynamic Mesh Option". Different options to manipulate the mesh can be combined: layering method, remeshing method, morphing and zone replacement for example. On the ANSYS Emag side a spring based morphing in combination with remeshing is used for the movable contact. In each simulation code the choice of the moving contact model has been motivated by the capability of conserving a constant minimum cell quality over the simulation time and minimizing the computational cost. For the switching device the selected method is focused on the morphing and remeshing method based on predefined meshes for different contact position. The contact velocity model has been implemented in ANSYS Fluent based on a rigid body motion using a predefined velocity profile closed to the measurement data.

2.3 Co-Simulation Procedure

MpCCI CouplingEnvironment is used to couple the quantities from a transient ANSYS Fluent fluid flow simulation with a steady state ANSYS Emag simulation according to the assumption in section 2.1.
The co-simulation scheme in Fig. 2 is based on a sequential communication with a data exchange on demand based on the electrical conductivity criteria computed in ANSYS Fluent. ANSYS Fluent will perform some subcycling time steps with a possible adaptive time step size (dt_f) until the relative change in the electrical conductivity ($\Delta\sigma$) satisfies the defined criteria value ($\Delta\sigma_{limit}$) in order to request an update of the Lorentz force (F_L), Joule heat field quantities, arc voltage (U_{arc}), arc current (I_{arc}), etc.

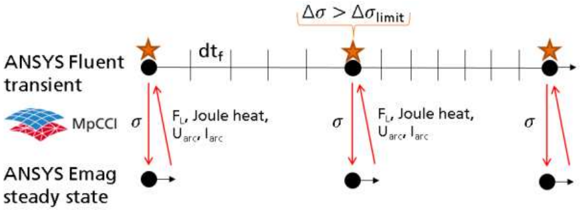

Fig. 2 Co-Simulation scheme

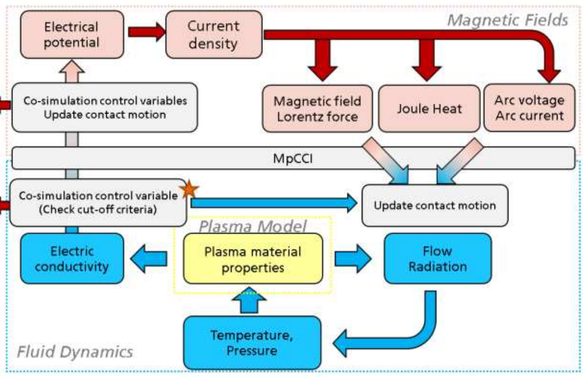

Fig. 3 Data exchange details

The quantities Joule heat, Lorentz force, magnetic field, arc voltage and current are transferred from the ANSYS Emag solution to the ANSYS Fluent simulation as source and momentum terms. After having updated the flow properties, the plasma material properties are updated according to the governing temperature and pressure values. In Fig. 3, additional control variables have been introduced to model the switch off phase, like the evaluation of the electric conductivity to trigger a data exchange or to stop the simulation if the cut-off happens. The contact displacement is provided to ANSYS Emag in order to synchronize the position of the movable contact.

3 Simulation Results

The computational model was run using the parallel capability of each simulation code (16 cores) and each simulation case took around two days to provide the results on an Intel Xeon E5-2660. During the development of different physical models, some parameter variations studies have been executed in order to validate each single model like the metal vapour model and understand the interaction with other models such as the radiation model. Fig. 5 shows a simple setup to quickly test some physical models. The simple case consists of two parallel contacts and the arc is initialized in the middle of the arc chamber. Some work has been done to calibrate the physical model in order to agree with the experimental data.

The simulation validation is based on the measurement of the cut-off time. In Fig. 4 we can observe the history of the arc voltage during the simulation of the opening contact. The cut-off time provided by the simulation provides an acceptable agreement with the measurement.

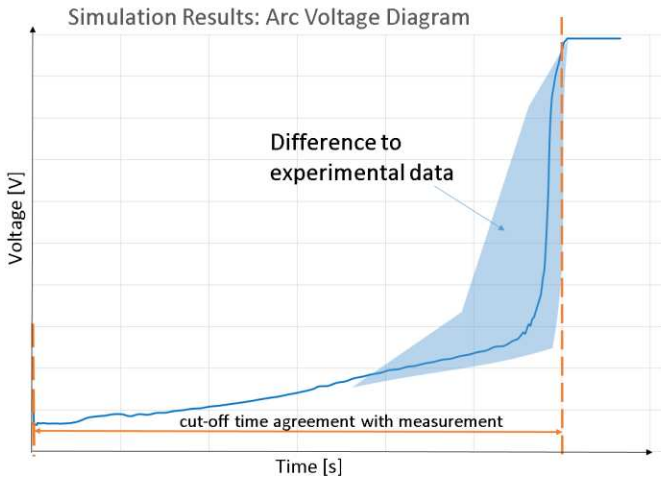

Fig. 4 Arc voltage over the time

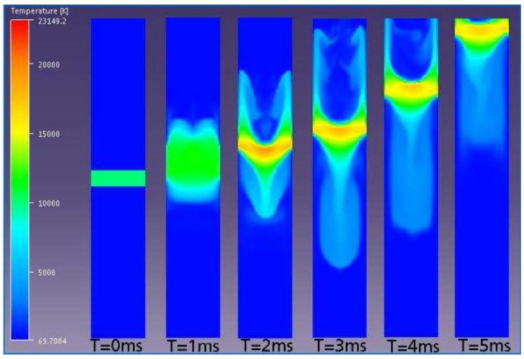

Fig. 5 Test case with parallel contacts

4 Conclusions and Outlook

Switching arcs can be modeled using ANSYS Emag to solve the magnetic field problem and ANSYS Fluent to solve the fluid dynamics problem – coupled in volume through MpCCI CouplingEnvironment [3]. Based on MHD equations, a 3D model for a switching arc considering Lorentz forces, Ohmic heating and radiation transport can be developed using a co-simulation approach. In addition to the co-simulation solution which allows to subdivide a complex problem in smaller problems, the challenge still remains in modelling the plasma. The modelling of the electric arc behaviour is governed by different stages, e.g. the arc motion, the arc elongation, the arc commutation and arc cutting process. The inclusion of all these phenomena in the analysis requires the consideration of additional models like the arc root, the material erosion, etc.

The resulting physical and material models for electric arcs provide methods and references for the optimization work of switching devices and have been integrated in MpCCI ArcLib as an add-on for MpCCI CouplingEnvironment. The tool includes the standard approximations for arc modelling used in industry like:

- Material properties computed in the LTE approximation
- Enhancement of standard radiation model implemented in flow solver
- Interaction of the arc with the electrodes

5 References

[1] Shi-Qjang Chen, Hai-Xing Wang, E.Y. Choueri: "Two-Temperature Thermodynamic and Transport Properties of Hydrogen Plasmas", IEPC-2011-152, 2011

[2] Nordborg, H.; Iordanidis, A. A. (2008): Self-consistent radiation based modelling of electric arcs: I. Efficient radiation approximations. In J. Phys. D: Appl. Phys. 41 (13), p. 135205. DOI: 10.1088/0022-3727/41/13/135205.

[3] Christian Rümpler: "Low-voltage circuit breaker arc interruption – multi-physics modeling challenge", Proceedings of NAFEMS UK Conference (Oxford), 2014