Arc Simulation in Low Voltage Switching Devices, a Case Study

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Arc simulations are becoming a valuable tool in the development of low voltage switching devices. Simulations reveal physical quantities that are experimentally not accessible and help in the investigation of the underlying phenomena. However, the strong interaction between different processes and the intrinsic multi-scale nature of the problem, both in time and space, pose great challenges to accurate and efficient simulations. At ABB Corporate Research, we developed a simulation tool capable of simulating the behavior of low voltage switchgear. To verify the accuracy and predictive capability of our platform, we validate the simulations by comparing their results with available experimental findings. After describing the tool, we provide here evidence of the good agreement between measured and simulated data on several commercial ABB devices.

Keywords: Arc, simulation, multiphysics, air switching

1 INTRODUCTION

The LVArcSim tool is a simulation suite developed at ABB Corporate Research with the aim to model the behavior of electric arcs in air based low voltage switchgear. The tool includes physical models of all relevant phenomena, which have to be considered to describe a switching operation accurately. From the simulation results, information about the functioning of the device can be extracted. This level of insight cannot be attained through the standard measurements performed during short-circuit tests, thus providing a powerful tool to understand the cause of possible problems and to generate ideas for improvements. Moreover, once the experimental behavior of a device has been correctly reproduced with the simulation tool, the latter can be used to evaluate the impact of design modifications. For example, some design alternatives could be ruled out, without the need to realize prototypes and carry out experiments. This renders the LVArcSim tool an extremely useful instrument for product improvements and reduction of development time. On the long term, the improvement of the prediction accuracy of the tool, i.e. the capability to provide reliable results with lower and lower need for experimental tests, and the reduction of computational times would allow to carry out design optimizations via numerical methods instead of time consuming and expensive experiments.

In this paper, we evaluate the effectiveness and

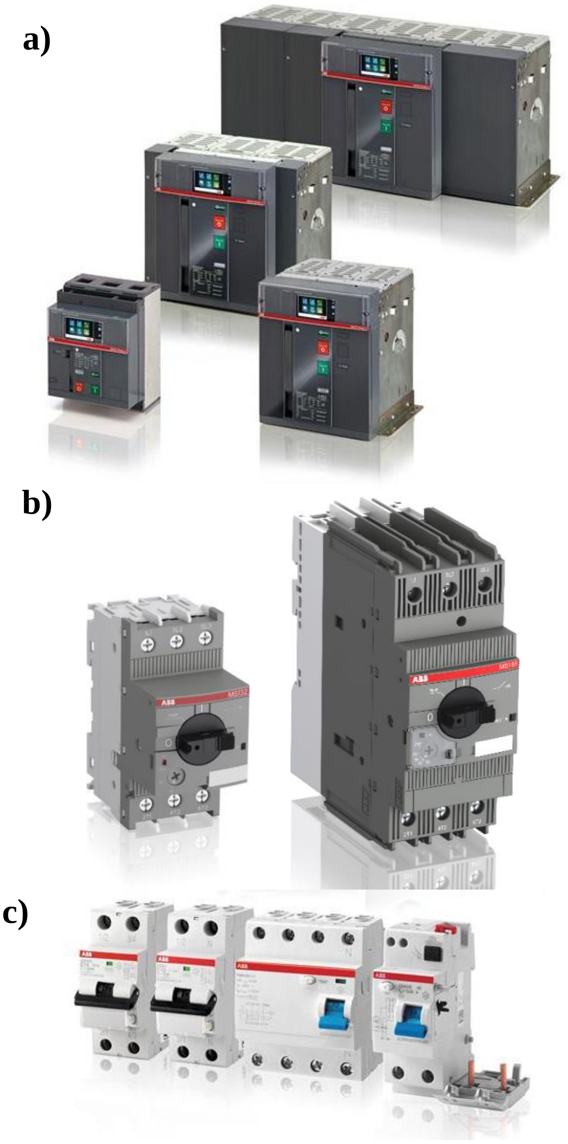

Fig.1: *Images of the simulated products. a) air circuit breakers, b) manual motor starters and c) residual current circuit breakers*

usability of the LVArcSim tool for product improvement/development, considering three diverse products in the ABB portfolio for which we compared the simulation results with available experimental tests. In particular, we chose an air circuit breaker (ACB), a manual motor starter (MMS) and a residual current circuit breaker (RCBO), as shown in Fig.1.

In the following, we describe the tool in section 2, section 3 shows a typical workflow when using the tool, while section 4 compares the obtained results from the simulations with experimental data.

2 THE COMPUTATIONAL TOOL

In the LVArcSim tool, the electric arc is treated using the magneto hydrodynamic (MHD) approach [1] [2], where the dynamics of electrically conductive fluids are represented combining the Reynolds-averaged Navier-Stokes (for the fluid part) and Maxwell (for the electromagnetic part) equations. In addition, equations for the radiative heat transfer are computed, since one of the dominant energy redistribution processes inside the arc is due to electromagnetic radiation [3]. The implemented approach using photo-hydrodynamic radiation equations is presented in more detail in [4]. Plasma properties are accounted for by the means of pre computed real gas tables such as enthalpy, density or electrical conductivity as functions of the local temperature, pressure, and composition [5] [6]. The complexity of the radiative properties is strongly reduced, leading to an efficient and still accurate model [7]. The local thermodynamic equilibrium (LTE) is assumed to hold everywhere in the plasma and a possible presence of space charges is neglected. The system of equations is closed with a set of appropriate boundary conditions, where particular care is taken in the modelling of ablating polymeric walls and eroding metallic surfaces [4] [8] [9] [10]. The motion of contacts inside the computational domain and the external network providing a current to the device are taken into account in our model with suitable differential equations. Deformations due to erosion or fusion of solid parts can however not be simulated with the described tool in the current state of development. The equations are simplified to enable faster computations. In particular, the solution of the fluid dynamic field distributions is only weakly coupled to the electromagnetic computations. The transient flow equations are solved in a first step using the commercial finite volume solver Fluent [11], where the electromagnetic contributions such as the Ohmic heating or Lorentz force are accounted for as external sources. The resulting electrical conductivity distribution is exported to an ABB in-house developed electromagnetic finite elements solver, which neglects transient electromagnetic effects such as eddy currents [12]. The solution of the electrostatic and magnetostatic problem (taking into account the magnetic saturation of ferromagnetic materials, resulting in a nonlinear BH curve) is then fed back to the flow simulation.

Three different species are modelled in the plasma: air, metal, and polymers. Their mixing is taken into account using real gas state equations; turbulence is treated with a k-ε model. The main energy source for erosion are the arc-roots, while the amount of eroded material is given by the vapor pressure curve. Presently, copper and silver are implemented and experimentally validated. A condensation model for the metallic plasma is also present. The ablation of polymeric walls is described by a simple, phenomenological model. Here, hydrogen atoms (or alternatively methylene groups, CH2) are detached from the polymeric chains due to the heat input from the arc and are responsible for the pressure build up in front of the isolating walls. A recent overview of related simulation tools can be found in [13].

3 WORKFLOW

The deployment of the tool to simulate a device for which a computer-aided design (CAD) geometry is available is usually performed along these lines:

1) Device and test condition selection
2) Simplification of the CAD geometry
3) Mesh generation
4) Definition of simulation parameters (network, model and materials)
5) Simulation running
6) Post processing and analysis

7) Iteration of the above, modifying the geometry, network or parameters

Simplifying the device geometry has two main goals: removing small features and tolerances to enable the generation of a mesh with a sensible amount of elements, and the definition of the plasma region.

From a simplified geometry comprising a set of non-overlapping bodies, we generate a mesh of finite volumes. We typically model 750’000-1’500’000 elements (depending on the size and features of the device). The employed tools are parametric, enabling to quickly generate a new mesh from small changes in the geometry.

Based on the chosen test conditions, the main setting file has to be chosen. The main user parameters describe the external network (voltage, currents, power factors, inductances …), the ignition conditions (time, position …) and the mechanics of the contact (rotation axis or translation direction, external forces, springs …). Additionally, some material parameters (mainly describing the interaction strength with the plasma and the main properties of the employed materials) should be fine-tuned.

Setting up the case and running a simulation is then straightforward. A workstation (i.e. 2 Intel Xeon E5-2667 v2 CPU’s with 64 Gb of memory and 16 cores) running Linux is used to avoid excessive computational time. On the mentioned workstation and a typical 750’000 element mesh 1ms of simulated time takes approximately 4 hours of machine time. This time is also subject to how fast the transients of the voltage across the device are, since the LVArcSim tool adapts the simulation time step (typically between 1 and 10 microseconds) in order to capture accurately quick changes (like back-ignitions) and keep the simulation stable. For a mesh with 1,200,000 elements and frequent back-ignitions, the simulation time is about 12 hours of machine time per ms (i.e. about 5 days for 10ms of simulation).

The simulation provides as output a diverse set of data composed mainly by:

1) Total arc voltage and current versus time
2) The position and forces acting on the mobile parts versus time
3) The total amount of eroded and ablated mass for each named surface versus time
4) At a preselected series of snapshot times, all local 3D fluid related variables such as pressure, temperature, composition, flow velocity, radiative power, …
5) At a preselected series of snapshot times, all local 3D electromagnetic variables such as current density, arc-root voltages, electric fields, magnetic fields, Lorentz forces, …

The described workflow is then iterated by modifying any part of interest such as the geometry, refining the mesh, changing short circuit prospective current, the contact force, opening additional outlets, or refining some material parameters, until satisfactory results with respect to the intended goal have been obtained.

4 RESULTS

Fig.*2* depicts the measured voltages and currents during short circuit tests of three selected devices from Fig.1 (1600A ACB, 65A MMS and 32A RCBO). We tested several samples of each device resulting in slightly different current and voltage characteristics reflecting the sample variability. The simulated values are shown in red on top of the measured traces.

The simulations start when the contacts separate, i.e. when the electric arc is ignited. The tool correctly predicts the initial arc voltage build-up, mainly due to the contact separation speed and the arc elongation. At a later stage, the arc moves towards a set of steel splitter plates building up a higher voltage and displaying a characteristic short voltage plateau before building up the maximal voltage. In some devices, the voltage is high enough to limit the current. Sudden voltage drops can be observed in the experimental traces and in the simulation results, characteristic for back ignitions.

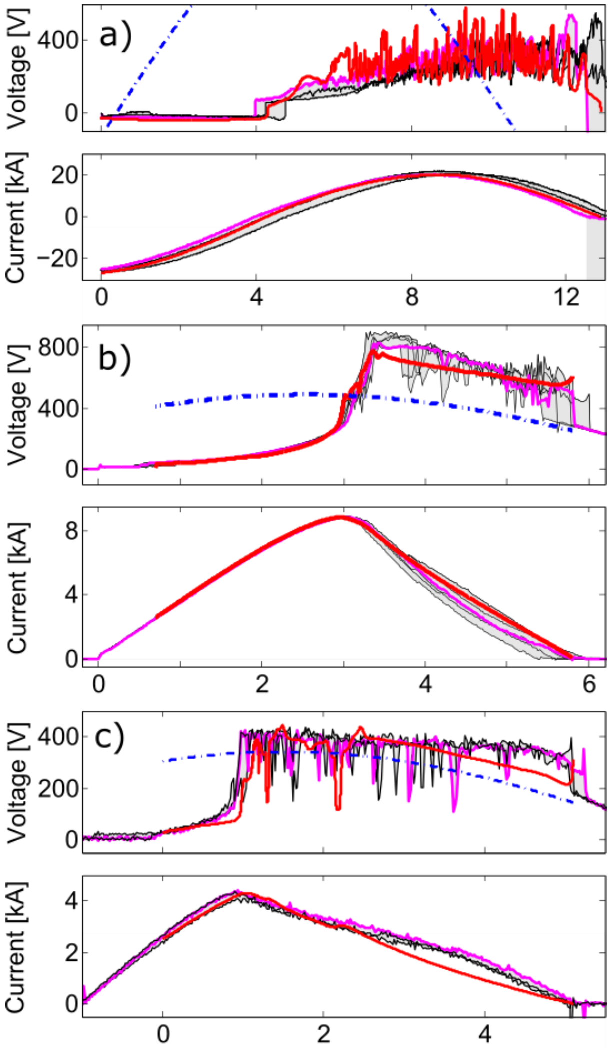

Fig.2: *Measured and simulated characteristics of the considered devices: a) 1600A ACB, b) 65A MMS and c) 32A RCBO. In black, we depict the maximum and minimum voltage and current measured on three different samples versus time in [ms]. The magenta line depicts an exemplary measurement, while the red trace depicts the simulated values and in blue, we show the simulated generator voltage.*

Finally, as the current is approaching a zero crossing the arc is extinguished. The deviations between observed and simulated current of the RCBO is probably due to the non ideality of the employed generator under short circuit conditions.

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