Interactions in low–voltage switchgear — a staggered simulation approach

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Abstract

This paper describes the approach for simulating various levels of multidisciplinary interactions in low-voltage electromechanical switching devices. One example of those switching devices are circuit breakers – the watchdogs in the electrical energy distribution network between the power plants and the end users. They monitor if the current stays within prescribed limits and interrupt the current autonomously within a few milliseconds once they detect a fault current. Examples for interactions are presented for the calculation of short-circuit currents, for the temperature rise of conductors and for the motion and voltage of the electric arc that occurs every time a current is switched off.
The methods used are:

- Lumped network models of the components of the circuit breaker for the calculation of the short-circuit current. In this model results of previous finite-element calculations are fed into the simulation model as two–dimensional tables.
- Sequential coupling of finite-element codes where the result of one calculation is used as load for the subsequent simulation with negligible retro-action.
- Tight coupling of magnetic field and fluid dynamic simulations that run simultaneously and share data whenever the results show that it is necessary.

Comparisons with measurements prove that these models with adapted levels of simulation complexity yield good results.

Keywords: switchgear; simulation; electric arc; code coupling

1 INTRODUCTION

Electromechanical switching devices such as circuit breakers and contactors are a good example for multidisciplinary interactions. Their design consists of mechanical parts that move under the influence of magnetic fields which are generated by electrical currents. Those currents also generate Joule heat that on one hand has to be dissipated to the environment and on the other hand is used for measuring purposes in circuit breakers with thermal bimetallic overload protection.
The increasing performance of computers and the large number of simulation tools available makes it more feasible to use numerical calculations during the development process.
A complete simulation of the behavior of a circuit breaker – from the electromagnetic forces on the instantaneous short-circuit release and the movable contact, the mechanical motion of these parts, the modeling of the complex arc movement in the arcing chamber up to the splitting of the arc in the deion plates and its extinction – is generally possible but can not reasonably be performed within one software application.
Thus the simulation task is separated into different levels of detail, as shown by a large number of publications by numerous authors as cited previously by the authors ([1] and [2]). This article emphasises the numerical procedure for typical tasks in the development process of electrical switching devices. They are characterized by different levels of complexity.

2 COUPLING OF ELECTRICAL SYSTEM SIMULATION WITH FEM

When a short-circuit happens a current-limiting circuit breaker has to detect that condition quickly and open its movable contacts within a few milliseconds in order to interrupt the current before it reaches its peak value. For the simulation of that process results of finite-element calculations of the forces on movable contacts are coupled with an electro-mechanical system simulator [3].
Since finite-element calculations typically take much longer than the system simulations the finite-element calculations are performed beforehand. The forces on the movable contact that depend on the current and the opening angle of the movable contact are fed into the system simulator as a two-dimensional lookup table.

2.1 Model

The physics of the model and the sequence of the calculation procedure has been described in detail before [1]; this is a quick summary of the actions depicted in **fig. 1**:

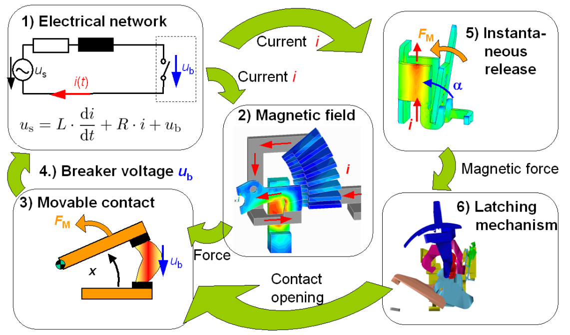

Fig. 1: Procedure of the calculations

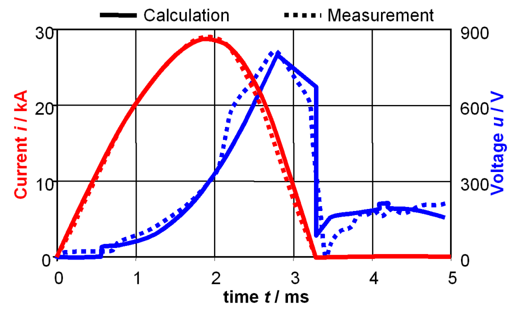

Fig. 2: Comparison of measurement (dashed) and simulation Current: red, voltage: blue

1. The **electrical network** consists of the source voltage, the impedance of cables and the breaker, that interacts with the electrical network through the voltage u_b across its terminals.

2. In the second step the **force on the movable contacts** is obtained from the lookup table containing the results of the finite-element calculations.

3. When the electromagnetic force exceeds the force of the contact springs the **motion of the movable contact** starts which is described by the equation of motion and an arc appears across the contacts.

4. For the **arc voltage** u_a we use an approach according to Pohl [4] who calculates the arc voltage as a function of the position x of the movable contact – and thus as a function of the length of the arc.

5. Parallel to step 2 the current also affects the **instantaneous short-circuit release** shown here as a ferromagnetic hinged armature. As for the movable contact the magnetic force on the armature has been calculated in advance with FEM simulations and is provided as a table for the system simulator.

6. The armature releases the **latching mechanism** which opens the movable contacts. The latching mechanism itself is calculated in separate multibody simulations; the delay time and the characteristics of the opening speed are transferred to this model as parameters.

2.2 Verification

During its development the breaker model has been repeatedly verified with results of experiments. As an example **fig. 2** shows the measured current- and arc voltage curves (dashed lines) of one phase of a three-phase short-circuit interruption for a 630 A breaker at 440 V with a prospective current of 50 kA in comparison to the calculated values (solid lines). A good agreement between the measured and calculated values can be seen especially for the current until the let-through current is reached.

2.3 Limitations of the model

Since this model does not include the geometry of the arcing chamber, changes of the geometry or materials cannot be considered; chapter 4 describes the simulation of the arc motion.

3 SIMULATION METHODS IN THERMAL DESIGN OF SWITCHGEAR

Market demands require a size reduction in electrical switchgear. This leads to an increase of the specific power loss per volume. An example for a manual motor starter shows that the specific power loss has increased fourfold from 5.9 kW/m^3 in 1959 to 27 kW/m^3 in the present generation.

For larger bus bar dimensions as they are typically used for devices with more than 800 A the current is not distributed uniformly within the cross-section of the conductor but is concentrated on the outside ("skin-effect").

A large part of the heat dissipation occurs along the current path through the copper with its superior thermal conductivity toward the bus bars where the heat is transferred to the surroundings by radiation and convection.

Our coupling approach here is a detailed finite-element calculation of the current distribution within the current path of the switching device that yields a space-dependent distribution of the Joule heat. The three phases of the electricity network influence each other ("proximity effect") leading to a higher power loss in the centre pole of the device as well as in the bus bars that are connected to it.

The calculation of the heat dissipation from the bus bars to the surroundings is a two-step procedure:

1. Calculate the heat transfer coefficients for different temperatures of the bus bars with 2D fluid dynamic simulations. **Fig. 3** shows an example of the local variation of the temperature rise for vertical bus bars that are placed horizontally at the terminals of a breaker.

2. Calculate the thermal resistance of the bus bars with a 3D finite-element model of those bus bars connected to the terminals of the switching device. The thermal loads for this model are the Joule heat of

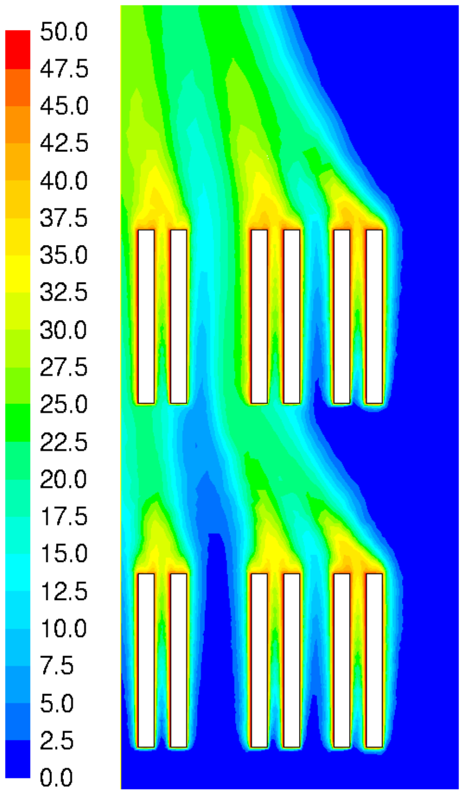

Fig. 3: Temperature rise of air surrounding the bus bars

the current and the heat dissipated from the switching device into the bus bars at the terminals. The thermal boundary of the model is defined by the temperature dependent heat transfer coefficients on the surface of the bus bars. The length of the bus bars in the model is adjusted such that at the other end of the model the self-heating temperature of the bus bars is reached, i. e. there is no significant heat transport along the conductors.

Finally a thermal model of the breaker uses this thermal resistance at the terminals to take into account the heat that is dissipated into the connected bus bars. Depending on the required accuracy within the breaker different degrees of detail are used for that thermal model ranging from spreadsheet calculations to full 3D finite-element models.

4 COUPLED FEM–FVM SIMULATION OF ELECTRIC ARCS

As pointed out in section 2 a detailed knowledge of the dynamic behavior of the **electric arc** moving inside the quenching chamber is of essential interest during the design of low voltage circuit breakers. Therefore the plasma processes are modeled in detail combining finite-element and finite-volume methods based on a **magneto-hydrodynamical approach** [5].

4.1 Model

The magneto-hydrodynamic equations are a combination of Navier-Stokes flow equations – extended to include arc specific source terms – with additional Maxwell equations for the electric and magnetic field.
In short, the current flow through an electrically conductive plasma is generating Joule heat which has to be considered in the energy balance. Additionally the magnetic field and current flow within the plasma generate Lorentz forces to be accounted for in the impulse balance.Besides these source terms the flow process and the electromagnetic process have to be coupled due to the temperature and pressure dependency of the electrical conductivity that is used in the equation of the electric potential.
The mass, momentum and energy balance equations are solved with the **finite-volume** CFD package ANSYS Fluent [6]. For the solution of electromagnetic equations the **finite-element** package ANSYS is used [7]. As mentioned above there is a need to exchange grid based quantities between the simulation tools. This is done by the **coupling software** MpCCI [8].
In addition to the short description of the problem detailed information is provided in [2]. One can also find some more information about additional modeling aspects regarding the consideration of radiation transport and metal vapor transport there.

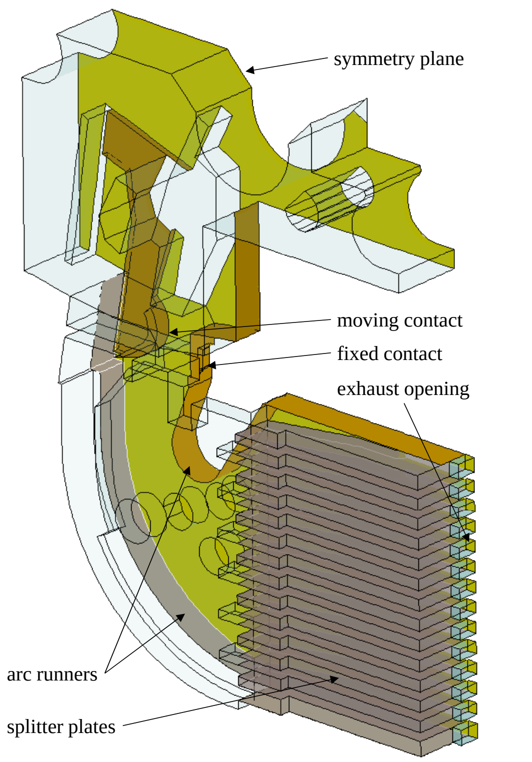

Fig. 4: Geometry of the miniature circuit breaker for CFD simulation

4.2 Example

The applicability and validity of the model is shown by comparison of measured and calculated values of a 16 A **miniature circuit breaker**. For this device the main focus of the developers is a realistic reproduction and forecast of the dynamic arc behavior within the geometrically complex quenching chamber. Especially the realistic calculation of the arc voltage is of interest, because the effective current limiting process depends on a fast increase of the arc voltage.

Fig. 4 shows the geometry of the fluid model, taking advantage of one symmetry plane. The contact opening process is not modeled here. Instead the calculation starts with open contacts defining a conductive channel between the contacts. In the finite-element model a symmetry plane is used as well. Because the 13 splitter plates are made of ferromagnetic iron, the magnetic field calculation has to consider the nonlinear relation between magnetic induction and magnetic field strength. The additional voltage drop on electrodes due to the plasma sheath is covered by additional transfer elements at the plasma-electrode interface. In doing so the voltage drop depends on the local current density and leads to a delayed arc attachment at the splitter plates [9].

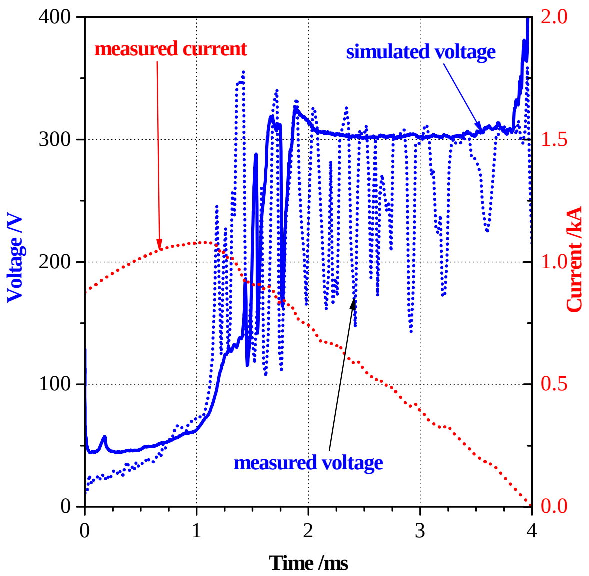

Fig. 5: Measured and calculated arc voltages

Measurements and calculations are performed with the prospective current of I_{cc}=1 kA as shown in **fig. 5**. The measured current curve is impressed in the calculation. Additionally the calculated arc voltage is shown in **fig. 5**. At the beginning of the simulation the arc voltage level is obviously higher compared to measurement because of the completely open contacts in the simulation model, leading to a higher voltage drop along the initial arc. In reality the voltage increases with increasing contact gap. Further on during the dynamic arc movement along the arc runners (see **fig. 4**) and particularly when the arc is quenched between the deion plates (splitter plates), the arc voltage level is represented realistically.

In the time frame between t=1.5 ms and t=2 ms re-ignitions in front of the deion plates occur. These effects can be seen in the diagram as sharp declines of the voltage in the measured curve as well as in the calculated curve.

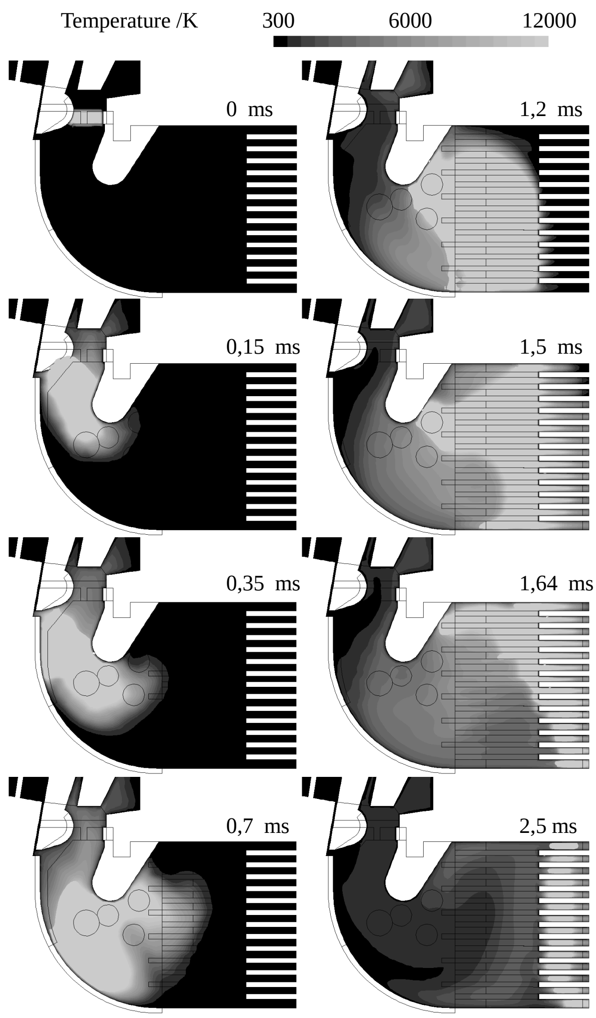

Fig. 6: Calculated temperature field for some time points

The temperature field in the symmetry plane as shown in **fig. 6** (legend scale is limited to a value of T=12 000 K) represents the dynamic behavior and the geometric arc characteristics. At time point t=0 ms one can see the initial arc between the open contacts. **Fig. 6** also shows the arc running along the runners at time points t=0.15 ms, 0.35 ms and 0.7 ms. The maximum of the calculated temperature in the plasma at t=0.7 ms is around T=22 800 K. Thereafter at t=1.2 ms the elongation of the arc leads to an increase of the arc voltage, see **fig. 5**. The arc quenching into the deion plates is shown in the figure at time points t=1.5 ms, 1.64 ms and 2.5 ms, respectively.

5 CONCLUSION

Various multidisciplinary interactions need to be considered in the development process of electromechanical switching devices. To cover these interactions a staggered approach seems to provide the best results, depending on the required accuracy and level of detail.
The electromechanical system simulation using finite element results to generate lookup tables is able to provide the dynamic behavior of circuit breakers within some limitations. The calculation of the thermal behavior is more complex, combining separate finite-element and finite-volume calculations where boundary conditions and source terms are exchanged manually. The most complex application is the simulation of the electric arc, leading to a code coupling of finite-element and finite-volume codes.
The applicability of the models for the development process is demonstrated with different examples.

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