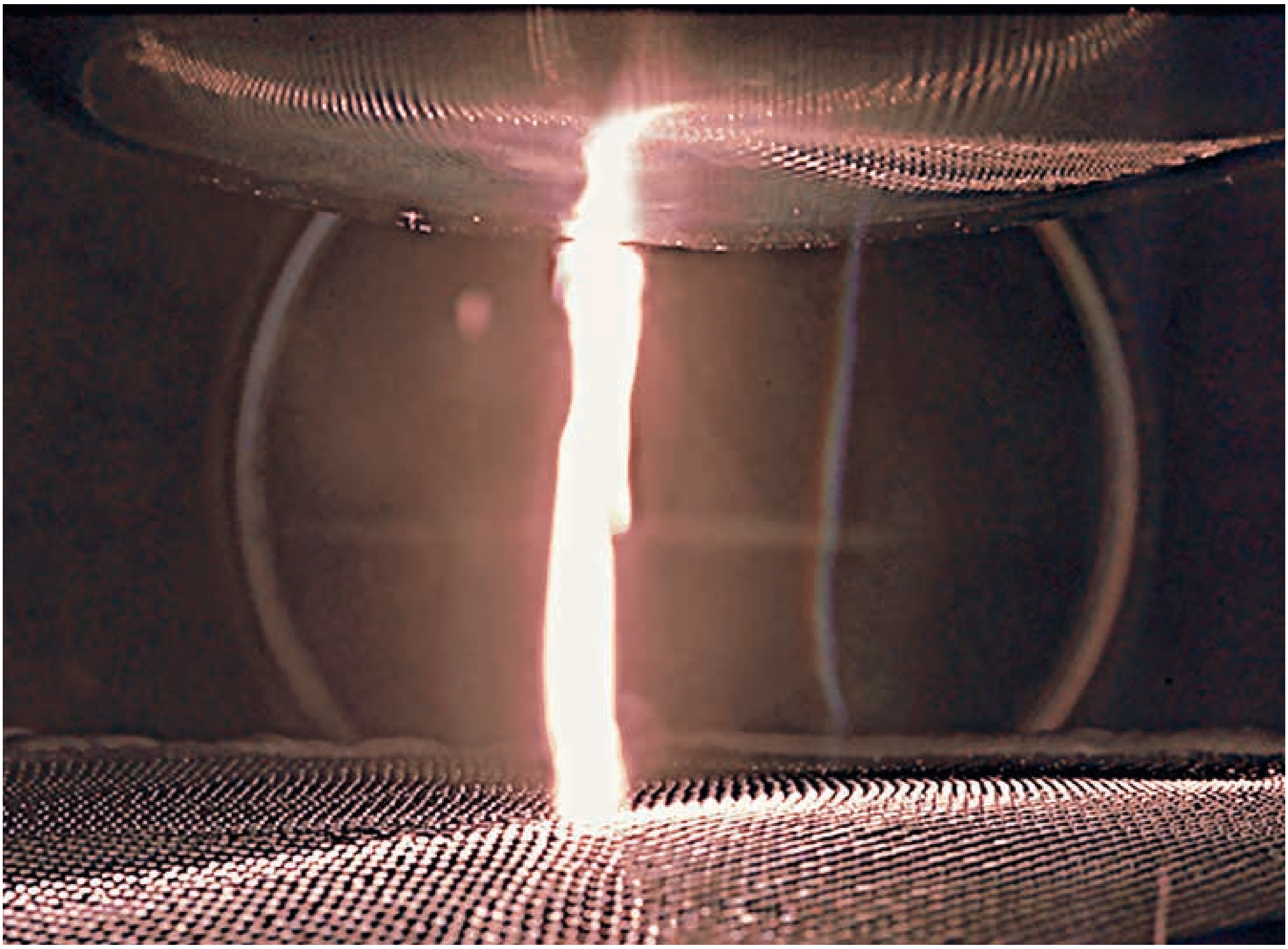
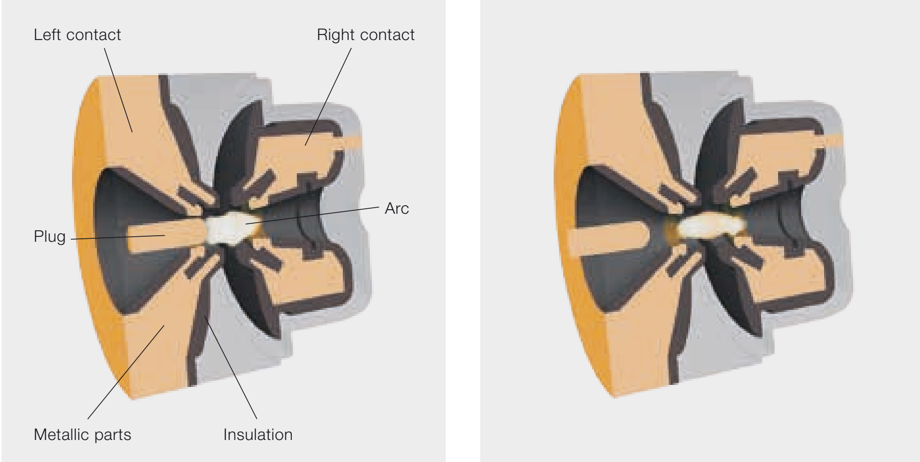


Switching analysis

Simulation of electric arcs in circuit breakers

JÖRG OSTROWSKI, MAHESH DHOTRE, BERNARDO GALLETTI, RUDOLF GATI, LUCA GHEZZI, MICHAEL SCHWINNE, XIANGYANG YE – Society is powered by a web of electrical generation, transmission and distribution equipment that reaches almost every corner of every country. Some of the most critical components of this infrastructure are the devices that switch and break the huge currents and voltages that are needed to move the vast amounts of power societies consume. At the heart of these devices lies the chamber where the electrical circuit is actually broken or completed and it is here that electric arcs test the mettle of the designer with some of the most extreme electrical conditions found in any standard equipment. Indeed, one of the most challenging simulation tasks in ABB today is to predict the plasma behavior of these arcs. Recently, tremendous progress has been made in this area and it is now possible to predict many aspects of arc behavior and its impact on circuit breakers.

1 Three-dimensional arc in a HEC 9 generator circuit breaker



1a The plug moves to the left and disconnects the left and the right electric contact.

1b The plug has moved out, the breaker is in the fully open position and the arc burns between the contacts.

The best-known example of an electrical arc is the lightning bolt that lights the sky during thunderstorms. The arcs created between the contacts of a circuit breaker as it opens or closes are on a much smaller scale, but the physical principles are the same: A channel of conductive, high-temperature ionized gas is formed and an electric current flows through it – the arc. The circuit breaker has the task of extinguishing this arc.

The conditions in the arc and its vicinity are extreme. The arc temperature easily exceeds 20,000 °C. In some cases, the pressure in the interruption chamber of the circuit breaker reaches 70 bar. Under these circumstances, measurements can only be carried out to a very limited extent, making product design very difficult and cumbersome. Therefore, simulations of the arc and its physical effects in the interruption chamber are of fundamental importance for the development of circuit breakers.

Title picture
The extreme physical conditions presented by arcing in circuit breakers throw down a challenge to the designer. Recently, there have been significant advances in the understanding and simulation of electrical arcs in breakers. The photo shows an arc imaged by a high-speed video camera.

A variety of physical processes on different scales have to be considered for such a simulation. The very hot arc loses energy via electromagnetic radiation that is partially transmitted through the surrounding gas to the enclosure of the interruption chamber. There, it heats and vaporizes the wall material, causing it to be ejected into the chamber. Ions generated in the arc also heat the surfaces, and cause vaporization, of the metallic contacts. This metal vapor then mixes with the gas components in the chamber.

Simulation of such a complex multi-physics and pan-scale process is not trivial and years were dedicated to physical and numerical research to come up with suitable computational methods. Progress has benefitted from the rapid advance in computing hardware: Calculations are now often carried out on multicore workstations or on high-performance computing clusters. All this has resulted in the successful simulation of arcing in several types of circuit breaker.

> The conditions in the arc and its vicinity are extreme: The arc temperature easily exceeds 20,000 °C and sometimes the pressure in the interruption chamber reaches 70 bar.

Generator circuit breakers

The world's largest SF_6 circuit breaker is ABB's HEC 9 generator circuit breaker. It is able to interrupt as much as a 250 kA rated short-circuit current, making it suitable for power plants up to 1.8 GW. On operation, an enormous amount of energy is released by the arc into the interruption chamber in a very short time. This generates huge pressures that are determined by the arc current, but also by the arc voltage, which, in turn, depends on the arc shape and temperature. As the pressure generated can be destructive, it is necessary to precisely simulate the flow conditions and the electromagnetic forces that influence the shape of the arc. Of equal importance is the simulation of the emitted radiation, because this is the major arc cooling mechanism.

In a HEC 9 interruption chamber, a plug connects the electric contacts when the breaker is in the closed position → 1. The arc is ignited between the plug and the right-hand contact at the moment the plug moves out and disconnects from this contact → 1a. The arc then commutes from the plug to the left-hand contact when the plug disconnects from the left-hand contact. The circuit breaker is in the fully open position after the plug is completely out. Then, the arc burns between the two contacts → 1b. Note that the arc is

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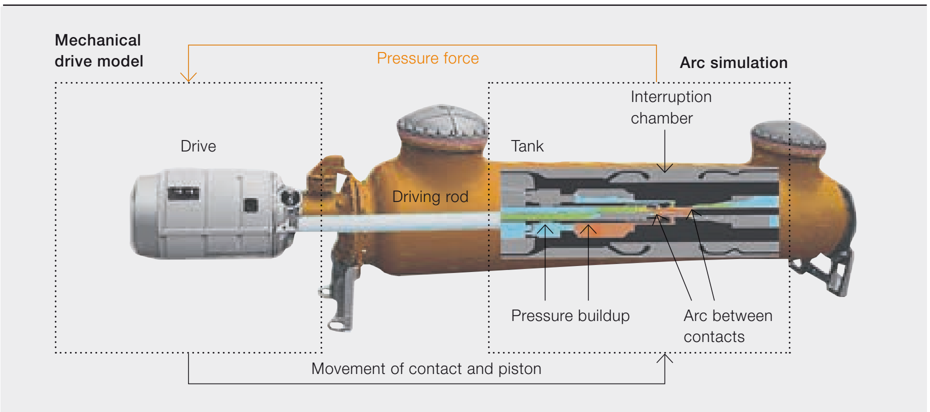
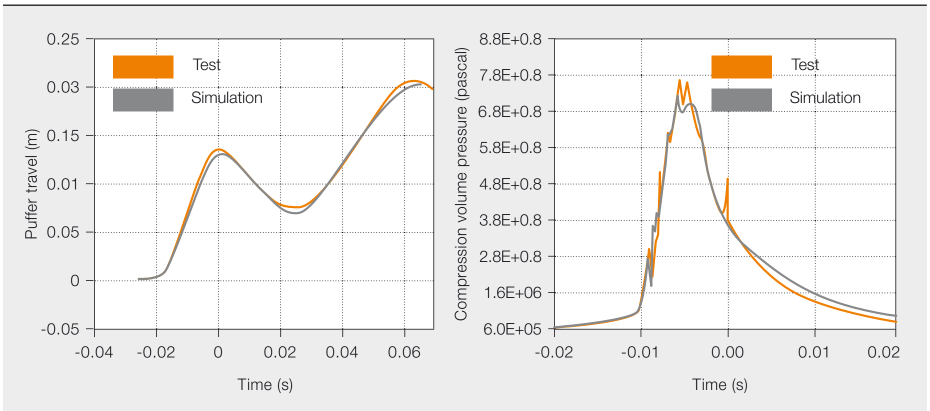
2 HV gas circuit breaker simulation



2a Arc simulation coupled with drive mechanical simulation



2b Comparison of test and simulation in pressure buildup in compression volume and in puffer piston travel

not axially symmetric; it fluctuates and forms loops, especially around current zero. Consequently, the arc voltage and the pressure in the interruption chamber fluctuate too.

Simulations of this situation give pressures that agree to within 10 percent of measured values.

Mechanical co-simulation of HV gas circuit breakers

High-voltage circuit breakers (HVCBs) are used to protect and control HV power transmission networks. Power levels and short-circuit currents are not as extreme as those seen in generator circuit breakers, but the electric field quickly reaches very high values after interruption. During the dielectric recovery, the hot gas between the arcing contacts has to be removed quickly by a strong gas flow if the electric field is not to cause problems.

ABB offers HVCB technology up to 1,100 kV, with rated breaking short-circuit currents up to 90 kA. For the prediction of a dielectric breakdown due to the high electric fields described, it is necessary to simulate the gas temperature and the gas density, as well as the electric field, shortly after current interruption. For this purpose, it is important to be able to predict the position of the electrodes precisely, bearing in mind that the interaction of the arc-generated pressure and the drive, which is mechanically coupled to the pressure chamber, determines electrode movement.

For current interruptions of this type, ABB invented the self-blast principle → 2. The idea is to use the thermal energy of the arc itself to build up a high-pressure, but comparatively cold, gas to blow out the arc.

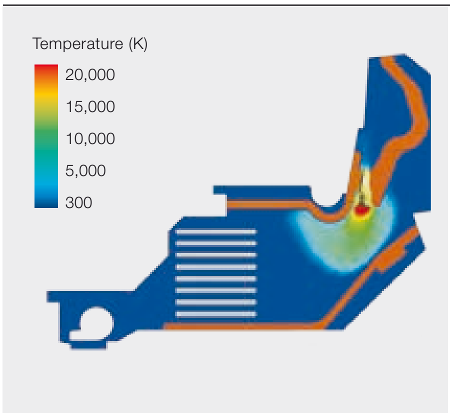
During the switching operation, the pressurized, heated gas mixes with the cold gas in the pressure chamber and this mixture flows back to the arcing zone to ensure the successful interruption of the electric current and dielectric recovery between the arcing contacts. The whole process takes 10 to 40 milliseconds. By using the fully coupled simulation of the arc physics and the mechanical drive, it is possible to predict the pressure buildup, arc voltage, gas mixing in the fixed volume and the flow pattern in the entire device accurately – information that is crucial for design and development of circuit breakers.

Further, because the pressures generated in the chamber can physically slow or reverse the contact movement, the movement is augmented by hydraulic or spring drives. The mechanical co-simulation described allows a drive to be designed that is not over-specified but that still fulfills all customer and type-test requirements regarding separation speed.

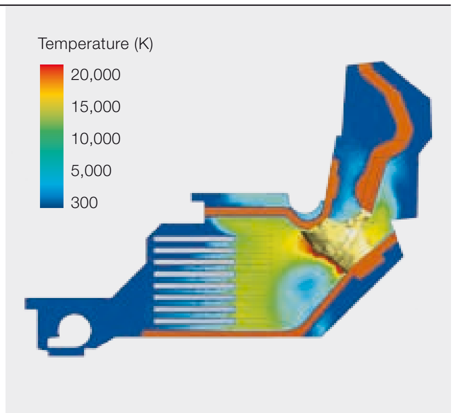
Moving arcs in low-voltage circuit breakers

Surprisingly, low-voltage circuit breakers are, in some ways, the most difficult to simulate. Here, further phenomena such as arc motion along rail electrodes, the interplay of ferromagnetic materials with arc-generated magnetic fields and the interaction between the arc and the external circuit have to be taken into account. The last phenomenon is especially important as low-voltage circuit breakers are inherently current-limiting. They build up a voltage that is comparable to the system voltage, thereby keeping the electric current below critical values and allowing for

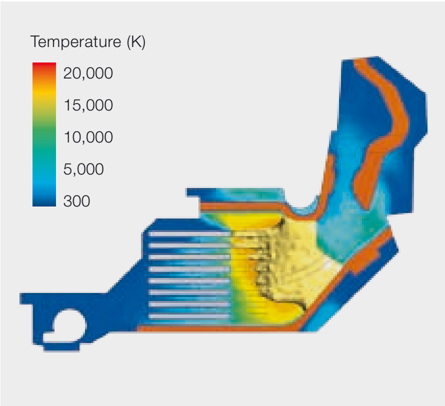
3 Transient simulation of a low-voltage short-circuit test. Gas temperature: blue to red. The arc is a white-yellow iso-surface for current density.



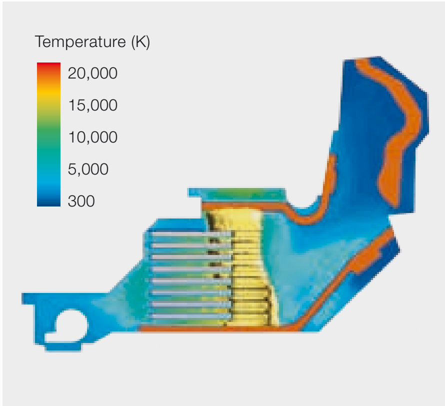
3a



3b



3c



3d

It is necessary to precisely simulate the flow conditions and the electromagnetic forces that influence the shape of the arc.

an interruption well before the natural zero crossing of the current.

Current limitation is achieved by increasing arcing voltage. This is done by ablating the polymeric housing materials and by splitting the arc into segments. By ablating the wall material, cold gas is added to the plasma, reducing its temperature. The cooling is improved further by splitting the arc into segments and allowing a larger metal surface area to absorb the energy emitted by the arc. Splitting can only be achieved if the arc can be transferred from its ignition point to the arcing chamber. This is done by employing the arc's self-generated magnetic field to drive the arc away from the nominal contacts. The driving force is increased by ferromagnetic material (usually steel plates) that concentrate and strongly enhance the magnetic field.

Simulating an arc in a low-voltage circuit breaker means following a fast evolution from ignition at electric contact separation → 3a, over commutation from the nominal contacts to the arc runners → 3b, along an electromagnetic force and pressure gradient driven run → 3c, up to extinction in a rack of metallic plates where the arc plasma is split into fragments and cooled down → 3d. The successful interruption of current in a low-voltage circuit breaker thus depends on a complex interplay of many physical phenomena taking place in the span of a few milliseconds. The simulation shown here is from the recent development of the ABB DSN200 electronic residual current circuit breaker with overload protection.

Outlook

Simulations of electric arcs are frequently used to support product design of circuit breakers and, in many cases, replace experiments that are very expensive, time-consuming or even impossible. But experiments cannot be replaced entirely. More elaborate physical models, faster computational methods and a better material understanding are all required to reach that goal.

Apart from support of product design, arc simulations greatly increase physical understanding of the process. In the future, these deeper insights will support the creation of new concepts for current interruption.

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