Understanding arcing

Simulation of high-current vacuum arcs

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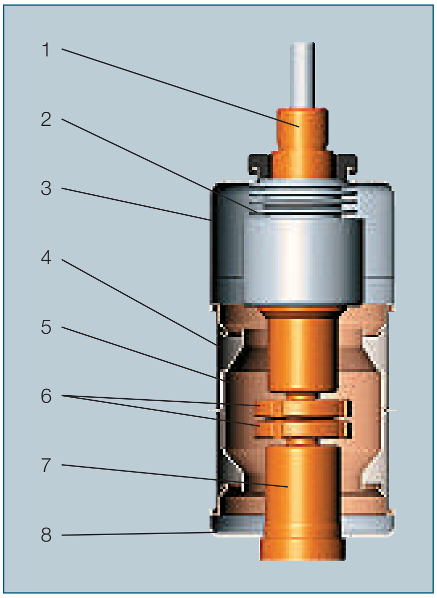
Vacuum technology today dominates medium-voltage (12–52 kV) interrupter design, and for good reason. Hallmarks such as high reliability, long life and environmental compatibility are the fruit of continuous development, aided by research into high-current interruption that has yielded a deep understanding of the underlying aspects of breaking phenomena.

A simulation tool currently under development at ABB aims at providing a better insight into the physical limits of high-current interruption under vacuum. Results of simulations carried out with the tool, which will make it easier to optimize interrupter design in the future, have been validated by experiments.

Unlike interrupters that use oil or gas as the interruption medium, vacuum interrupters have contacts that are designed to work under vacuum. Since there is no oil or gas (such as air or SF_6) the electrical arc that builds up between the contacts on separation consists entirely of charge carriers produced by evaporation and ionization of the contact material. So a vacuum arc is really a metal vapor arc.

1 The components of a vacuum interrupter



1	Stem/terminal	5	Shield
2	Metal bellows	6	Contacts
3	Interrupter lid	7	Stem
4	Ceramic insulator	8	Interrupter lid

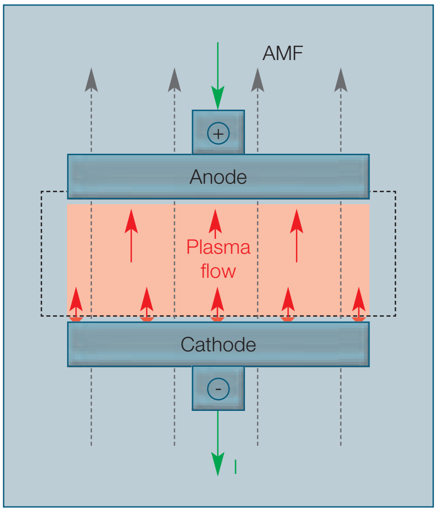
The inherent advantages of vacuum interrupters – minimal maintenance and environmental friendliness – are primarily due to the fact that they have fewer and simpler parts than other types of interrupter and are sealed for life, usually decades. If an electric arc burns in gas or oil it creates decomposition products; in a vacuum interrupter pure metals are vaporized and afterwards re-deposited.

What goes on inside a vacuum interrupter?

1 shows a typical ABB vacuum interrupter1). It consists of two copper/chrome contacts, one of them fixed (the lower one shown) and the other movable. The contacts are located inside a vessel which is evacuated to a pressure below 10-5 Pa. This vessel consists of a ceramic insulator, a metal bellows for the movable contact, and two steel lids that attach the contacts to the ceramic insulator. A shield protects the ceramic insulator from the hot metal vapor arc.

When the contacts separate in this vacuum, metal from the contact surfaces is evaporated and highly ionized, forming an electric arc. This arc is sustained by the external supply of energy until the next time the current passes through zero. It is fed from many micro-plasma sources – so-called cathode spots – distributed over the contact (at currents below about 10 kA, the cathode is the only plasma source). As the current decreases the production of new plasma slows down. In the ideal case, no new plasma will be produced at current zero, the remaining ions and electrons recombining quickly and then condensing on the contacts and shield. Low or moderate currents cause the arc to spread over the entire contact surface

2 Geometry of the model used. Plasma is generated at the cathode. The anode acts as a sink for the impinging atoms.



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1) ABB vacuum interrupters are developed and manufactured at ABB Calor Emag Mittelspannung GmbH in Ratingen (Germany).

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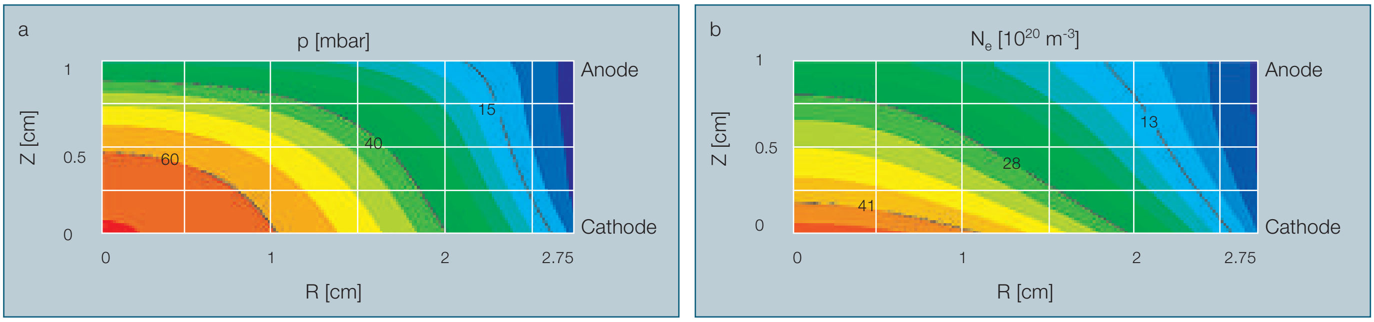
Calculation of pressure (a) and electron density (b) of a subsonic diffuse arc at 15 kA, AMF 5mT/kA



(called the diffuse mode), so that the anode surface temperatures are not high enough to cause additional evaporation of the contact material. However, as experiments with higher currents, such as occur during short-circuit interruptions, have clearly shown, the arc constricts. Without an axial magnetic field (AMF) this occurs usually at around 10 kA. Introducing an AMF shifts the constriction to higher currents [1]. Contact erosion is much greater in the constricted arc mode than in the diffuse mode as the arc's energy is not distributed over the entire contact surface. The result is intense melting of the contact materials and an increase in evaporation at current zero. This determines the interruption capability of a vacuum interrupter.

Understanding processes like constriction and the parameters that influence the heat flow to the contact surfaces at maximum current is therefore essential for an optimal interrupter design. Making this an important research goal, ABB, in cooperation with the Institute of Electrophysics at the Russian Academy of Sciences (RAS), began in 2001 to develop a numerical model with which to simulate high-current vacuum arcs [2–4].

ABB and the Russian Academy of Sciences have worked together since 2001 to develop a numerical model for simulating high-current vacuum arcs.

Choosing the right model

Since models, by definition, simplify reality and neglect certain aspects, they can only have a limited validity. For example, the same model cannot be used to simulate a vacuum interrupter in all its different states (closed, breakdown, initiation of arc, open with arc burning, open after extinguished arc). It is therefore necessary to check the applicability of different models and, where necessary, adapt or couple them for different situations.

If the Debye length – the characteristic distance over which charges are shielded in a plasma – is much smaller than the mean free path of the electrons, ie the mean distance between two collisions of an electron, and the mean free path is much smaller than the typical extension of the arc plasma (the contact distance), then the magneto-hydrodynamic (MHD) approximation can be applied. In this case the simulations are performed for a constant current and gap. This is justified, as the response by the plasma is fast compared with the speed of the variations resulting from changes in current and contact movement [4].

2 shows the geometry of the model used. This has an AMF externally su-

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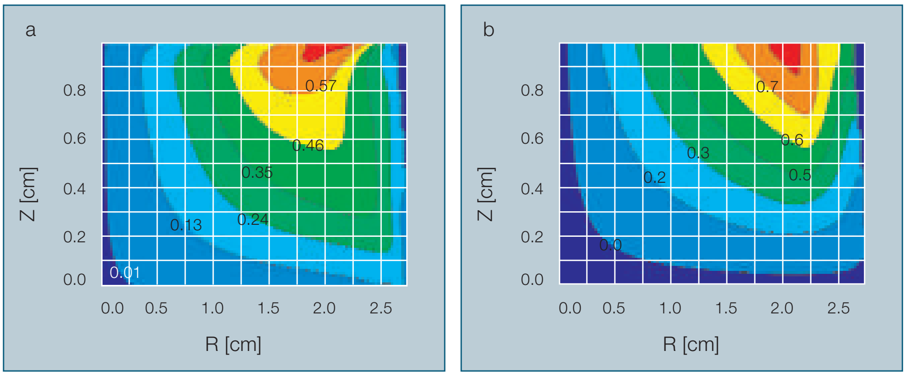
Distribution of (a) azimuthal current density (kA/cm^2) and (b) azimuthal ion velocity (10^4 m/s) for a subsonic diffuse arc at 22 kA, 5 mT/kA



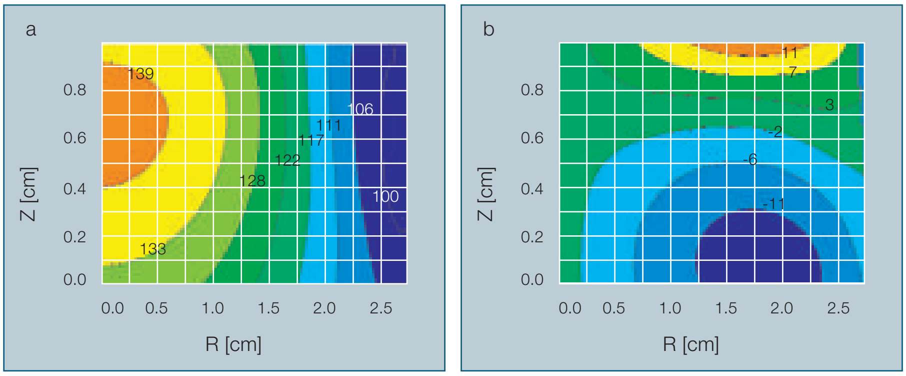
perimposed on it. As in a real interrupter, the AMF is approximately proportional to the current. It is assumed that only an axial component of the current exists at the cathode boundary. The single cathode spots are not considered, as in a high-current arc their plasma jets mix after a short distance. As a first approximation the anode is taken to be a sink for all the impinging plasma flow. However, in reality total condensation does not take place, especially when the surface temperature is close to the melting temperature or the contacts are already molten. ABB is using the present model to also study the consequences of this effect.

> Simulations have to be performed with subsonic inflow conditions as these are of most interest for the study of high-current vacuum arcs in interrupters.

The equations used are basically the balances of mass, momentum and energy, the induction equation and Ohm's law. The induction equation follows from Maxwell's equations in combination with Ohm's law. Consideration of the energy balance is essential because the interchange of kinetic energy and thermal energy, as well as ohmic heating, decisively influences the behavior of the plasma flow. Pressure and electro-dynamic forces affect the flow from cathode to anode. Whereas the characteristic appearance of the arc in gas switches is mainly defined by a strong gas flow, the defining characteristic of a vacuum arc is the electromagnetic field. This is one reason for commercial software not having been available until now.

Rotational symmetry is being assumed at the moment to reduce the calculation time, but once the model is established it is planned to shift to three dimensions and complicated geometries, as exemplified by radial magnetic field (RMF) contacts. It is also worth noting that the basic equations used are not limited exclusively to AMF interrupters.

5 Distribution of (a) axial (mT) and (b) radial magnetic field component (mT) for a subsonic diffuse arc at 22 kA, 5 mT/kA

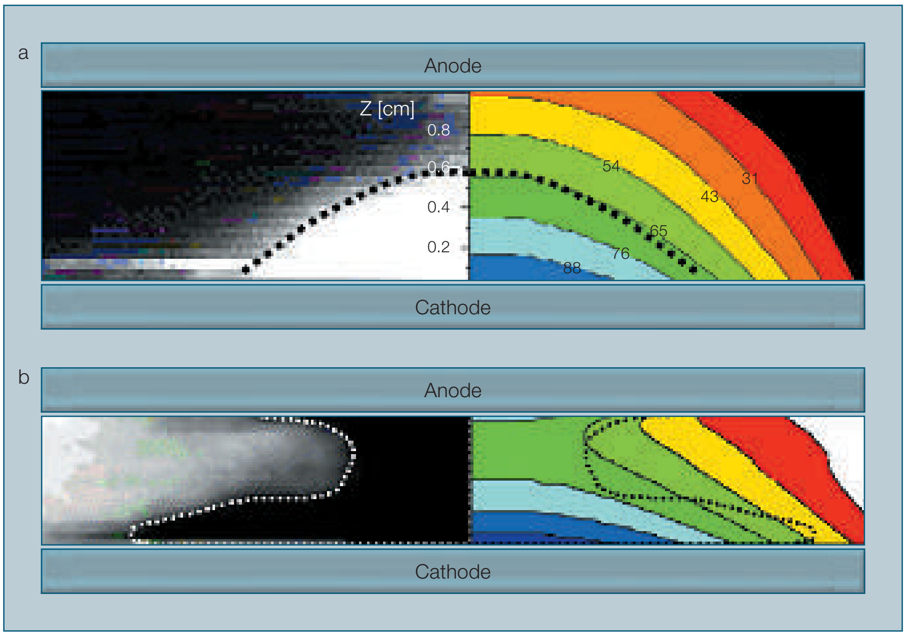


Going deeper – inside the arc

The numerical simulations were started with supersonic inflow conditions [4,5]. When supersonic flows constrict, the velocity drops and the kinetic energy that is released is converted into thermal energy. This is a typical characteristic of supersonic flow, and the opposite of subsonic flow behavior. (The supersonic diffuse arc exists only at low AMF or zero AMF and small currents.)

Subsequently, simulations were performed with subsonic inflow conditions, which are the main range of interest for

6 Comparison of light intensities obtained by experiment (left) and with simulation (right). The arc peak current is 15 kA for a diffuse arc (a) and 22 kA for a diffuse columnar arc (b).



the study of high-current vacuum arcs in interrupters.

The model allows quantities to be calculated which are otherwise difficult to access, such as pressure 3 and current flow in the plasma, as well as their consequences for arc behavior. Lorentz forces act on the moving ions and electrons, causing azimuthal current and mass flow. The direction of azimuthal motion of the ions is in opposition to that of the electrons. In the vicinity of the anode the plasma rotates like a solid body and the azimuthal ion velocity increases approximately linearly in the radial direction. 4 shows, as an example, a subsonic diffuse arc at 22 kA and 5 mT/kA. The ring-shaped azimuthal current produces a magnetic field not unlike a dipole field 5. This field is superimposed on the applied AMF, leading to a higher axial component of the magnetic field in the center of the contacts. In the past it has not been possible to calculate the impact of the current in the plasma on the applied AMF.

> The numerical model allows quantities to be calculated which are otherwise difficult to access, such as pressure and current flow in the plasma.

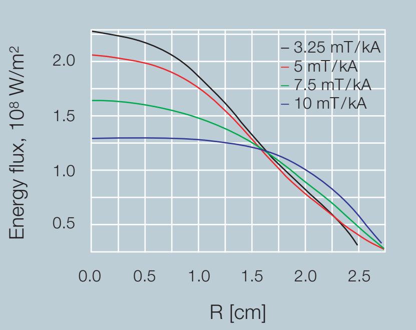
Video recordings confirm the existence of higher pressures and plasma densities in front of the cathode. What is more, high-speed photography images of diffuse arcs at high currents show that the maximum light intensities are always directly in front of the cathode.

The importance of verification by experiment

As a first approximation it can be assumed that the volumetric light emission is proportional to the plasma density. The local emission has to be integrated along the path of view to obtain the intensity registered side-on in experiments. 6a compares one half of a video image (left) with the computer simulation (right) for comparable conditions. The contour of the bright zone (dotted line, left) is flipped horizontally onto the simulation result. The agreement is reasonable if it is considered that the limited dynamic range of the recording system affects the registered light signal and makes the intensity variation seem more abrupt than it is in reality.

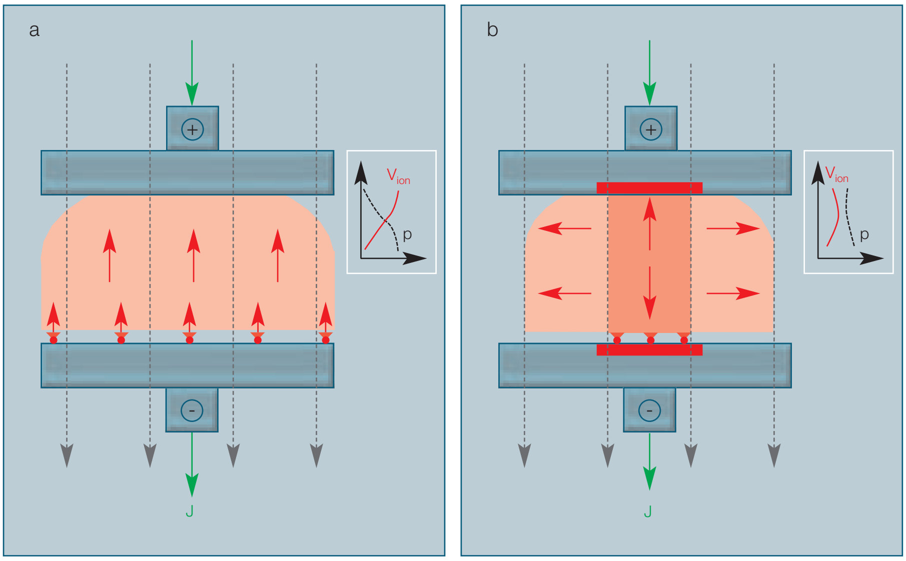
However, a comparison of the shapes of video recordings alone is not enough to verify the applied model. Absolute quantities, such as pressure, ion velocities and densities, also have to be calculated and compared with the experimental results. As these quantities are difficult to access experimentally the amount of data available is limited. Nevertheless, the calculated electron temperatures and densities, the azimuthal rotation of the plasma and the axial magnetic field generated by the azimuthal current, are all in fair agreement with measurements. As for other quantities like the axial ion temperatures and velocities, it was only possible to reproduce trends. This could have been due to the simplified geometry. It

7 Variation in radial distribution



Variation in radial distribution of the heat flux density as a function of the applied axial magnetic field at a constant arc current of 15 kA

8 Conditions for (a) a subsonic diffuse and (b) diffuse columnar arc



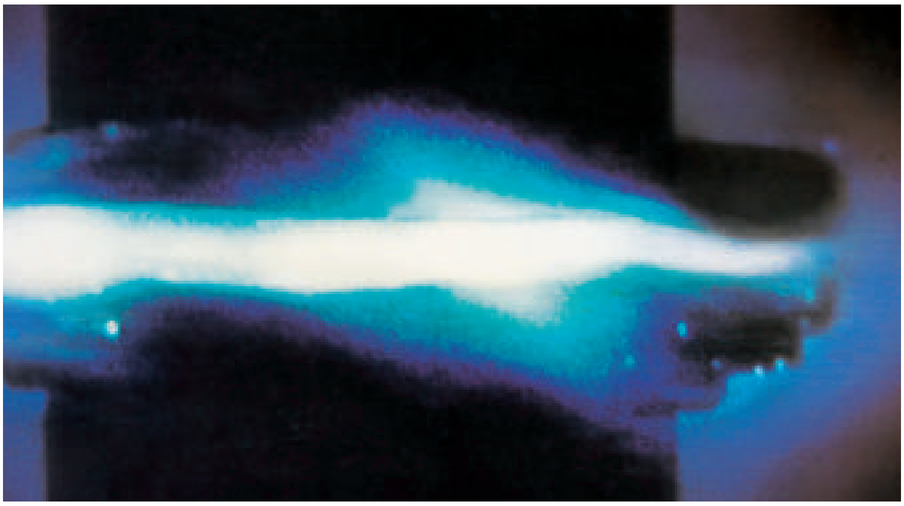
J Current flow from anode to cathode
P Pressure distribution along axis from cathode to anode
V_{ion} Ion velocity distribution along axis from cathode to anode

is worth noting, however, that no opposite trends were observed that might have indicated that certain assumptions or simplifications were wrong.

The heat flux on the contacts is one of the key parameters in vacuum interrupter development. This is because the onset of considerable contact material evaporation affects the transition from diffuse to diffuse columnar mode. Importantly, metal vapor density and, indirectly, the extent of melting at current zero determine the limit of interruption capability. Heat is transferred to the anode as a result of the impingement of two carriers – electrons and ions. The radial distribution of the heat flux becomes broader as the AMF becomes stronger 7.

A separate model is used to calculate the electrode temperature, the depth of melt, and parameters like the vapor density and pressure, which depend on the surface temperature. The time-dependent heat equation is solved for the liquid pool and the adjoining solid metal. The calculation, which is one-dimensional, considers the energy lost not only through heat conduction but also through contact material evaporation and thermal radiation. The advantage of the MHD simulation here is that it provides useful input data for the modeling of the melting of the electrode, for which empirical or assumed values had to be used in the past.

> Further work will yield a powerful tool allowing a better understanding of vacuum arc phenomena and new configurations to be tested before experiments are begun.



Another important result was the reproduction of the transition from a diffuse arc to a diffuse columnar arc. A typical characteristic of the diffuse arc is the decreasing pressure toward the anode 8a; in the case of the diffuse columnar arc, as indicated by simulations, the pressure along the axis equalizes 8b. 6b shows the correlation between the simulation results and experimental data for a diffuse columnar arc. This model is also being used to investigate the influence of the electrode gap and current distribution as well as the impact of other boundary conditions.

Further improvements to this model and its implementation for real geometries will yield a powerful tool capable of providing a better understanding of the phenomena occurring inside a vacuum arc and allowing new configurations and the effect of changing design parameters to be tested before experiments are begun. Notwithstanding this capability, ABB is committed to carrying out experiments in order to verify results and obtain ‘final proof’ of the practicality of design changes.

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