Vacuum interrupters with axial magnetic field contacts

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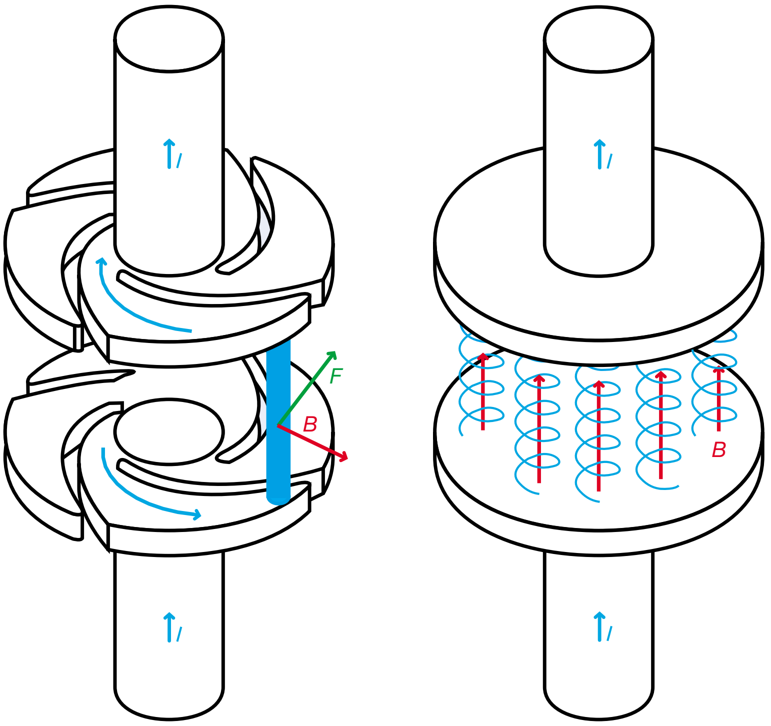
Vacuum is a proven switching medium with numerous advantages over alternative media, especially for medium-voltage applications. In the past, ABB has fitted its vacuum interrupters for circuit-breakers with radial magnetic field contacts. Newly developed interrupters with axial magnetic field contacts enable short-circuit currents of 63 kA and more to be reliably interrupted.

Vacuum has today largely replaced other arc-quenching media, such as oil or SF_6 gas, for many switching applications in the medium-voltage sector. Among the advantages of vacuum interrupters are a compact design, maintenance-free operation, long service life and excellent environmental compatibility.

ABB Calor Emag Mittelspannung GmbH has been developing and manufacturing vacuum interrupters since the early 1980s 1 [1]. At the company's R&D center in Ratingen, Germany, engineers use state-of-the-art tools and powerful computer software to optimize the design and functionality of the interrupters. The most recent results of this work include a new family of vacuum interrupters for contactors and switches [2] and an innovative process for the in-house production of contacts.

New production facilities completed in 1999 underscore the company's commitment to high quality and cost-saving while also adding to its manufacturing capacity.

1 *Some of the vacuum interrupters available from ABB*



2 ***Working principle of a radial magnetic field contact (spiral contact, left) and an axial magnetic field contact (right)***

B Magnetic flux density
I Current
F Azimuthal electromagnetic force

How interrupter contact systems work

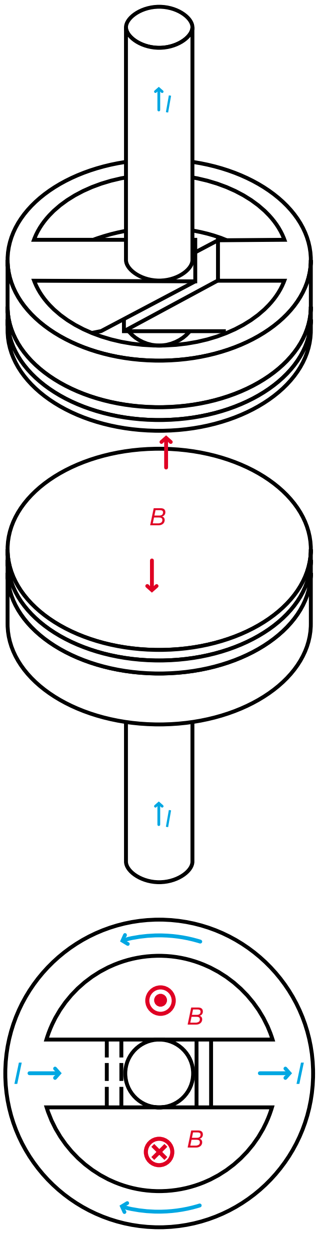
When contacts through which current flows are separated, the explosion of the last ‘metallic bridge‘ causes a metal vapor arc to form. This arc, which consists exclusively of the vaporizing contact material, is sustained by the external supply of energy up until the next time the current passes through zero. At the instant of this zero-crossing, the arc is finally extinguished and the vacuum interrupter regains its insulating capability, ie it is able to withstand the transient recovery voltage. To ensure successful quenching at the current zero-crossing, the contacts are not allowed to suffer more than minimal arc erosion during passage of the strongest current. At currents of around 10 kA the vacuum arc begins to contract, being initially noticeable in the form of anode spots. The contraction, which partly depends on the contact material, causes more energy to be supplied to the contacts, thereby reducing the vacuum gap’s capacity to extinguish the arc after the current zero-crossing. One way in which the switching capacity can be improved is to change the contact geometry. (The electrode geometry generates magnetic fields, so such changes influence the arc’s behavior.) Until recently, ABB has always used spiral contacts in its vacuum interrupters for circuit-breakers. These contacts generate a radial magnetic field (RMF), which causes an azimuthal electromagnetic force to act on the contracted vacuum arc **2**.

The contracted arc moves over the contact’s surface at a speed of 70–150 m/s [3]. This high velocity ensures that there is less contact erosion and also significantly improves the current interrupting capability [4].

The switching capacity of vacuum interrupters can also be increased by using contact systems which generate an axial magnetic field (AMF). When a magnetic flux density is applied parallel to the flow of current in the arc, the mobility of the charge carriers perpendicular to the flow is considerably reduced. This applies especially to the electrons, which have a smaller mass than the ions. The electrons gyrate around the magnetic lines of force **2**, so that the contraction of the arc is shifted towards the higher currents. The arc burns with a diffused light and the supply of energy to the electrodes is reduced. This is also indicated by the arc voltage, which is lower than with RMF contacts.

The advantage of the RMF contact system lies in its simple physical structure, while another advantage of the spiral contact is that in the closed state the current can flow through the contacts directly via the stem, thereby ensuring lower power losses for the vacuum interrupter at nominal current.

In many AMF contact systems the axial magnetic field is generated by a coil located behind the contacts. As a result, the resistance of the interrupter increases and the additional resistive losses occurring in service reduce the nominal current performance. The only practical way in which a vacuum interrupter can dissipate the generated heat is via the copper conductors, since convection is not an option in vacuum. As already mentioned, the diffused arc of the AMF contact systems results in an excellent short-circuit current breaking capacity. This applies particularly to currents of 63 kA and higher. In this short-circuit current range, the more complex AMF contact systems are superior to the conventional RMF contacts and are definitely to be preferred. Networks with a rated frequency of 16 2/3 Hz, eg for traction power supplies, represent another area in which it pays to use AMF systems. Due to the extremely long arcing times, vacuum interrupters with AMF contacts have to be installed in these systems at current levels as low as 31.5 kA.

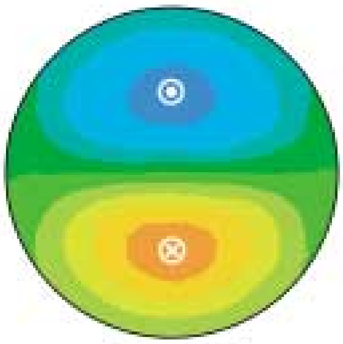


3 *Working principle of the bipolar AMF contact system. Coils behind each of the contact plates generate a two-pole axial magnetic field in the contact gap.*

B Magnetic flux density
I Current

Newly developed AMF contact systems

ABB has developed two innovative AMF contact systems for the interruption of high short-circuit currents. Both of the systems were dimensioned with the help of modern programs based on FEM. Steady-state and quasi-steady-state simulations as well as transient simulations were performed. Consideration was also given by the R&D specialists to non-linear material parameters, such as the permeability of the ferromagnetic material.



4 *Distribution of the magnetic flux density in the median plane between the contacts of a bipolar AMF contact system*

Bipolar AMF contact system

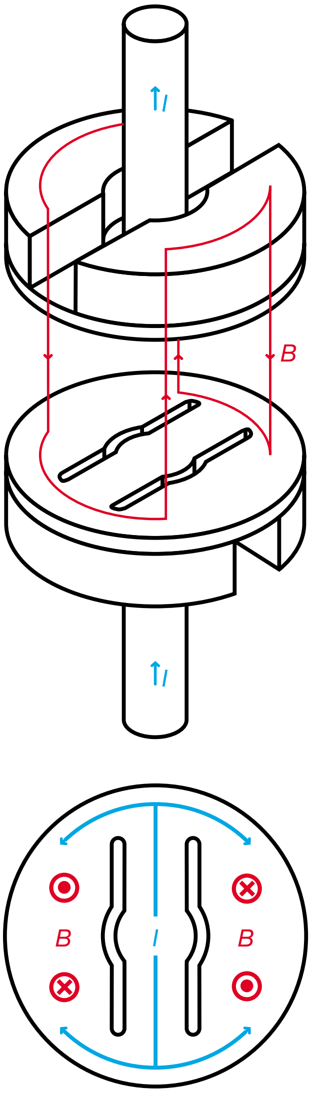
3 shows the principle of operation of the bipolar AMF contact system. Behind each of the contact plates are coils that generate a two-pole axial magnetic field in the contact gap.

The magnetic flux density in the middle of the gap with this arrangement is shown in **4**. The surface is divided into two sectors in which identical conditions exist. The only difference between them is the direction of the magnetic flux density. On the line separating the two areas from each other the flux density is zero, whereas it is relatively high towards their outer edges.

Quadrupole AMF contact system

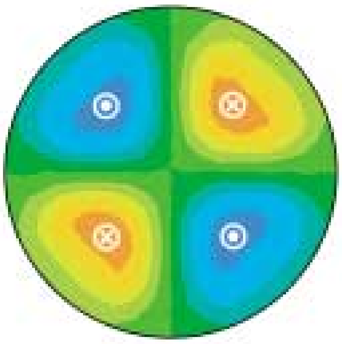
The principle on which the newly developed quadrupole contact system is based is shown in **5**. Unlike the bipolar contact system, this contact system does not use a coil to generate the axial magnetic field, creating it instead through a hybrid arrangement that comprises a magnetic circuit and slots in the contact plate. The magnetic circuit is made up of the ferromagnetic material through which the flux is guided. The field poles are arranged in such a way that the flux crosses the contact gap four times during one revolution, thereby generating a quadrupole axial magnetic field. Slotting the contact plate forces a portion of the current to form a loop when the contacts are open in order to supply energy to the roots of the arc on the electrode. The formation of this loop strengthens the magnetic field.

6 shows the magnetic flux density in the middle of the contact gap of the quadrupole contact system. Four sectors are visible; the conditions with respect to the magnetic flux densities are the same in each of the sectors, but their directions are different. In the case of the quadrupole contact system, the magnetic flux density at the ‘cross‘ separating the four sectors is zero. As in the bipolar contact systems, the axial magnetic field is relatively strong in the outer areas of the contact gap.



5 ***Working principle of the quadrupole AMF contact system.***
The axial magnetic field is created by a hybrid arrangement consisting of a magnetic circuit and slots in the contact plate.
B Magnetic flux density
I Current

The main parameters considered when dimensioning AMF contacts are the size, distribution and phase relation of the axial magnetic field. In the case of the latter it should be noted that, ideally, the goal is to have no phase displacement between the high current and the magnetic field it generates. However, because of the inherent losses in the contact system such an ideal case will always be out of reach. An important parameter is the eddy current produced in the contact plate by the changing magnetic flux density; this eddy current is responsible for both the phase displacement and the reduced axial magnetic field. Since only the areas enclosed by the eddy currents passed through in one direction by the magnetic lines of force are concerned, they are smaller than in the unipolar contact systems [5]. Thus, the eddy current losses are also lower. The undesirable effect of the eddy currents on the value and phase relation of the magnetic flux density is therefore reduced in the case of both the bipolar and the quadrupole contact system.

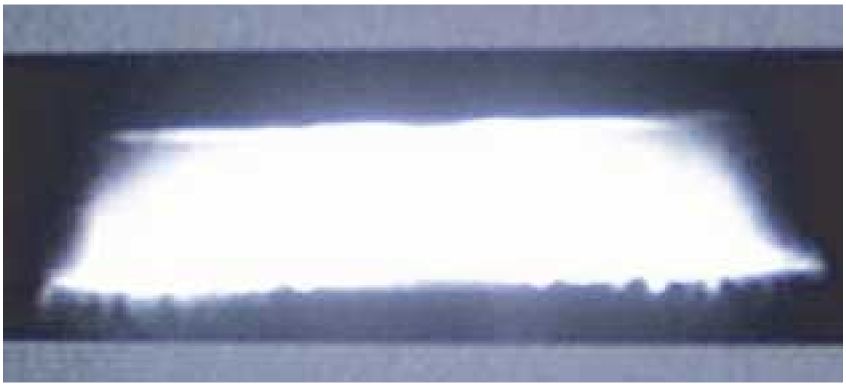


6 ***Distribution of the magnetic flux density in the median plane between the contacts of a quadrupole AMF contact system***

Experimental investigation and tests

Besides theoretical studies, optical tests were also carried out in order to observe the arc behavior of the contact systems. 7 shows the metal vapor arc in vacuum for the quadrupole contact system, recorded with the help of a high-speed CCD video camera. The arc is shown close to the peak value of a 50-Hz half-wave with an rms current value of 31.5 kA. The diameter of the contact is 68.5 mm. An ultra high vacuum test chamber was used for the tests. As predicted by the theoretical studies, the arc is in a diffused state. Consequently, the thermal stress caused by the vacuum arc is distributed relatively uniformly over the contact plates. Contact erosion, which considerably reduces the breaking capacity, is significantly lower due to the diffused vacuum arc. The initial stages of arc contraction are visible on the upper electrode, ie the anode. However, this effect remains marginal due to the well-dimensioned magnetic field.
A similar arc behavior is exhibited by the bipolar contact system, which also shows a diffused vacuum arc up to the higher cur-

7 ***Vacuum arc under the influence of a quadrupole axial magnetic field (I = 31.5 kA; photo taken in the region of the peak current value; contact diameter 68.5 mm; anode at top, cathode at bottom)***



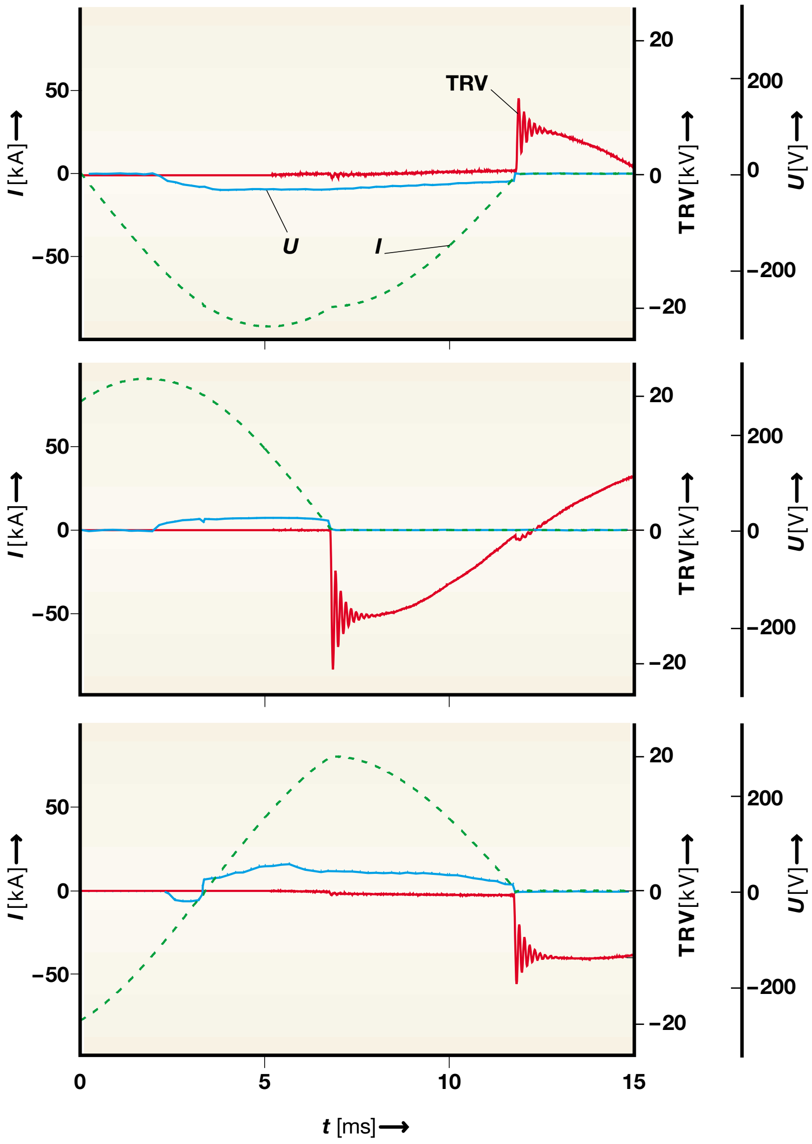
rent values. It was observed during many of the tests that the vacuum arc originates at a single location – the last metallic bridge. During the next 2 to 3 ms it propagates over the entire surface of the contacts, independently of the polarity of the magnetic flux density. This behavior is the same for both types of contact system.

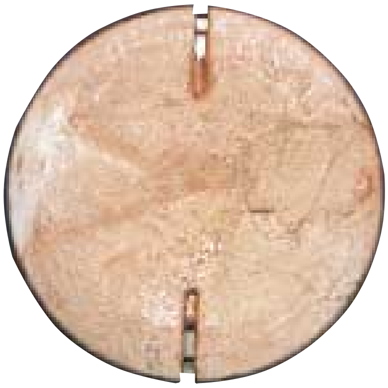
It is the arc behavior that makes AMF contact systems best suited for high short-circuit currents. **8** shows a short-circuit current breaking operation for 12 kV/63 kA according to IEC 60056 [6] with the bipolar contact system. The diameter of the contact in this case was 100 mm. The smooth curve of the arc voltage indicates that the vacuum arc remains in a diffused state in spite of the very high peak current value of 90 kA. The vacuum breaker interrupts the current at the earliest possible instant. Both of the contact systems (contact diameter 100 mm) are able to withstand the switching tests at 12 kV/63 kA. Vacuum circuit-breakers with the described AMF contact systems were subjected to currents of 63 kA up to 25 times. In every case, they extinguished the arc reliably.

9 and **10** show the contact surfaces after more than 20 63-kA current interruptions for a bipolar and a quadrupole contact system, respectively (contact diameter 100 mm). Just a slight melting of the contact surface is noticeable in

8 ***Oscillogram of a three-phase short-circuit current interruption of 12 kV/63 kA (symmetrical) with the bipolar contact system (contact diameter 100 mm)***

TRV	*Transient recovery voltage*	*I*	*Short-circuit current*
U	*Arc voltage*		

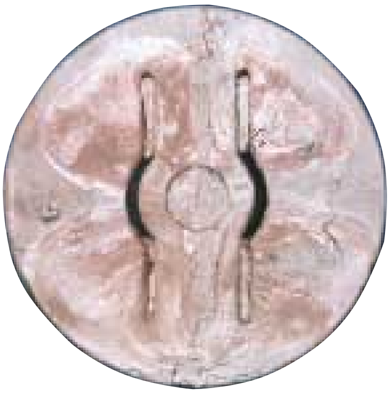




9 ***Contact surface of a bipolar contact system after multiple short-circuit current interruptions (63 kA; contact diameter 100 mm)***

each case, indicating that the electrical lifetime has not yet been reached. A look at the melting shows that the arc follows the field lines of the magnetic flux density. The contacts of the bipolar system exhibit two regions where stronger melting has occurred, in the case of the quadrupole system four. Comparison with 4 and 6, which show the axial magnetic flux density in the contact gap, demonstrates clearly that the melting follows the flux density distribution. This is further proof of the accuracy of the theoretical observations.

10 ***Contact surface of a quadrupole contact system after multiple short-circuit current interruptions (63 kA; contact diameter 100 mm)***



Comparing the bipolar contact system with the quadrupole system, it can be stated that the latter is able to generate the axial magnetic field without any need for coils. In the closed state, the current flows directly through the stem and the contacts, resembling the flow with a spiral contact. Thus, the rated current carrying capacity is comparable. However, the resistance of the interrupter, assuming the same conductor dimensions, is higher for the bipolar contact system, so that for numerous high-current applications the higher rated current requires a more costly system for dissipating the heat. The advantages of the bipolar contact system come to the fore in applications involving rated voltages of 36 kV and higher. In the case of the quadrupole systems, the larger contact movements these applications require do not allow the magnetic flux to be so effectively guided through the contact gap. This is because the flux is also able to flow, via the gaps, between the field poles behind the contact plates and forms a closed circuit.

The development of axial magnetic field contacts enables vacuum interrupters to be used for interrupting very high short-circuit currents, eg close to the generator terminals. Since the arc remains diffused even at high current intensities, the contact surface can be utilized efficiently, which makes the interrupter compact and competitively priced. ■

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