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Vacuum switching

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Foreword

no. 198

Vacuum switching

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Hired in 1982 by Merlin Gerin, he has held different positions, primarily in the technical field of the Medium Voltage division.
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Vacuum switching

This "Cahier Technique" constitutes a general presentation of basic notions relative to the functioning and use of vacuum switching devices.

The first section, entitled Theory and Use of vacuum switching, is a brief description of the physical phenomena that are associated with vacuum switching, and of their use. It also includes a presentation of the different technological options that are available to vacuum interrupter designers.

The second section is dedicated to the interaction between vacuum switching devices and the electrical network, in inductive circuits for which vacuum switching may cause overvoltages, and to overvoltage protection means.

In the third section, the author explains how vacuum switching characteristics, which have been presented in the two preceding sections, determine the application fields best suited to this technique, depending on voltage levels and switchgear types.

This "Cahier Technique" is completed with an extensive bibliography of works and other documents which the reader can consult if he wishes to acquire more in-depth information on a particular point.

Contents

1 Introduction: use of vacuum as a breaking medium in the electrical switchgear industry

SF6 and vacuum are the two most modern breaking techniques in the fields of Medium Voltage (from 1 to 52 kV) and High Voltage (> 72.5 kV). They appeared in the 1960's and rapidly developed as of the 1970's. Today they have replaced the former air and oil breaking techniques (see **fig. 1**).

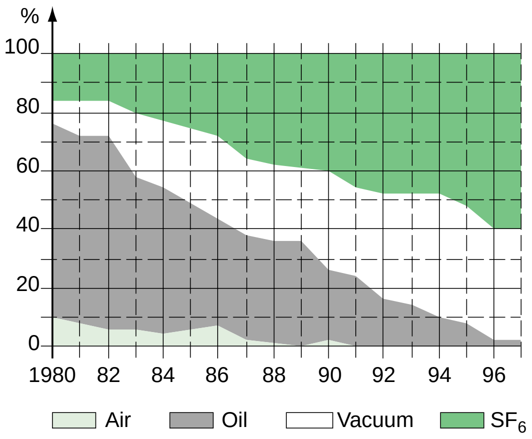


***Fig. 1**: evolution of MV circuit-breaker markets in Europe.*

Whereas SF6 is used in all of the medium voltage and high voltage ranges, vacuum has primarily developed in the medium voltage field, with limited incursions in low voltage and in high voltage: the two techniques only compete with each other in the medium voltage field.

This notion of rivalry between the two techniques is now in fact out of date: even if at some time there was commercial competition between manufacturers that opted for one or the other of these techniques, today all large-scale manufacturers offer both techniques so as to be able to satisfy as best as possible their client's needs. Indeed, each technique has its strong points and its weak points. Even if each is highly multi-functional and can offer a reliable and competitive solution for most medium voltage interruption problems, users want to be able to choose for themselves in function of their applications, operation and maintenance policies, priorities … and of course habits!

In the past, the vacuum switching technique was first developed by American and English manufacturers (the pioneers were General Electric and VIL), followed by the Japanese and the Germans: these countries have the common feature of using networks with relatively low voltage ratings (from 7.2 to 15 kV) for medium voltage electrical energy distribution. However, in countries like France and Italy which distribute electricity with voltage levels near 24 kV, manufacturers opted for the SF6 breaking technique.

It is remarkable to note, 30 years later, the appropriateness of these technological choices in regard to the foreseen application. In fact still today, a global technical-financial evaluation of both techniques shows an equivalence when using voltages between 12 and 24 kV, with a relative advantage for SF6 above this voltage level, and for vacuum below this level. However, the difference in cost remains low, which explains how the two offers, vacuum and SF6, can coexist, for all medium voltage levels from 7.2 to 36 kV.

2 Theory and use of vacuum switching

2.1 The dielectric properties of vacuum

Any breaking medium must first be a good insulator for it is to stop current from flowing through it. Vacuum is not an exception to the rule: it has interesting yet particular dielectric properties in comparison to other insulating gases that are commonly used under pressure that is higher than or equal to 1 bar.

Vacuum, that is qualified as being “high” (pressure range from 10^{-1} to 10^{-5} Pa, i.e. 10^{-3} to 10^{-7} mbar) of vacuum switch interrupters (see **fig. 2**) is in fact a low pressure gas: typically 10^{-6} mbar in a new interrupter.

__Fig. 2__: a 17.5 kV vacuum interrupter by Schneider Electric.

At this pressure, a 1 mm^3 volume still contains 27.10^6 gas molecules, but their interactions are negligible since their mean free path between two collisions is of the order of a hundred meters: the term "vacuum" is thus appropriate since each molecule behaves as if it were practically alone.

Reminder concerning the dielectric behaviour of gases

At normal pressure levels (atmospheric pressure and above) the dielectric behaviour of gases is represented by the right branch of the Paschen curve (see **fig. 3**): the breakdown voltage V is a growing function of the p d product (**p** = pressure, **d** = distance between the electrodes). This relation characterises the chain ionisation mechanism (Townsend avalanche effect) responsible for the breakdown: the electrons must acquire between two collisions sufficient energy (proportional to $\frac{V}{p\,d}$) to ionise the gas molecules and thus create other electrons.

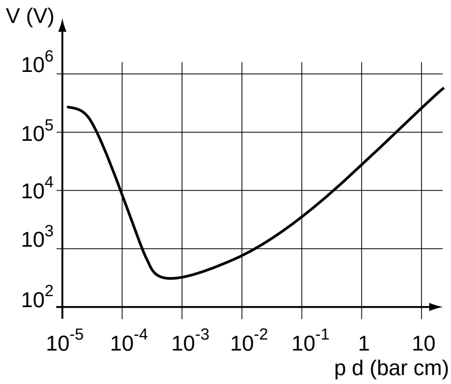


__Fig. 3__: change in dielectric strength of the air in function of the pressure (Paschen curve)

At low pressure values, this mechanism no longer functions. In fact, the electrons can acquire a lot of energy during their mean free path, but the probability that they encounter molecules to be ionised before reaching the electrode becomes weak: the electron avalanche and multiplication process of the charged particles cannot take place and the dielectric withstand is improved. This is what the Paschen curve shows: a minimum dielectric withstand for a p d product in the region of 1 Pa m for nitrogen. Below this value, the dielectric withstand rapidly improves (left branch of the Paschen curve) up to a level of values for p d that are lower than 10^{-2} Pa m. This level characterises the dielectric behaviour in vacuum interrupters (pressure lower than 10^{-3} mbar, i.e. 10^{-1} Pa, distances in the region of 1 to 10 cm). It corresponds to a high withstand level that is comparable to that of SF6 gas which is at roughly 2 bars for intervals in the region of one cm. In this field, it is no longer the residual gas ionisation mechanisms that limit the dielectric withstand but rather phenomena linked to the surface condition of electrodes, such as field electron emission and the presence of detachable particles.

c Field emission
Electron emission consists in extracting electrons from the metal of electrodes. This can

be done by sufficiently raising the temperature of the metal: it's the thermionic emission that is produced at the heated cathode level of the electron tubes. Another means is to apply a sufficiently strong electric field to the metal surface. This last phenomenon, field emission, is likely to be encountered in vacuum interrupters. It is controlled by the Fowler-Nordheim equation that, in a simplified form, is written:

$$j_e = \frac{AE^2}{\phi} \exp\left(-\frac{B\,\phi^{1.5}}{E}\right), \text{ where}$$

j_e is the electronic current density in Am^{-2}
$A = 1.54 \times 10^{-6}$ AJV^{-2}
E is the electric field in Vm^{-1}
ϕ is the work function in eV (4.5 eV for copper)
$B = 6.83 \times 10^9$ $VJ^{-1.5}$ m^{-1}
As can be seen from the values indicated above, field emission only becomes appreciable for field values on the surface of metals that are included between a few 10^9 Vm^{-1} and 10^{10} Vm^{-1}.
Very high values are being dealt with here; values that are significantly higher than the macroscopic field values for typical vacuum interrupters (in the region of 10^7 Vm^{-1} = 100 kV/cm). Even so field emission has been acknowledged in vacuum interrupters: it must therefore be concluded that locally, at the microscopic site level, the electric field is reinforced by an enhancement factor β in the region of a few 10^2 or 10^3. The phenomena that could explain these high β values have not yet been completely elucidated by researchers, who in general favour the microscopic point effect, or the inclusion of insulating particles at the surface of metals.

v Voltage conditioning
The existence of active microscopic emission sites in general results in poor dielectric withstand of new interrupters (a few 10 kV/cm); however, it has been experimentally noted that repeated dielectric breakdowns destroy these sites or at least considerably reduce the value of the enhancement factor that characterises them. A satisfactory dielectric withstand (in regard to assigned values) can thus be obtained only once the voltage conditioning process has been completed. It consists in applying a high voltage (around the expected withstand value) for a few minutes: the multiple breakdowns that occur, progressively raise the withstand between electrodes. This phenomenon is illustrated in **figure 4** which shows the change over time of the breakdown voltage as discharges pass: an upper limit for dielectric withstand improvement appears near 10^8 Vm^{-1}, which again corresponds to an "irreducible" microscopic β of about 100.

v Breakdown mechanisms
Dielectric breakdowns that originate in electronic current emission implement additional mechanisms: in fact, stable electronic currents (for maximum values of a few mA) do not

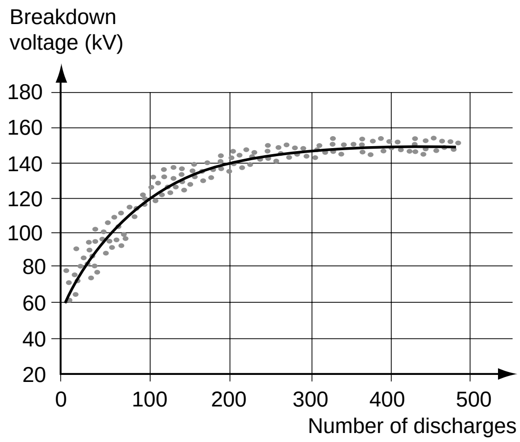


Fig. 4: improvement of the breakdown voltage between two electrodes in vacuum as a function of the number of discharges.

necessarily degenerate into a breakdown if the applied voltage is not increased, they may even diminish by themselves through the conditioning effect. Breakdown, itself, is linked to the creation of localised plasma (ionised gas), which is sufficiently dense for the electron avalanche phenomenon characteristic of gaseous discharges to be produced.
The plasma may be produced on the cathode side through the explosion of the microscopic emissive site caused by the intense overheating due to the current density which is locally very high (Joule effect): breakdown is produced in the metal vapour that was generated by the destruction of the emissive site.
The plasma may also be produced on the anode side which is bombarded by a beam of highly energetic electrons (which also results in the emission of X-rays). This localised flow of energy causes the desorption of gases absorbed on the surface and the vaporisation of anode metal: the gas produced from this is thus ionised by beam electrons, and the breakdown occurs.

c The influence of detachable particles
A second factor is likely to cause dielectric breakdowns in vacuum: detachable particles present on the surface of the vacuum interrupter walls. Set free, either by a shock, or by the effect of electrostatic forces, these charged particles acquire energy by going through the inter-electrode gap. At the moment when they impact with an electrode that attracts them, they are likely to trigger a breakdown in two ways, which may be complementary:

v through a local rise in the gas density due to the desorption of absorbed gas molecules;

v by triggering the field emission phenomenon and the partial vaporisation of the particle or of the electrode under the effect of the beam that bombards them.

Confirmation of the practical importance of the particles is the experimental observation that the dielectric withstand in vacuum between two electrodes increases approximately in proportion to the square root of the distance which separates them. This relation can be explained by the hypothesis that the particles must reach sufficient energy (proportional to V^2/d) to be able to cause a breakdown. For this same reason, large particles, that can carry a higher electrical charge, are more troublesome than small ones.

From the unfavourable influence that detachable particles have on the dielectric withstand of vacuum interrupters, two consequences are to be noted:

c it is difficult to reach very high withstands, even with a great amount of space between electrodes (see **fig. 5**),

c the dielectric withstand of a vacuum interrupter presents a random character: a delayed breakdown can occur in regard to voltage application and for a voltage of less than that which was tolerated right before without a breakdown.

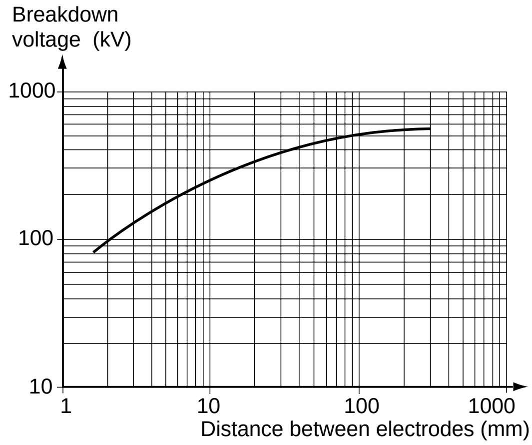


***Fig. 5**: accessible withstands for very large distances between electrodes.*

Resume

c Vacuum shows interesting dielectric properties if applied voltages are limited to a region of 100 to 200 kV, which corresponds to an insulation level required for voltage ratings of i 36 kV for which distances of a few centimetres between electrodes suffice. Above this level, reaching the necessary dielectric withstand level becomes laborious and less efficient than with SF6 gas insulation.

c The dielectric withstand of a vacuum switching device evolves over time. Indeed, mechanical operations and the effect of electrical arcing modify the contact surface condition and generate particles: the withstand level reached after voltage conditioning therefore cannot be considered as permanently acquired. Vacuum is thus not the ideal insulating medium when the reliability of dielectric withstand is essential, for example for a disconnector application.

2.2 Electrical arcing in vacuum

Even though, as described in the above section, vacuum may be an excellent dielectric, an arc can very well "live" in the "vacuum". In fact, the arc voltages in vacuum are in general considerably lower than those of arcs that develop in other mediums, which constitutes an advantage in regard to the energy that is dissipated in the arc. Arcs in vacuum occur, by voluntarily simplifying, in two main forms: the diffuse mode and the constricted mode.

A diffuse mode, characteristic of the "vacuum" medium

The diffuse mode is specific to arcing under vacuum: it shows remarkable particularities which clearly differentiate it from arcings in gaseous mediums. It is the mode which a vacuum arc naturally adopts for a current range covering a few amps to a few kA.

The main characteristics of the diffuse mode are as follows:

c the cathode emits into the inter-electrode gap, via one or several cathode spots, a globally neutral plasma made up of electrons and of high speed ions whose velocity is primarily directed perpendicularly to the surface of the cathode;

c the anode, with its entire surface immersed by this plasma, reacts as a passive charge collector.

The cathode spots and the plasma are specificities of the arc in the diffuse mode.

c The cathode spot

The cathode spot is a very small sized zone (radius in the region of 5 to 10 µm), capable of emitting a current that can reach some hundred amps.

Extreme temperature and electric field conditions rule at the cathode spot level (typically 5000 K and 5 10^9 V/m). These conditions allow for electronic emission by combining thermionic and field emission mechanisms into thermo-field emission which is capable of producing very high current densities (between 10^{11} to 10^{12} A/m^2).

Above 100 A, this spot subdivides itself and several spots coexist on the cathode, in sufficient number to transit the current at the rate of some hundred amps each. They mutually drive each other back, which led their movement to be qualified as “retrograde” for it is contradictory to the normal effect of electromagnetic forces. Thus arcing in the diffuse mode tends to occupy the entire available surface on the cathode (even if at any given moment the emissive sites only represent a very small fraction of the cathode).

c The plasma

At the macroscopic level, the cathode spot (crater and close-range plasma that is associated with it) seems to be the production point of a low density plasma coming from the spot and which fills the inter-electrode gap. This globally neutral plasma (equal densities of **+** and **-** charges), is made up of electrons and ions which are typically double charged (for arcing on electrodes with a Cu base). One of the characteristics of this plasma is the great speed of the ions which have an energy that is higher than the arc voltage (which testifies to the highly energetic phenomena that are produced in the zone of the cathode spot). It is therefore not difficult for these ions, which emanate from the spot with a distribution of speed approximately in cos (angle/normal) to reach the anode and create an ionic current in the opposite direction to the main electronic current which typically represents 10 % of the arc current. The directed velocity of these ions is in the region of 10^4 m/s, higher than their thermal agitation speed.

One of the significant consequences of the high speed of the ions created by the cathode spots is their low transit time through the inter-electrode gap (typically in the region of 1 µs). The plasma, created by a cathode spot, is made up of highly mobile particles (rapid electrons and ions, virtually no neutral particles) and thus disappears very rapidly when the spot stops functioning (around current zero).

The anode is immersed in the plasma that emanates from the cathode spots. It behaves like a passive electrode that collects charges and extracts the current that is imposed by the circuit by adjusting its voltage: it is negative with respect to the plasma as long as the current is lower than the one that corresponds to the impacts linked to the thermal agitation of electrons.

The distribution of voltages in the arc is as follows:

v a cathode voltage drop in the region of 20 V in the immediate area of the cathode;

v a voltage drop of a few volts in the plasma which increases with the distance and the current (positive characteristic allowing for the coexistence of several parallel arcs, contrary to arcs in gas);

v a negative anode drop in the case considered above (moderate current absorbed by the anode).

In this mode, there is little cathode erosion: it corresponds to the ion flow leaving the cathode, i.e. roughly 40 µg/C. A significant number of these ions place themselves on the anode which, in alternating current, means that net erosion is much lower: approximately divided by a factor of 10 for contactors that operate in this mode with limited currents and electrodes with little spacing.

A constricted mode similar to the one of an arc in a gaseous medium

When the current increases, the previously described situation tends to evolve first of all on the anode side. Several phenomena converge towards this evolution.

c First a contraction of the plasma column generally explained by the Hall effect (charge deviation by the azimuthal magnetic field created by the other current lines, from which the appearance of a radial component tends to confine the current lines towards the axis): the current is concentrated on a more limited area of the anode.

c Furthermore the anode attracts more and more electrons, and the neutrality of the plasma is no longer ensured: positive ions are lacking to balance the space charge of electrons near the anode. This leads to the formation of a positive anode voltage drop which is needed to attract electrons despite the space charge. The energy received by the anode increases and tends to be concentrated on a reduced area: the anode heats up and starts to emit neutral particles that are ionised by the incident electrons. Near the anode, a secondary plasma, made up of secondary electrons and ions that are less energetic than those emitted by the cathode spots, appears.

These phenomena result in the appearance of a luminous anode spot, considerably larger (in the region of a cm^2) than the cathode spots, made of molton metal which spills considerable amounts of vapour, which becomes ionised in the flow coming from the cathode, into the inter-electrode gap.

This contraction effect on the anode side also leads to a contraction on the cathode side since a preferential path is created thanks to the plasma generated by the anode: a cathode spot corresponding to the anode spot is established and the arc takes up the constricted mode that is characteristic of arcs in a gaseous medium. Here, we are dealing with an arc in an atmosphere of dense metallic vapours, for which operating mechanisms now rely on the ionisation of the gaseous medium.

This arc in the constricted mode is thus characterised by a plasma made up of electrons (most of which are secondary), of neutral particles and ions the energy of which is near that of the neutral particles, thus relatively slow.

2.3 Phenomena associated with breaking at current zero

General breaking principles

All medium voltage circuit-breakers take advantage of the natural passage of alternating current through zero (twice per period, i.e. every 10 ms for a 50 Hz current) to interrupt the current.

c The inevitable arc phase
Once a fault current has been established in a circuit, the separation of circuit-breaker contacts does not have an immediate repercussion on current flow. At the level of the last contact points, the current density becomes very high, which causes a local fusion and the appearance of a liquid metal bridge. The contacts continue to move away from each other, this bridge is heated up by the current and becomes unstable and its rupture results in the appearance of a constricted arc in the metal vapours originating from the liquid bridge explosion. The arc voltage that appears is, in the case of a vacuum, low in comparison to the electromotive forces of LV or HV network generators: the current flowing in the circuit is thus not considerably affected, nor limited, by this arc voltage.

This arc will adopt the diffuse mode or the constricted mode described in the preceding section, possibly evolve from one to the other, and will be maintained up to current zero.

c The recovery phase after current zero
If the plasma, which up to now allowed for the current to flow through, takes advantage of this break to dissipate itself very rapidly, the current may be prevented from establishing itself for the following half-cycle. A transient recovery voltage (TRV), imposed by the circuit, then appears at the terminals of the element that has switched from a conductive state to an insulating state. In the case of a short-circuit, this TRV is caused by the oscillations between the local capacitances and the network inductances. In its initial phase, it approximately presents a (1-cosinus) shape with a natural frequency in the order of a few tens of kHz in MV network and reaches a peak value that is greater than the normal network voltage, which corresponds to average rates of rise of a few kV/µs.
If the newly insulating medium tolerates the dielectric stress which is then applied to it, the current is successfully interrupted (see **fig. 6**).

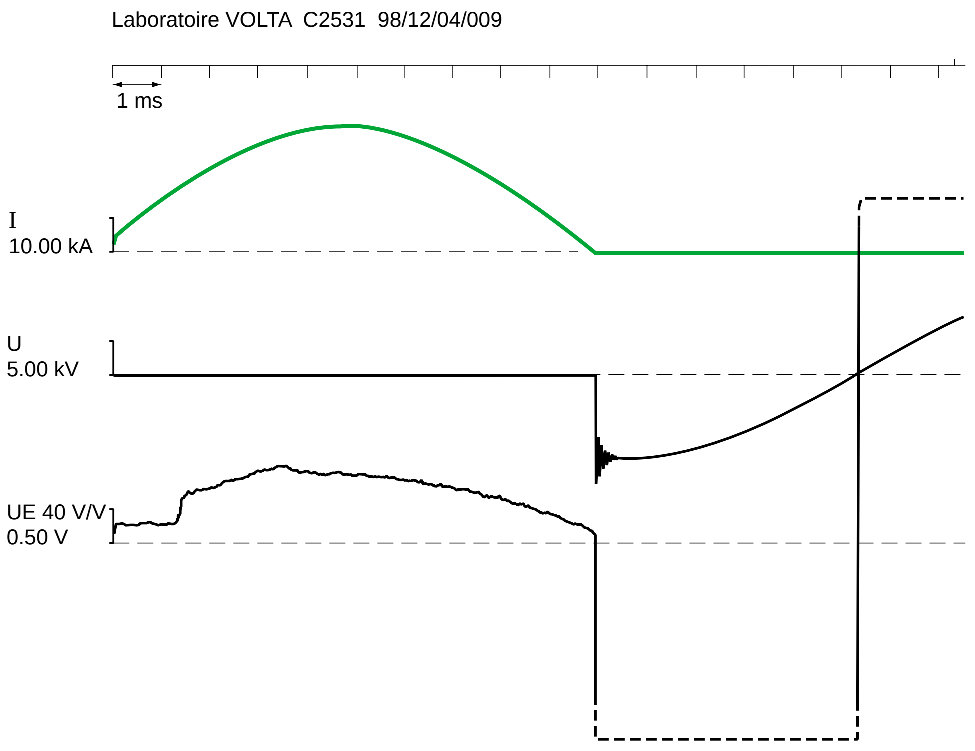


Fig. 6: a successful current interruption (source Merlin Gerin).

Case of vacuum switching

To determine the conditions for successful current interruption, it is necessary to study the phenomena that intervene near current zero in the vacuum arc plasma.

c Post-arc current

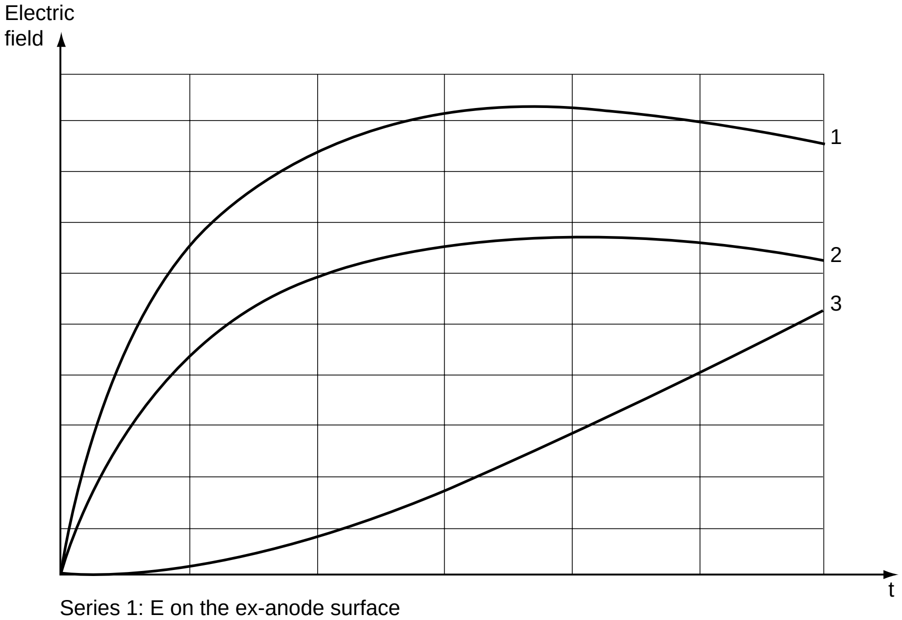
Near the end of the half-cycle, the current decreases at a rate which is proportional to the peak current value and to network frequency (di/dt = $\omega \hat{I}$). The vacuum arc returns to the diffuse mode and, near current zero, only a single cathode spot remains. However, the inter-contact gap is still filled with a residual, globally neutral plasma, that is made up of electrons, ions and neutral particles which come from the preceding arc.

At the time of current zero, the last cathode spot extinguishes itself because the arc voltage disappears. Thus, the emissive site, which created charged particles (electrons and ions) needed to transport the electric current, no longer exists.

From this moment on, a voltage with an inverse polarity to that of the preceding arc voltage (the TRV), starts to appear between the two contacts: the ex-anode becomes negative in regard to the ex-cathode and drives back the electrons. The current that flows in the circuit is now only made up of ionic current that the ex-anode extracts from the residual plasma that becomes scarce: this current with an inverse polarity to that of the arc current is called post-arc current.

The ex-anode is thus no longer in contact with the neutral plasma which is still present in the inter-contact gap: it is separated from it by a sheath from which the electrons, driven back by the negative voltage of the ex-anode, are absent. Only positive ions cross the neutral plasma boarder into the sheath and are then accelerated towards the ex-anode. The voltage that appears between the ex-cathode and the ex-anode is thus applied only to the thickness of the sheath that separates the neutral plasma from the ex-anode. Moreover, the presence of positive space charges in this sheath reinforces the electric field on the surface of the ex-anode which is higher than the average field that corresponds to the TRV value divided by the sheath thickness (see **fig. 7**).

The thickness of the sheath that surrounds the ex-anode is proportional to the voltage applied between the neutral plasma and the electrode and inversely proportional to the density of the positive ions: it thus increases according to the change in TRV and all the more rapidly as the plasma rarefies. When the limit of the sheath reaches the ex-cathode, the residual plasma has disappeared, since all of its charges have



Series 1: E on the ex-anode surface
Series 2: U_{TRV} / sheath thickness, average field in the sheath
Series 3: U_{TRV} / inter-contact gap

Fig. 7: *electric field on the surface of the ex-anode and the corresponding average field between the electrodes.*

been used by the post-arc current which becomes nil.

These phenomena take place on a very reduced time scale: the total length of post-arc current is typically 1 to 10 µs (see **fig. 8**).

c Causes of interruption failure

So that current can be maintained, mechanisms that create electrical charges must replace the cathode spots that have extinguished on the ex-cathode.

The first possible mechanism is the ionisation of the neutral metal vapour that is present in the inter-contact gap. This ionisation is all the more easy that the density of neutral particles is higher. If the vapour density is very high (very hot zones on the contacts produce a great amount of metal vapours), the current does not interrupt at all: there is no increase in the TRV, this is called "thermal non-breaking".

If the density of neutral particles is sufficiently high so that the dielectric withstand of the vacuum can be reduced (approaching the minimum value of the PASCHEN curve), the current can be interrupted, but the inter-contact gap cannot tolerate the applied TRV and a breakdown occurs during the rise in the TRV, here we have "dielectric non-breaking".

A second possible mechanism is the appearance of cathode spots on the ex-anode. For this, electronic emission conditions must be locally reunited on the surface of the ex-anode:

v thermionic emission if very hot points remain, this is the case when the anode contains refractory metal (W);

v field emission or combined T.F. emission if the electrical field applied to the surface is significant at certain sites with a high enhancement factor β.

We previously saw that the electric field applied to the surface of the ex-anode appears with high values as of the start of TRV application since the sheath is thin; the higher the ion density, the thinner the sheath is. Furthermore, the ex-anode is bombarded by ions that have been accelerated in the sheath by the TRV, which causes localised overheating. The probability of cathode spots appearing on the ex-anode is thus greater if the density of ions in the residual plasma is high, which goes hand in hand with a high density of neutral particles which slow down, through collision, the rapid ions emitted by the cathode spots, thermalize them (average energy near the temperature of the plasma) and slow their diffusion at the time of current zero.

If plasma density is sufficiently low at the time of current zero, the conditions for successful breaking have probably been satisfied: the current is interrupted and the inter-contact gap withstands the recovery voltage up to its peak value.

In the case of vacuum circuit-breakers, success is not however entirely guaranteed once this stage has been completed. In fact, for a few

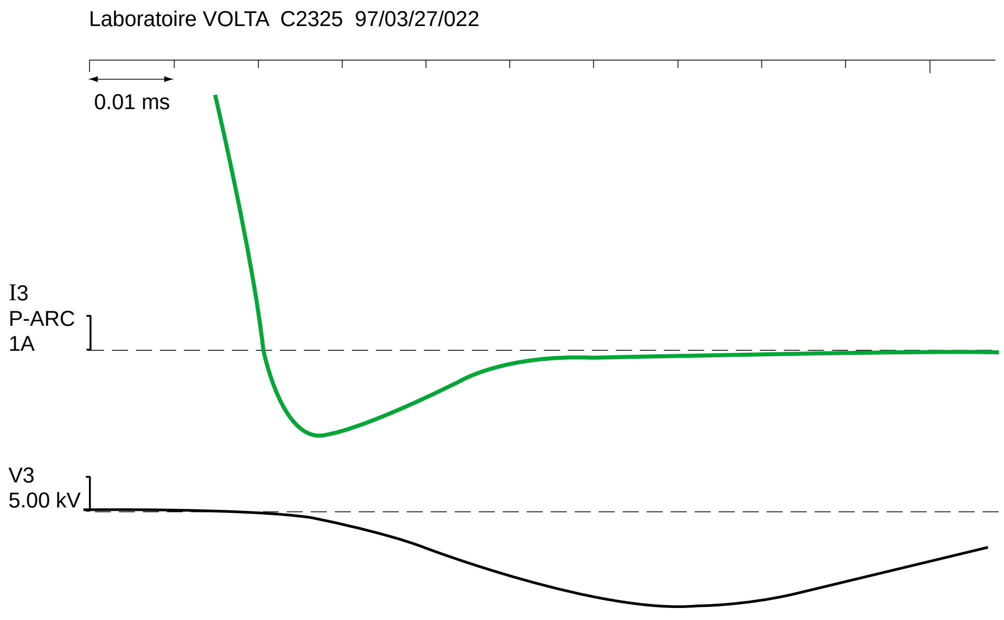


Fig. 8: post-arc current with a particularly long length of roughly 40 µs, test at the breaking capacity limit of the interrupter.

milliseconds after the break, the situation inside the interrupter can still change and dielectric breakdowns can occur:

v particles generated during the arcing phase can detach themselves from the walls under the effect of vibrations and/or electrostatic forces;

v molten areas on contacts can emit droplets under the effect of electrostatic forces;

v solidification of the liquid metal can modify the surface of the contact or free dissolved gas.

When a vacuum interrupter is tested at the limit of its breaking capacity, after breaking that appears to be successful, it is not rare to see late occurring dielectric breakdowns (see **fig. 9**) which may be:

v either transient (duration of a few µs) for the interrupter is able to break the HF current that follows the discharge. If these transient breakdowns occur more than a quarter of the industrial frequency period after current zero, they are considered as non-sustained disruptive discharges (NSDD) and interpreted as a sign of device weakness (for this reason the maximum number of NSDD that is tolerated is three for a complete series of breaking tests on a circuit-breaker as in IEC 60056);

v or complete and, in this case, the power current reappears after a more or less long interruption period (in the region of 0.1 to 1 ms).

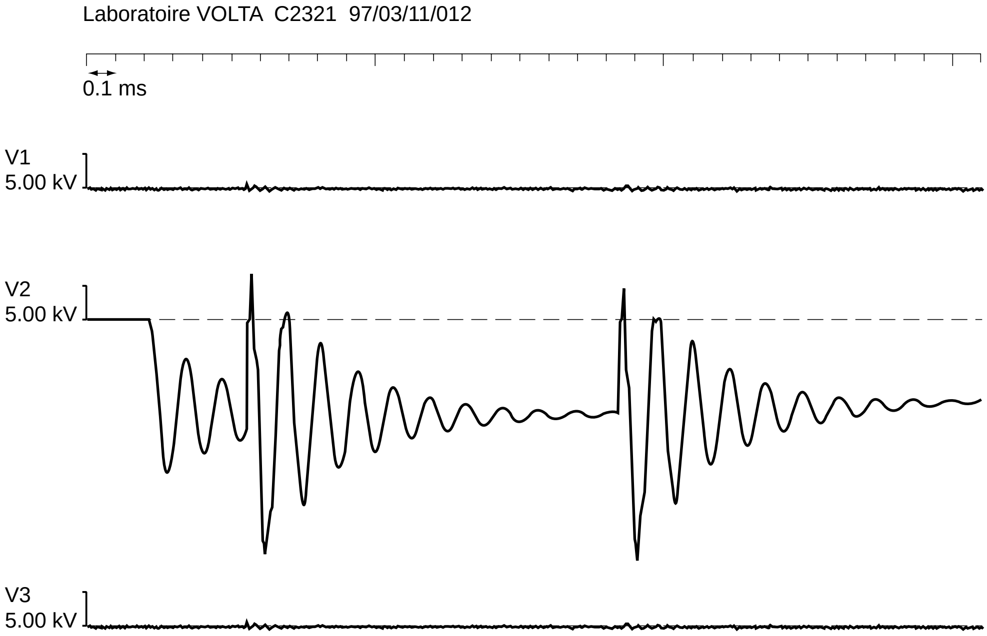


Fig. 9*: example of late occurring dielectric breakdowns.*

2.4 The practical design of vacuum interrupters

Choice of the breaking technique

The preceding section highlighted the conditions that must be satisfied for successful breaking. These conditions are almost always satisfied when an arc remains in the diffuse mode, that is to say when currents to be interrupted do not exceed a few kA. It is the case for switches and contactors that can therefore use very simple butt contacts.

When an arc passes into the constricted mode, the energy is dissipated onto a reduced electrode surface, and it causes localised overheating and considerable vaporisation. If this arc remains immobile, breaking is no longer guaranteed.

Two methods are used to overcome the difficulties that are produced by the passage of an arc into the constricted mode.

v The first consists in causing a rapid circular movement of the constricted arc so that the energy is distributed onto a large part of the contact and overheating is limited at all points: this is obtained through the application of a radial magnetic field $\vec{Br}$ in the arc zone.

- The second consists in preventing the passage into the constricted mode through the application of an axial magnetic field: when the field reaches a sufficient value, the arc is stabilised in a mode qualified as a diffuse column and does not concentrate itself ; even though it is immobile the arc uses most of the contacts' surface and overheating therefore remains limited in this case as well.

- Radial magnetic field technique $\overrightarrow{Br}$

The constricted arc can be compared to a conductor through which a current flows, the direction of which is parallel to the axis of the contacts. If a radial magnetic field (RMF) is applied to this conductor, the resulting electromagnetic force will have an azimuthal direction and cause rotation of the arc around the axis of the contacts.

The $\overrightarrow{Br}$ field is caused by the path imposed on the current in the contacts. Two types of contact structures are used to obtain this result (see **fig. 10**):

- contacts of the spiral type,
- contacts of the "cup" or "contrate" type.

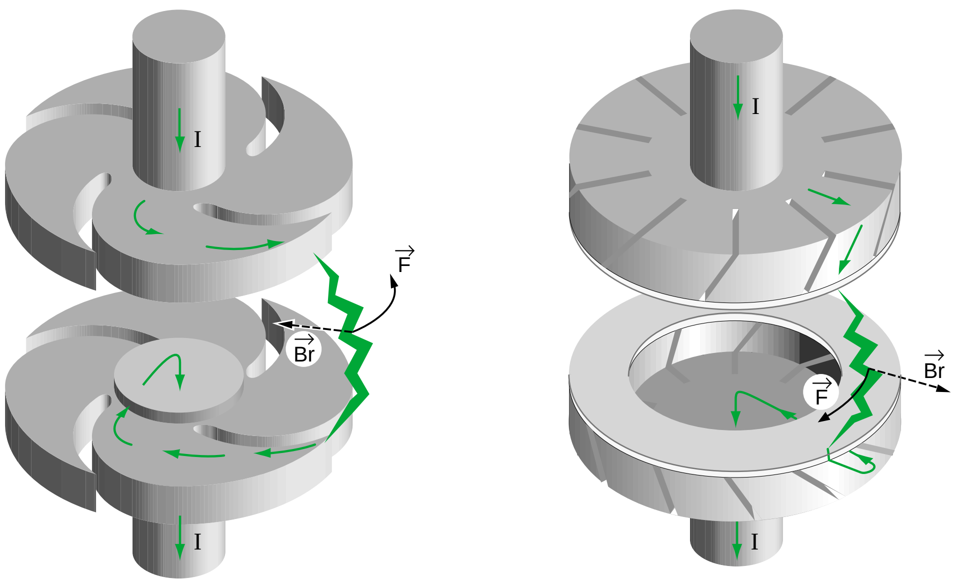
Correct functioning of RMF interrupters is linked to obtaining a satisfactory compromise at the contact geometry level and in particular of the slot width for contacts of the spiral type:

- if the width is too large, the arc has a hard time "jumping" from one part of the contact to the other, which may make it stationary at the end of the track and thus overheat part of the contact (since the arc is in the constricted mode);
- if the width is too small, the slot may be easily filled by the fusion of contact material, and the current path, thus modified, leads to the disappearance of the RMF and immobilisation of the arc.

Even though mobile, the rotating arc remains constricted and therefore exerts energetic force on the part of the electrode which carries it, the high pressure of the arcs roots expulses the molton contact material in the form of droplets. This process is an efficient means of limiting the overheating of the rest of the electrode (or to facilitate its cooling), for the energy brought by the arc is taken away with the expulsed material which has condensed on the surrounding walls; in return, it leads to relatively high contact erosion.

- Axial magnetic field technique $\overrightarrow{Ba}$

When an arc plasma is submitted to a sufficient axial magnetic field (AMF), the electrons are obliged to follow trajectories that are parallel to the field lines which are helical-shaped lines, the axis of which is parallel to the contact axis since $\overrightarrow{Ba}$ is combined with the azimuthal field produced by the current itself.



a - Spiral

b - Contrate

Fig. 10: *contact structures used to create the RMF (spiral and "contrate").*

The much heavier positive ions in the plasma are not controlled as efficiently by the field, but are retained by the electrostatic force developed by the negative space charge of the electrons trapped by the AMF: these electrostatic forces ensure that the plasma has a tendency to remain globally neutral. Consequently, electron confinement results in the confinement of all of the plasma in a column that corresponds to the field tube intercepted by the cathode: if this tube is parallel to the electrode axis, most of the plasma produced by the cathode arrives at the anode. The arc, in these conditions, conserves most of the diffuse mode characteristics although with a current density level that is considerably higher:

v the arc voltage remains moderate since the plasma conserves its neutrality up to near the anode (no ion "starvation" phenomenon);

v the tendency of the arc to concentrate on the anode side (the Hall effect) is interfered with by the AMF which forces electrons to maintain a trajectory that is essentially parallel to the axis;

v if the surface of electrodes, in particular of the anode, which is intersected by the arc column, is sufficient for the current, then the energy density and thus overheating remain limited. The vaporisation of contact material is sufficiently reduced so that the nature of the plasma is not modified by the ionisation of neutral particles.

Two main conditions need to be satisfied so that the arc remains in this diffuse column mode that is favourable to current interruption:

v $\vec{Ba}$ must be sufficiently high. The critical AMF needed to prevent the formation of an anode spot is given in the experimental formula:
$Ba_{crit} = 3.9\ (Ip - 10)$
(Ba in mT, with Ip peak current value in kA),

v the surface of the electrode must be sufficient for a given current value: the current density not to be exceeded is in the region of 17 A/mm^2 (RENTZ formula). In fact, this current density limit is only valid as a first approximation and the breaking capacity of interrupters with AMF does not change in direct proportion to the surface of the contacts. In fact, the initial constricted arc that was produced at contact separation and the time needed for it to occupy the entire available electrode surface must be taken into account: the breaking capacity, as a function of contact diameter, approximately follows a variation of $d^{1.4}$.

The arc in an AMF interrupter is much less mobile than in a RMF interrupter. Even if the current density is sufficiently high to cause the fusion of anode material, projections remain limited. Contact erosion is therefore slighter than in a RMF, however the molton material remains in place and delays the cooling of the electrode surface. Due to this, even though in principle the use of the available contact surface appears more efficient in an AMF then in a RMF this is not always verified. In particular, for high currents and low voltages, in a RMF higher breaking capacities can be reached for a given surface, the price to pay however being significant erosion.

Diverse solutions can be used to obtain the AMF between contacts by using the current being interrupted:

v coils integrated behind the contacts (see **fig. 11**);

v a magnetic circuit that channels the azimuthal field created by the power leads and which straightens it into an AMF in the inter-contact zone;

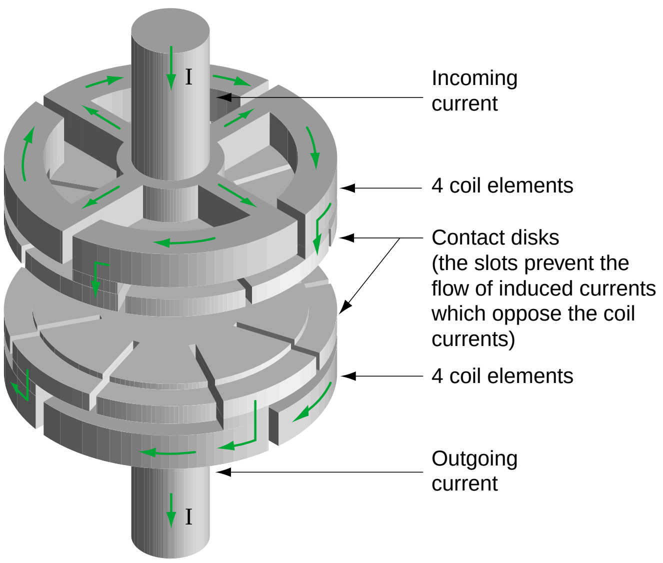


***Fig. 11**: example of axial magnetic field contacts .*

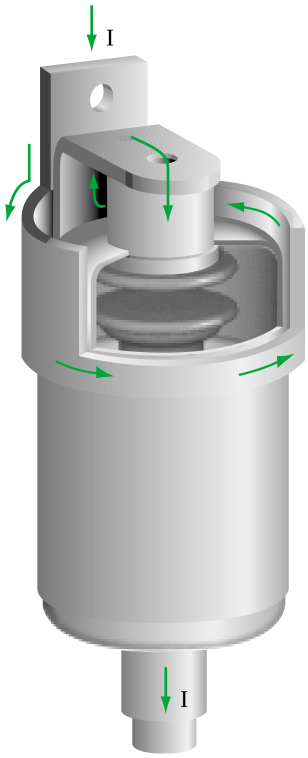


Fig. 12: axial magnetic field interrupter with external coil.

v an external coil that surrounds the inter contact zone (see **fig. 12**).

In general, the path imposed on the current, to create a sufficient AMF in the inter-contact gap, is longer than the one needed to create a local RMF. For a given volume, contact resistance is thus lower with the RMF technique, which is advantageous for circuit-breakers with high continuous current ratings.

However, the shapes needed for RMF contacts are more angular than those of AMF contacts and therefore less favourable on the dielectric level: the AMF is thus advantageous for high voltages.

The engineer thus chooses one of the two techniques in function of their respective advantages and depending on the foreseen application (see **fig. 13**).

Capacity:	**RMF technique**	**AMF technique**
High continuous current	+++	+
High voltage rating	+	+++
Electrical endurance	+	+++
Breaking capacity	++	++

legend: +++ = very good ++ = good + = average

Fig. 13: comparison table for the two breaking techniques

Choice of the architecture

c Vacuum interrupter components.

A vacuum interrupter is made up of few components (see **fig. 14**).

v Two electric contact assemblies of the butt type (since, under vacuum, sliding contacts would weld with each other); one is fixed, the other mobile. Each assembly includes a cylindrical electrode that conducts the current to the contact disks.

v A gas-tight enclosure including an insulator that ensures electric insulation between fixed and mobile contacts.

v A shield that protects the internal side of the insulator against condensation of metal vapour produced by the arc.

v A metal bellows which allows for the mobile contact to move while maintaining the enclosure tightness.

These are the basic components that are included in all interrupters. Moreover, in circuit-breaker interrupters, there are devices that generate magnetic fields (radial or axial) needed for breaking the power arc.

Variations are mainly possible at the shield level and on devices that produce magnetic fields.

c Shield configurations

The main choices at the shield level deal with:

v its fixing mode which determines its voltage: the voltage is fixed (is the same as that of the fixed electrode) if the shield is connected to this end of the interrupter, it is floating if the shield is fixed to an intermediary point on the insulator without an electric connection with one of the contacts.

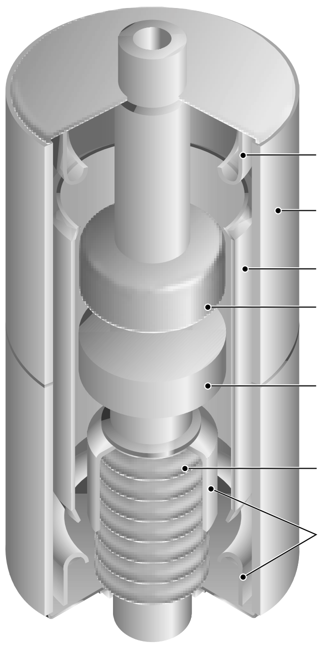


Fig. 14: vacuum interrupter components.

v its position which can be inside or outside the enclosure, in the latter case the shield is part of the enclosure and must be gas-tight.

By combining these different options, four configurations are possible, they are all used in function of desired characteristics.

As a general rule:

v a shield with fixed voltage is chosen when low cost is desired and a shield with floating voltage when high performance is sought.

v an external shield is chosen for compactity in diameter and an internal shield because it is simple to make.

c Devices that generate radial or axial magnetic fields
Devices that produce the RMF needed to rotate the arc must be positioned as close as possible to the arc: they are therefore built-into the same structure as the contacts inside the interrupter. The two most common geometries were described in the preceding chapter: "spiral" contacts and contacts of the “cup” or contrate” type. The choice of one solution over the other does not modify the general architecture of the interrupter.

However, there are two possible architectural choices for AMF interrupters.
In fact, the device that generates the AMF (most often elements of circular coils with an axis parallel to that of the interrupter) can be housed in the internal contact structure as with RMF interrupters, or outside of the interrupter. In the last case, there is a coil that surrounds the contact separation zone. The coil is in series with the fixed contact and the circuit current flows through it. **Figure 15** shows a realisation of this type of configuration: it can be noted that, to reduce the dissipated power in the device, the coil is made up of three parallel elements. One of the disadvantages of this architecture is the path length imposed on the current to create a sufficient AMF in a significant volume. This therefore leads to greater losses that however do not necessarily result in greater temperature rise, the coils in the air being more efficiently cooled (by convection) than those that are integrated into the contacts on the interrupter.

Moreover, the presence of a coil with the same voltage as the fixed contact, around the contacts, practically imposes the choice of a shield with a fixed voltage for this type of interrupter.

One might think that the presence of an external coil presents a disadvantage in regard to interrupter dimensions by increasing its external diameter. In fact, the possibility of using the entire contact surface that is subjected to the relatively uniform AMF created by the external coils (which is not the case for contacts that have integrated coils) compensates this disadvantage and dimensions are comparable. The main advantage of AMF architecture with an external coil is the possibility of making a compact interrupter, simple thus economical. The disadvantages on the heat dissipation and dielectric levels (because of the fixed shield design) make the architectures with devices integrated into the contacts (AMF or RMF) more attractive for high voltage levels (u 24 kV) or for high current ratings (u 3150 A).

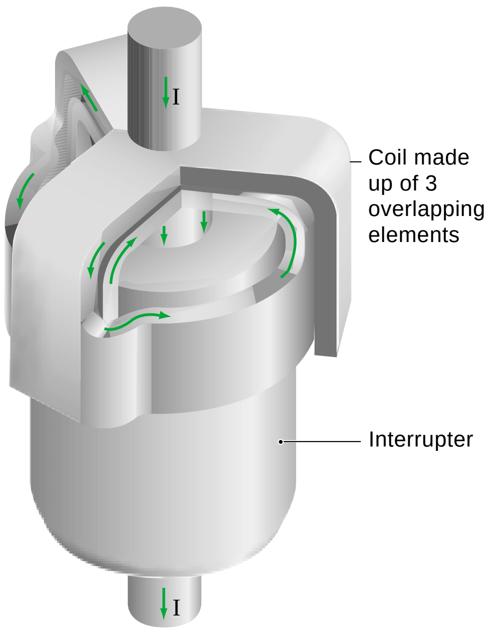


***Fig. 15**: example of a coil, surrounding the contact separation zone, made up of three parallel elements.*

Choice of materials and manufacturing technologies

For vacuum interrupters, the choice of materials and manufacturing technologies are guided by the need to:

v guarantee the preservation of high-vacuum (< 10^{-3} mbar) needed to operate the interrupter for its life span (30 years),

v ensure the rated performances and in particular the breaking capacity.

c Choice relative to the requirements for vacuum quality
All vacuum chambers are subjected to deterioration of the vacuum level that is linked to degassing phenomena which appear when pressure reaches sufficiently low values. Degassing is first of all a surface phenomenon that corresponds to the detachment of gas molecules absorbed on the walls. This gas is rather easily and rapidly eliminated by relatively moderate heating (in the region of 200 °C) of the walls of the enclosure during pumping.

Then volume degassing, which corresponds to the diffusion, towards the surface of metal materials, of dissolved gases such as hydrogen, appears.
To prevent degassing, mainly coming from massive parts, from progressively degrading the vacuum level of the interrupter, it is important to:

v use materials with as low a gas content as possible (for example copper Cu-OFE oxygen free);

v proceed with high degassing of materials by conducting long-term pumping of the interrupter at a sufficiently high temperature (typically for some ten hours at a temperature in the region of 500 °C).

Gases bound to the metals (in the shape of chemical compounds) are not sensitive to degassing, however they can be freed under the arc effect. Therefore, the materials used for arc contacts must be elaborated in a vacuum environment so as to have the lowest possible gas content.

The enclosure of the interrupter must be perfectly tight, which implies the absence of leakages and permeation in service conditions. That is why enclosures are made of metal and ceramic materials: insulators made of alumina ceramic have replaced glass for they can tolerate much higher temperatures and thus allow for better degassing.

Bonding between the metal parts of the enclosure are welded or brazed. Ceramic and metal are also brazed, either using reactive brazing which enables a direct bond with the ceramic, or using traditional brazing by coating the ceramic with metal beforehand (Mo-Mn + Ni).

Final brazing operations are conducted in a furnace, under a vacuum to ensure the degassing of materials. More and more often, sealing of the interrupter is conducted during the brazing under vacuum process as well, which allows for the pumping operation to be eliminated.

Taking into account the tightness level needed to allow the mobile contact to move, the metal bellows is the only solution used. It is generally made of thin austenitic stainless steel (typically 0.1 to 0.2 mm). Its design and that of brazing joints with the rest of the enclosure must be carefully studied so as to ensure high mechanical endurance despite the unfavourable effect of thermal cycles imposed by brazing.

Lastly, materials that are used in small quantities, but which play an important role in obtaining and maintaining high-vacuum over time must be mentioned. Getters are based on very chemically active metals (barium, zirconium, titanium, etc.) with most of the gases that are likely to be found in vacuum enclosures. The getters are activated, under high-vacuum, through heating at a sufficient temperature to cause the diffusion of the passivated superficial layer into the bulk, and the regeneration of an active metal surface capable of absorbing the gas molecules that are in the interrupter. This activation operation is conducted during pumping or when the interrupter is sealed using brazing under vacuum: it is in particular due to getters materials that this last procedure, more industrial than pumping, while ensuring a satisfactory quality of vacuum, was able to be developed.

c Choice of contact material.
Good contact material for a vacuum interrupter must meet a certain number of requirements:

v be a good electrical conductor, so as to offer reduced contact resistance;

v present good mechanical resistance to repeated shock which the contacts undergo when closing;

v must not form solid welding upon on-load or short-circuit closings so that the opening mechanism can separate the contacts and so that the break of the welded zone does not create excessive damage to their surfaces;

v produce little metal vapour during the arc phase so as to enable rapid dielectric recovery of the inter-contact gap after breaking, which implies:
- low vapour pressure,
- reduced droplet production during the material fusion phase;

v present good dielectric characteristics during the TRV application phase, which implies:
- a sufficiently smooth surface, without any notable roughness (low β),
- no overheated points emitting by thermionic effect (case of refractory materials with reduced thermal conductibility),
- no likelihood of forming easily detachable particles;

v allow the existence of stable cathode spots up to low current values so as to minimise the chopped current and overvoltages associated with this phenomenon, which in particular implies a sufficiently high vapour pressure.

It turns out that these numerous required qualities are sometimes contradictory. It is thus necessary to find an acceptable compromise for the foreseen application in function of privileged properties which are:

v for circuit-breakers, dielectric recovery after the high current arc phase (good breaking capacity);

v for contactors, low erosion and minimum chopped current (electrical endurance and reduction of overvoltages);

v for switches, resistance to welding and dielectric withstand under high voltages (absence of restrikes).

Presently, the best compromises have been obtained with composite materials and the three material families that are the most often used are:

v CuCr for circuit-breaker applications;

v AgWC for contactor applications;

- WCu for switch applications and in particular those designed for the control of high voltage capacitors.

CuCr have been proven to be the best materials for circuit-breaker applications and do not appear to be able to be dethroned in the short-run, even if changes cannot be excluded.

Proportions used vary between 80 and 50 % for Cu, the remaining percentage for Cr.

A high proportion of Cu is favourable for the electric conductivity (low contact resistance) and thermal conductivity (good evacuation of arc energy).

A high proportion of Cr is favourable for withstanding welding and dielectric withstand under high voltage.

The gas content of material must be as low as possible since, when it is fused or vaporised, these gases are freed into the inter-contact gap and are harmful to breaking. The long-term effect on the vacuum level is less disturbing than could be imagined since Cr condensed on interrupter walls plays the role of getter and reabsorbs these gases.

Lastly it must be noted that the arc modifies the superficial layer of the material and improves its qualities by:

- eliminating included gases and surface oxides,
- obtaining very fine granulometry (precipitation of Cr melted in the copper matrix),
- homogenising material.

This effect is sometimes qualified as "current conditioning" (through analogy with voltage conditioning): in general the behaviour of contacts and the breaking performance improve after a few breakings.

3 Breaking in vacuum and overvoltages during switching of inductive circuits

Vacuum switching devices (contactors, circuit-breakers, switches) are likely to generate overvoltages when interrupting current in inductive circuits (no-load transformer, non-charged motor or motor in the start-up phase). Due to the special properties of vacuum, these overvoltages can be of a different nature than those generated in the same conditions by switchgear that uses another type of medium (air, SF6, oil, etc.).

In general these overvoltages do not pose a problem and do not need any special device. However in the case of sensitive loads (for example motors) it is recommended to install overvoltage limiting equipment.

3.1 Overvoltage generating phenomena

Overvoltage associated with an ideal breaking

Even in the theoretically perfect breaking case using an ideal circuit-breaker, a certain overvoltage level is inherent to the interruption of current in an inductive circuit. Indeed, voltage values at the terminals of different circuit elements must reach a new steady state that corresponds to the open state.

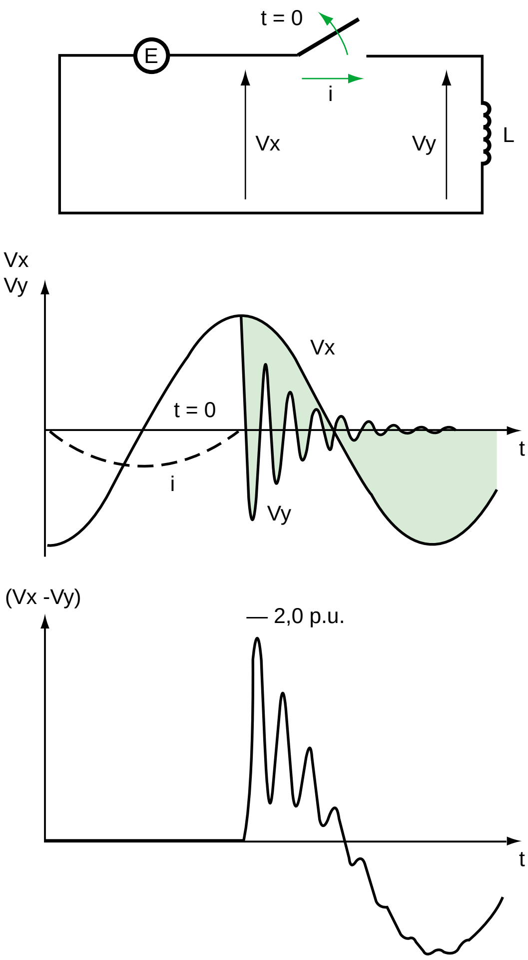
The transition in regards to the closed state preceding the breaking moment (current zero) leads to oscillations around the new steady state and produces overvoltages in comparison to normal maximum network voltage (see **fig. 16**).

In the case of a three-phase interruption, the fact that the interruption is not simultaneous on the three phases also introduces a transient state which generates overvoltages. As an example, in the case of the breaking of a short-circuit current in a system without a directly earthed neutral, the recovery voltage at the terminals of the first pole to clear reaches roughly 2.1 to 2.2 p.u. (IEC standardised TRV) and 2.5 p.u. for the breaking of a capacitor bank with isolated neutral.

Current chopping

The best known and most widespread phenomenon, for it deals with all breaking techniques, is current chopping: premature interruption of the alternating current before its natural passage through zero. This phenomenon above all concerns circuit-breakers, that are sized for breaking short-circuit currents, when they interrupt small currents.

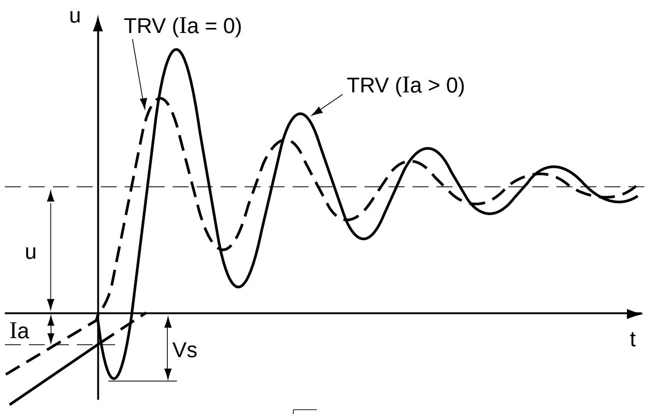
If I_a is the chopped current value, current that flows in the load inductance L immediately before breaking, the electromagnetic energy that is stored in the load is transferred in the form of electrostatic energy in capacitance C located at the terminals of the load ($1/2\ L\ I_a^2 = 1/2\ C\ V^2$). A voltage increase on the load side appears which accentuates the gap in regard to the "open circuit" steady state and amplifies the



1 p.u. = maximum nominal phase to earth voltage

$$= \frac{Un\sqrt{2}}{\sqrt{3}}$$

Fig. 16: overvoltages in comparison to maximum normal network voltage during the breaking of an inductive circuit.



Vs : Suppression voltage = Ia $\sqrt{\frac{L}{C}}$

Fig. 17: overvoltages associated with the breaking of a circuit with current chopping.

overvoltages associated with the break (see **fig. 17**).

These overvoltages are therefore proportional to the chopped current and the characteristic impedance (surge impedance) $\sqrt{\frac{L}{C}}$ of the load.

In the case of vacuum switching, current chopping corresponds to the premature extinguishing of the last cathode spot due to its instability at low current values: this characteristic primarily depends on the nature of contact material. The average chopped current values for a few common materials are given in the following table (see **fig. 18**).

In practise, chopped current values of a few amps, characteristic of the CuCr material, do not pose a problem. However values obtained using pure copper are excessive and explain, with other considerations, that this material cannot be used as such.

Multiple pre-strikings and re-ignitions

There is striking between the contacts when the applied voltage is higher than the dielectric withstand of the interval. This phenomenon is inevitable when this interval is very short (at the end of closing and at the beginning of opening).

Pre-striking upon closing thus systematically occurs when the operation is conducted under voltage: the time interval between the pre-striking and the moment when the contacts touch each other (pre-arcing time) depends on the closing speed and the voltage value applied at the moment when the contacts move closer to each other.

Re-ignition upon opening only occurs if the arcing time (time interval between contact separation and current break) is low: in this case the contact gap is not sufficient enough to tolerate the TRV and there is another dielectric breakdown.

Material	$I_{chopped}$ ave.	$I_{chopped}$ max.
Cu	15	21
CuCr	4	8
AgWC	0.5	1.1

Fig. 18: average chopped current values for a few common materials (Cu, CuCr, AgWC).

During pre-striking or re-ignition, the oscillating discharge of local capacitances results in an HF current (some ten kHz) that flows between the contacts superimposed on the power frequency current that progressively establishes itself (as it is nil before ignition).

These inevitable phenomena concern all types of switchgear. The particularity of vacuum switchgear is their ability to interrupt HF current following striking whereas other breaking techniques are in general incapable of this due to high di/dt at the time this current passes through zero.

The breaking of HF current generates a new applied TRV between the contacts the gap of which has only slightly varied, for these phenomena occur on a small time scale in comparison to the contact movement time, which thus leads to new striking and repetition of the same phenomena (see **fig. 19**). There is a succession of multiple strikings associated with variable amplitude voltage waves depending on the change in the contact gap:

- upon closing the amplitude of the overvoltage train linearly decreases until the contacts touch each other,
- upon opening amplitudes increase until the gap between the contacts is finally sufficient enough to withstand the recovery voltage which, due to voltage escalation, is still higher than the voltage that corresponds to normal breaking.

Overvoltage trains with steep fronts, generated by these multiple striking phenomena, are

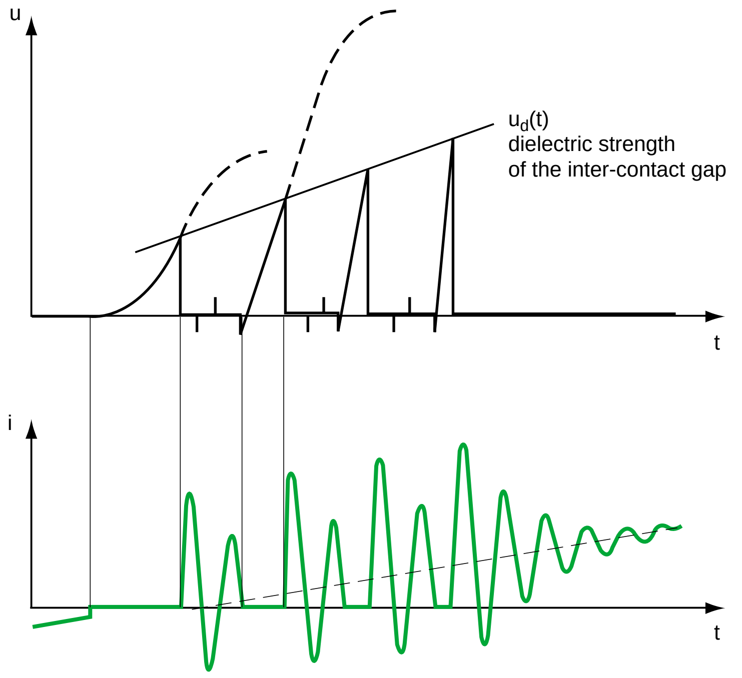


Fig. 19: *succession of multiple strikings associated with voltage waves with varying amplitudes.*

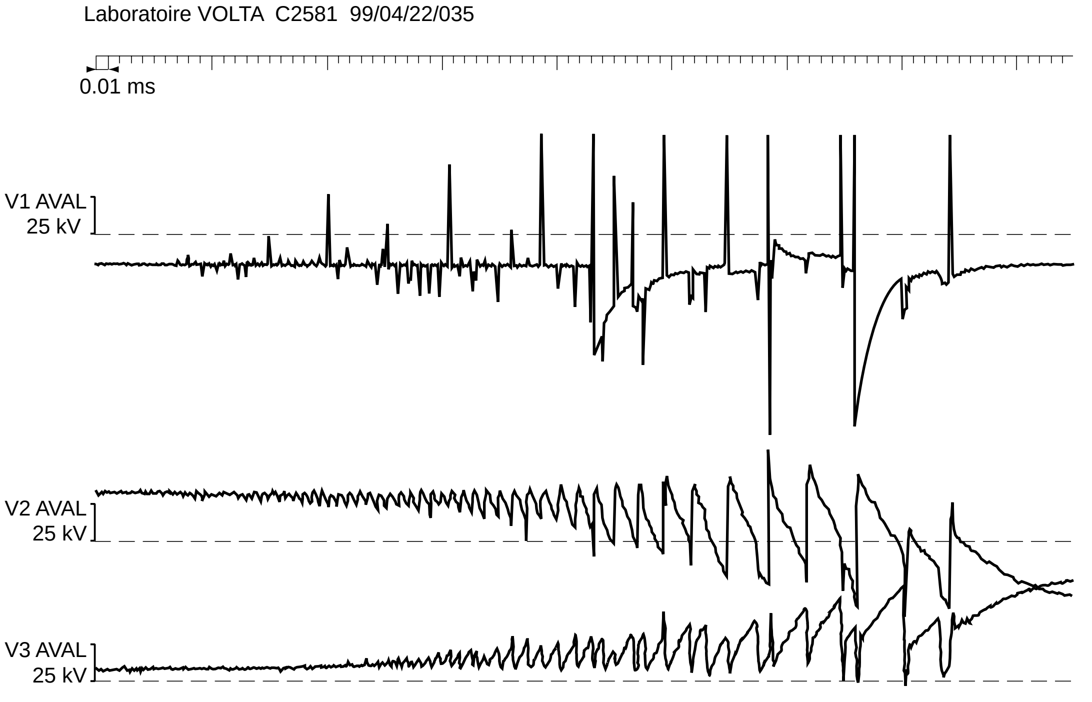


Fig. 20: *multiple striking phenomena during contact separation and the breaking of small inductive current.*

therefore still limited by the inter-contact gap that is maintained and which plays the role of spark-gap. However this limitation is only truly efficient upon closing; upon opening, the values reached can be high (see **fig. 20**).

The characteristics of these two types of similar phenomena are summarised in the table in **figure 21**.

Type of multiple striking	Occurrence	Amplitude of overvoltages
Pre-striking upon closing	Systematic	Low
Re-ignition upon opening	Occasional	High

Fig. 21: *characteristics of overvoltages linked to multiple striking phenomena.*

The disadvantage of these overvoltage trains are due more to their steep front than to their amplitude. In fact, these voltage waves with low rise times (in the region of 0.2 to 0.5 µs) are not distributed in a uniform manner in transformer and motor windings, rather they mainly stress the first turns (see **fig. 22**). They can therefore cause deterioration and accelerated ageing of the insulation between these turns.

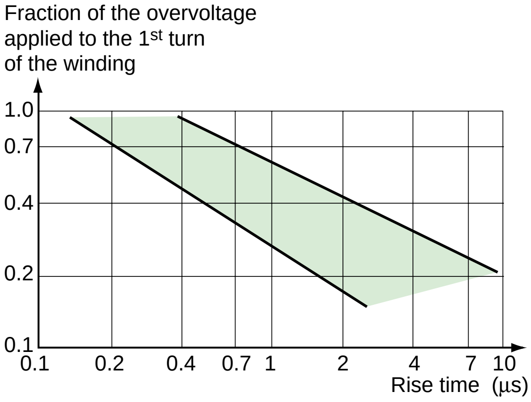


***Fig. 22**: percentage of the overvoltage applied to the first coil in the winding depending on the rise time.*

3.2 Means of protection against overvoltages

"Soft" contact materials

Contact materials (ex: AgWC, CuBi) that have a very low chopped current value were developed for the contactor application. This performance was reached by combining low thermal conductivity with high vapour pressure so as to obtain stable cathode spots up to very small current values.

These characteristics go against the breaking capacity: that which is acceptable for a contactor application is not acceptable for a circuit-breaker application.

Furthermore, the use of these materials is only efficient in reducing overvoltages linked to chopped current, which does not pose a problem in practice if it does not exceed a few amps (case of CuCr).

"Soft" contact materials do not bring an improvement when compared with traditional "hard" materials (CuCr) on the multiple striking level. In fact these materials are also capable of breaking currents with high di/dt and are characterised by a slower dielectric recovery rate after contact separation (see **fig. 23**): consequently overvoltage trains with steep fronts are not eliminated but, on the contrary, have a tendency to remain longer than with better performing material for breaking.

Virtual current chopping

In special configurations (rarely encountered in practice) that are characterised by strong capacitive / inductive coupling between circuit phases, the multiple re-ignition phenomena on the first phase that attempts to break, lead not only to significant HF current oscillations in the phase dealt with, but also in the neighbouring phases in which a notable current still flows, for they are far from their natural zero.

If induced HF currents reach an amplitude exceeding that of the power frequency current, current zeros ("artificial" but nonetheless real, and not virtual) are produced. The device can take advantage of it to break the current well before its natural zero. In such cases the chopped currents can be tens, or even hundreds of amps and the associated overvoltages are very high.

A possible solution is to open one of the device poles in advance so that during the time interval when multiple re-ignitions are likely to occur, the two other phases remain closed and thus insensitive to induced disturbances. In practice, this solution has not been applied due to the problems that it poses (stress non-uniformly distributed between the poles during the breaking of a short-circuit current) and due to the exceptional character of the phenomenon.

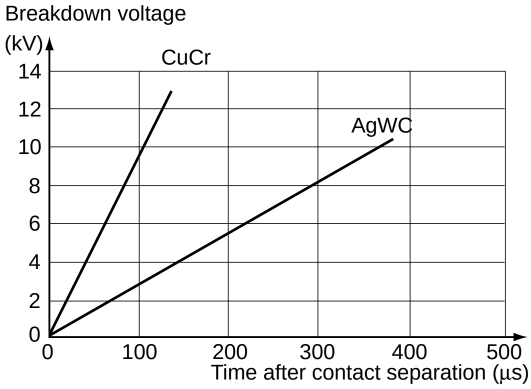


***Fig. 23**: change in the dielectric withstand between contacts from the moment of their separation depending on their materials.*

Synchronised breaking

A theoretical solution to eliminate these multiple re-ignition phenomena would be to control the moment when contacts are opened in regard to the current wave so as to prevent short arc times. In practice, it poses complex reliability problems concerning the response time of the control mechanism; it is therefore only used in the High Voltage field where mastering switching overvoltages can justify the cost difference at the switchgear level. In the Medium Voltage field it is more economical to call upon overvoltage protection devices when a load is to be protected.

Protection devices providing overvoltage limitation

As mentioned above, the worst phenomenon is that of multiple strikings which calls primarily upon the first turns of transformer or motor windings. These two types of load must be taken into consideration separately.

Indeed, transformers are designed to tolerate dielectric stress generated by lightning impulses which are overvoltages with steep fronts, they thus have a good level of insulation of the first turns. Moreover the inductive currents to be switched are small (no-load transformer) and associated overvoltages remain limited.

As a general rule, it is not necessary to provide special protection for transformers that are operated by vacuum switchgear, except possibly for solid insulated transformers that are more sensitive than those insulated in oil.

Motors have a dielectric withstand lower than that of transformers, whereas the currents to be interrupted may be high (breaking in start-up phase or stalled rotor) and thus overvoltages are severe. As a general rule, it is recommended to place protective devices at terminals of a motor whatever its control device may be, contactor or circuit-breaker, and whatever the contact material used may be. These devices may be capacitors which reduce the rise time of overvoltages, or RC circuits (typically C in the region of 0.1 to 0.5 µF and R of 10 to 50 Ω) and/or ZnO surge arresters.

4 The main fields of application for vacuum switching

Vacuum properties as a breaking medium for electrical switchgear are summarized in the table in **figure 24**.

Field	Characteristics	Strong points	Weak points
Breaking capacity	Very rapid dielectric recovery	Breaking of fault currents with severe di/dt and TRV.	Breaking of HF currentsfollowing restrikes: overvoltages are generated, protection devices necessary in certain networks.
	Low arc voltage (energy).	High electrical endurance.	No current limiting effect in LV.
	Ability to break even without contact movement.	Current interruption in case of striking between open contacts (partly compensates for the lack of reliability of the dielectric withstand).	
Dielectric withstand	Influenced by the surface condition of electrodes and the presence of particles.		Intrinsic dielectric withstand limited in HV and may change over time.
	Influenced by the arc phase that immediately preceded.		Random post-break dielectric withstand: risk of re-striking after capacitive breaking if the interrupter is not adapted.
Current flow	Non-compensated contacts of the butt type.		High contact pressure needed to prevent "popping" by electromagnetic force.
	Contacts in vacuum.	Constant contact resistance (no oxidation and no deterioration upon breaking).	Tends to weld upon closing.
	Same contacts for continuous current flow and breaking.		High contact resistance: significant thermal dissipation for high ratings.
Breaking environment	Vacuum < 10^{-3} mbar.	No decomposition products and no effects on the environment.	Permanent monitoring of the vacuum level is impossible: periodic dielectric checks make shutdown necessary.

***Fig. 24**: vacuum properties as a breaking medium.*

These strong and weak points of the vacuum switching technique have thus led to its use being favoured in certain fields of application for electrical switchgear. In the presentation that follows, the different fields of application are segmented in the following manner:

c by voltage level;

c then by function, or type of switchgear;

c lastly, depending on the type of load to be switched.

This chapter successively reviews the Medium Voltage (MV: 1< U < 52 kV), Low Voltage (LV: U < 1 kV) and High Voltage (HV: U u 52 kV) fields. The section that is the most developed is dedicated to MV which is the primary field of application for the vacuum switching technique. The LV and HV fields are only briefly described for the intrinsic limitations of vacuum switching only allow for this technique to occupy a marginal position: dominating techniques are breaking in air for LV and breaking in SF6 for HV.

4.1 Vacuum switching applications in Medium Voltage

Medium Voltage is primarily used for electrical energy distribution, between the transmission over long distances that is carried out using High Voltage (HV) and use that is mainly carried out in Low Voltage (LV). The lower voltage levels of the MV field are also used to supply loads of unit power that is too high for LV.
In MV, the main types of switchgear that are used are switches, disconnectors, circuit-breakers and contactors (see **fig. 25**).

Switches are simple and relatively economical devices that are used in normal operation of electrical networks: they are operated upon an order coming from an operator and allow the current to be established or interrupted in a network element. They are capable of breaking the normal load current of the circuit in which they have been inserted, and to establish the fault current caused by a short-circuit located downstream from their position in regard to the supply of electrical energy.

General purpose switches that are designed for MV distribution networks, upon which the switching frequency is low, have, through their design, an electrical and mechanical endurance that is relatively limited, typically:
- some hundred breaks at In;
- some thousand mechanical operations.

For special applications, certain types of switches must be able to counter more severe stress, for example:
- switches for arc furnaces operate frequently with high currents;
- switches for back-to-back capacitor banks that operate rather frequently and must establish inrush currents (with high frequency and amplitude).

Disconnectors are not strictly speaking breaking devices for they operate without a load (they must however be able to interrupt the residual capacitive currents of open circuits). They are used to isolate a circuit from the rest of the network and allow for safe intervention on the circuit. To that effect, they must have a high dielectric withstand between contacts and must respect the construction measures that aim at preventing the crossing over of the isolating distance even in the case of overvoltage on the network. Despite these measures, the safety of persons intervening in the system is not fully guaranteed unless the network element that was isolated by a disconnector is earthed in an efficient manner as well. Disconnectors are often combined with switchgear that does not satisfy the disconnection function, in general circuit-breakers and contactors. Switches are, however, most of the time also able to fulfil the disconnection function: they are then referred to as switch-disconnectors.

Circuit-breakers are safety devices that protect the network by automatically separating the faulty sections of the network: they are able to interrupt maximum short-circuit current likely to occur at the place where they are installed.

Circuit-breakers can therefore be considered as high-performance switches that are capable of operating upon an order from an operator or

Type of switchgear	IEC definition	Applicable standard for MV
Switch	A switching device capable of making, carrying and breaking currents under normal circuit conditions which may include specified operating overload conditions and also carrying for a specified time currents under specified abnormal circuit conditions such as those of short circuit. (IEV 60050-441-14-10).	IEC 60265-1
Disconnector	A switching device which provides, in the open position, an isolating distance in accordance with specified requirements. (IEV 60050-441-14-05).	IEC 60129
Circuit-breaker	A switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short circuit. (IEV 60050-441-14-20).	IEC 60056
Contactor	A switching device having only one position of rest, operated otherwise than by hand, capable of making, carrying and breaking currents under normal circuit conditions including operating overload conditions. (IEV 60050-441-14-33).	IEC 60470

***Fig. 25**: standardised definitions of the main types of switchgear.*

from an automatic protection device that detects fault situations. These devices must be highly reliable since safety and network availability depend on their correct operation.

Circuit-breakers require higher electrical and mechanical endurance than switches, typically:

c from 10 to 100 short-circuit current breaks;

c from 2000 to 10000 mechanical switching operations and breaks at In.

Contactors are control devices for loads that function in an intermittent manner, notably electric motors. They are switches with high operating rates that must be able to break overload currents that are higher than nominal current (ex: starting motor or stalled rotor currents) but not short-circuit currents which are eliminated by a combined protection device (circuit-breaker or fuse). Their high mechanical and electrical endurance generally amounts to several hundred thousand operations.

The graph in **figure 26** enables the respective positions of the four types of switchgear described above to be visualised.

One of the strong points of the vacuum switching technique is its ability to obtain a high breaking capacity and electrical endurance: that is why this technique is primarily used for circuit-breakers and contactors.

Circuit-breaker application in MV

A high breaking capacity is required for a circuit-breaker application. Vacuum interrupters used for this application either call upon RMF technology, or on AMF technology. Both can reach the highest breaking capacities required in MV (up to 63 kA); they are thus used in function of their respective advantages (see fig. 13). As with SF6, vacuum offers for this application the advantages of an enclosed break with no external manifestations and a maintenance free design with high electrical endurance.

The very rapid dielectric recovery of the vacuum can be an advantage in comparison with SF6 in special applications for which the rate of rise of the TRV is faster than that required by the IEC 56 and ANSI C37-06 standards (ex: case of a circuit-breaker directly connected to the secondary of a high power transformer). In such cases, not very frequent for standardised TRVs cover the great majority of applications, vacuum circuit-breakers need less derating than SF6 circuit-breakers.

Since vacuum switching is conducted without an external energy supply, vacuum circuit-breakers require less operating energy than SF6 circuit-breakers of the puffer type. For that which deals with SF6 circuit-breakers with rotating arc or with self-expansion, the gap is less significant.

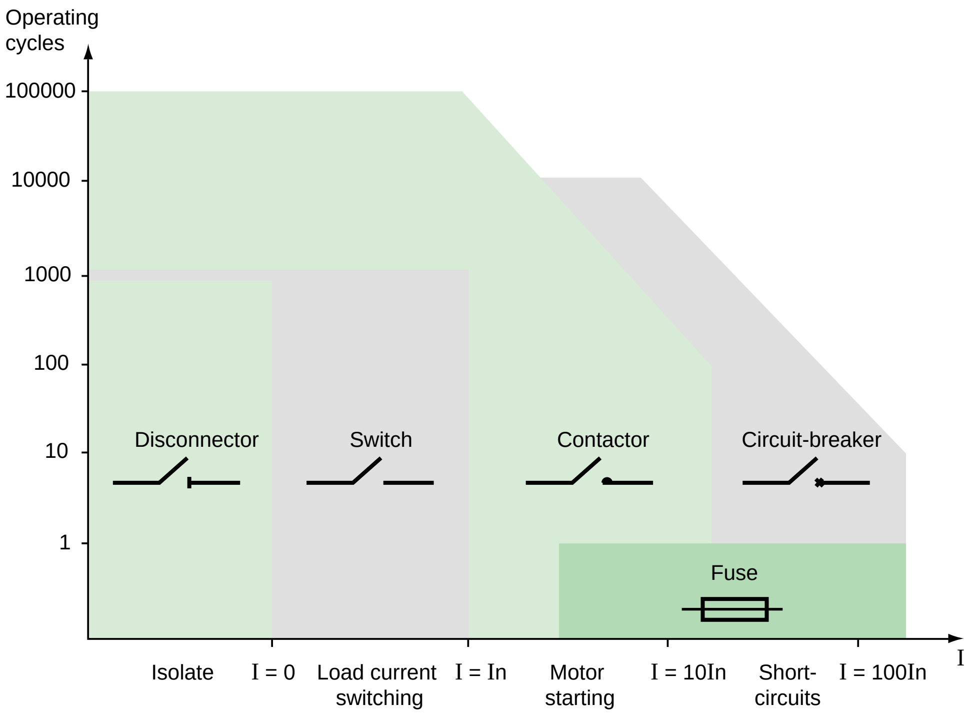


Fig. 26: respective positions of the four types of switchgear in terms of the current to be broken and of the number of operations to be conducted.

This advantage is however counterbalanced by the inherent disadvantages of the vacuum technique which can only use butt contacts. These contacts need high contact pressure to prevent repulsion and contact welding upon closing on fault: contact pressure needed per pole is in the region of 200 daN for a 25 kA circuit-breaker and of 600 daN for a 50 kA circuit-breaker. This requirement leads to a rise in the operating energy for closing and to reinforced pole structure that must tolerate these permanent stresses in the closed position.

Furthermore, despite high contact pressure, the use of butt contacts made of CuCr material does not allow for contact resistance as low as with silver-plated multiple contacts to be obtained: vacuum circuit-breakers thus have a handicap in comparison with SF6 circuit-breakers through higher thermal dissipation for high nominal currents (2500 A and above). Contacts in vacuum tubes, sheltered from oxidation, are not limited in overheating, unlike contacts of other circuit-breakers, but the interrupter’s environment must evacuate the calories generated by it while respecting the admissible temperature limits on the connections and contacts; that is why vacuum circuit-breakers with high ratings are characterised by particularly large-sized connections and cooling fins.

Aside from their environment, vacuum interrupters are limited in overheating as well, not through the nature of the materials of which they are made or through their manufacturing process (high temperature brazing), but rather due to the properties of gas permeation through metal walls (in particular of the metal bellows) which become significant concerning atmospheric hydrogen as of 200-250 °C.

In conclusion, the vacuum switching technique is well adapted for general purpose circuit-breaker applications in MV and covers all of the normally required performances for voltage, nominal current and breaking capacity. For special applications such as the control of inductive or capacitive loads, special precautions must be taken, or other technologies may be better suited.

Contactor application in MV

This application is especially well adapted to the vacuum switching technique, which has acquired a dominating position in this segment. In fact, currents to be broken are located in the range of currents that are easily interrupted by diffuse vacuum arcing, with contacts that have simple shapes and low contact material wear, thence excellent electrical endurance. Contact pressure can be low, since nominal currents are modest and fault current is limited through the use of combined fuses, and even more so since the contact materials used have a very reduced tendency to welding and thus tolerate a certain degree of repulsion.

Supply voltages for MV motors located in the bottom of the MV range (in general ≤ 7.2 kV) authorise a small contact gap (in the region of 4 mm) and the realisation of compact interrupters which have high mechanical endurance and are especially well adapted to electro-magnet operating mechanisms.

All these advantages explain the success of the vacuum switching technique for the MV contactor application. However, the risk of overvoltages during the switching of inductive circuits, which is specific to vacuum technique, must not be overlooked (motor in the start-up phase, no-load transformer) and the need for adapted protection devices (see chapter 3). This problem, which concerns all types of vacuum switchgear, must be especially taken into account in the case of motor switching, motors being loads that are sensitive to overvoltages.

Switch and disconnector applications in MV

The vacuum switching technique which allows for MV circuit-breakers and contactors to be made, can also, a fortiori, fulfil the more modest requirements of switches. It has however encountered limited success for this application. In fact, low performances can, in general, be obtained in a more economical manner by using breaking techniques in air or in SF6.

But above all, this function is often combined with the disconnector function, which is easily attainable using the air or SF6 technique, but not using vacuum. Combining a vacuum switch with a conventional disconnector makes this solution non-competitive.

The impossibility of ensuring disconnection with a vacuum interrupter is due to the voltage deconditioning phenomenon which is caused by the deterioration of the contact surface condition caused by mechanical and electrical switching operations. This deconditioning does not allow for the dielectric withstand that was obtained without any particular difficulty at the end of the voltage conditioning procedure on a new interrupter, to be guaranteed. Furthermore, it is impossible to continuously monitor the integrity of the dielectric medium in a vacuum interrupter which also limits its use as a disconnector.

With a switch, closing upon a short-circuit is particularly penalising for the dielectric withstand between contacts, for it is not followed by a fault current interruption that is capable of eroding the roughness caused by the break of the contact weld due to the pre-striking.

To prevent significant deterioration of their dielectric withstand, during consecutive closings upon short-circuit, switch contacts are made of materials that do not easily weld such as WCu, instead of CuCr which is used for circuit-breakers.

For special applications which require high electrical endurance (ex.: switches for arc furnaces), the vacuum switching technique is well suited and is widely used, even if overvoltage problems due to vacuum can, in certain cases, privilege the use of SF6 technology despite its lower endurance.

Another special application is that of the back-to back capacitor bank switch, which can be ensured by using a standard SF6 circuit-breaker, but which, using the vacuum technique, requires a special interrupter. In fact, the electrical charge of the capacitor induces a recovery voltage, applied to the terminals of the switching device, that is especially high. The post-break dielectric withstand of a vacuum interrupter is not its strong point due to the possibility of breakdown caused by the particles generated during the arcing period (see chapter 2).

In the case of capacitor banks in parallel that are separately closed, the risk of re-striking is accentuated by the effect of the high frequency inrush current due to the discharge of neighbouring capacitors in the one which is energised: this inrush current imposes the use of contact materials of the WCu type which do not easily weld and which is incompatible with the vacuum circuit-breaker application. Furthermore, to prevent attempts to interrupt HF inrush current during the pre-striking phase, which result in overvoltages that are harmful to capacitor banks, measures must be taken: the addition of surge inductances reduces the inrush current frequency, raising the closing speed reduces the pre-striking time.

In brief: the vacuum switching technique is not to be excluded for controlling capacitive loads, but other techniques, in particular the SF6 technique, are better suited.

4.2 Vacuum switching applications in Low Voltage

The vacuum switching technique, widely used in MV for the circuit-breaker and contactor functions, can also fulfil the same functions in LV. It is however rarely used at this voltage level. In fact, on the one hand, it competes with the air breaking technique which is simpler, more economical and better adapted, and on the other hand, the disadvantages that have been noted in MV use are more disturbing in LV.

The main shortcoming of the vacuum switching technique in LV for the circuit-breaker function is due to the low arc voltage which cannot reach or exceed the network voltage like in an air circuit-breaker: it therefore cannot limit the fault current to a notably lower value than the prospective short-circuit current. This limiting effect is particularly useful for it avoids intense electrodynamic forces, that would be produced by prospective short-circuit currents that are often high in LV (up to 100 kA and above). This limiting effect also facilitates the natural selectivity between circuit-breakers for it is all the more accentuated, the smaller the circuit-breaker rating.

Furthermore, the disadvantages of vacuum interrupters, mentioned above for MV, that are linked to the use of butt contacts (high contact pressure and relatively high contact resistance), are more disturbing in LV power circuits which are characterized by high values of short-circuit currents (non-limited) and need higher continuous current ratings than in MV.

Lastly the high breaking capacity needed in LV imposes penalising dimensions for vacuum interrupters in comparison to air solutions for circuit-breakers with small current ratings.

For these different reasons, the use of vacuum interrupters in LV circuit-breakers is limited to a restrained section that corresponds to the following performances:

- breaking capacity $\leq$ 75 kA,
- ratings between 800 and 2500 A.

In this context, even though vacuum switching is not cheaper than in air, it is worth considering for the following reasons:

- enclosed breaking with no external manifestations,
- use in polluted and explosive atmospheres,
- higher electrical endurance.

In LV contactor use, the disadvantages of vacuum interrupters, mentioned above for use in circuit-breakers are no longer to be taken into consideration. The main factors that slow down the development of this technique in this field are:

- first of all, the cost advantage in favour of classical air solutions;
- then, the specificities of vacuum concerning overvoltages generated during the interruption already explained in chapter 3.

In brief, in low voltage, the vacuum switching technique is not really able to compete with air breaking, except in special cases where enclosed breaking is significantly advantageous.

4.3 Vacuum switching applications in High Voltage

In the field of HV, the vacuum switching technique can be considered for use in the circuit-breaker function: diverse attempts have been made, without convincing success to date. In fact, it seems that the characteristics of vacuum switching do not allow it to truly rival the SF6 breaking technique in High Voltage.

One of the main difficulties to be overcome is the production of vacuum interrupters with a sufficiently high unit voltage rating. If vacuum interrupters capable of breaking under 36 kV are commonly made, already as of 52 kV it is often necessary to use two interrupters in series. Today, the highest voltage level at which a circuit-breaker equipped with a single interrupter per pole is available on the market is 72.5 kV.

Interrupters designed for use in applications at 123-145 kV are still, at present, in the prototype stage whereas SF6 breaking chambers up to a unit voltage rating of 420 kV are available.
The solution which consists in placing a large number of interrupters in series to reach high voltages, above and beyond the technical problems that it poses (voltage distribution, reliability, etc.), can obviously not financially rival with the SF6 breaking technique.
The main obstacle for obtaining a vacuum interrupter with a high unit voltage rating is the ceiling value of the dielectric performance for high voltages that is around 500 kV (see fig. 5), which corresponds to the lightning impulse voltage level to be reached for 123-145 kV devices. Presently, no technological solution is foreseeable.

Furthermore the use of vacuum at high unit voltage poses the problem of X rays that are likely to be emitted by interrupters subjected to supply voltages in the region of a hundred kV. Here we are dealing with voltage levels applied to MV interrupters to condition them: this operation is carried out in shielded enclosures so as to protect the operators against X-ray emission.

Using interrupters that have a dielectric design which is adapted to HV and already conditioned, the emitted radiation level (in the open position) should remain acceptable, but since interrupter operation can lead to partial deconditioning, this concern cannot be totally eliminated.

For physical limitation reasons, vacuum switching cannot therefore even come close to rivalling SF6 except for the lowest voltage levels in HV and only in unfavourable economic conditions. For very special applications, the combination of the two techniques, vacuum and SF6, can be foreseen, as was done for a 250 kV direct current circuit-breaker that uses a vacuum interrupter in series with an SF6 breaking chamber. This solution combines the qualities of vacuum, for breaking with high di/dt and initial TRV rate of rise, with those of SF6 which relays it to ensure withstand at the end of the TRV rise. For common HV circuit-breaker applications, it is not certain that hybrid solutions can rival on a financial level, with solutions that are 100 % SF6, even if on the technical level such solutions are attractive because they allow for the qualities of each breaking technique to be combined.

5 Conclusion

To conclude this overview, the vacuum switching technique appears, because of its good breaking capacity and electrical endurance performance, to be in general well adapted to circuit-breaker and contactor applications in medium voltage.

However the SF6 breaking technique is often better suited when privileged characteristics are dielectric withstand, low level of switching overvoltages or the ability to deal with high continuous currents.

Even though it has matured, the vacuum switching technique still presents notable potential for progress to be made concerning its performances, in particular using the relatively recent AMF technology. And so, the trend to reduction of the circuit-breaker interrupter size should be maintained. For this, progress is to be made in the optimisation of the use of contact surfaces and in the increase of permissible current densities. With these objectives, current research is primarily focused on:

c modelling of the arc and its interactions with the axial magnetic field;

c the mechanisms for diffusing and distributing the arc energy on the surface of contacts;

c improving contact material characteristics.

To widen the fields of application of the vacuum switching technique, and better use its qualities, switchgear manufacturers also foresee new solutions and notably its combination with other techniques, in particular with the SF6 technique, so as to combine their respective advantages. This approach is already used for certain medium voltage cubicles with gas insulation that unite the qualities of vacuum switching with those of insulation in SF6.

Another possibility, as of yet little explored, is the realisation of hybrid circuit-breakers that combine two breaking techniques, vacuum and SF6. A priori more expensive, it could however prove to be interesting in certain fields of application if it can efficiently conciliate the best of the two technologies.

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