9

Vacuum Interrupters

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9.1 Historical Development

In the medium voltage range the vacuum switching principle is well-established. Today vacuum circuit breakers are available up to 52 kV voltage and 72 kA short-circuit current. Main advantages are:

- high number of operations,
- maintenance-free operations,
- environmental compatibility.

Most of the applications are in power transmission and distribution. But the vacuum interrupting principle is entering new domains which have been dominated by other quenching media in the past.

Different AC switching devices have in common the principle of arc interruption during current zero. The differences are in the extinguishing media. During middle of the twentieth century air- and oil-circuit breakers dominated the medium voltage applications. Since the 1970s SF_6- and vacuum-interrupters have gained attention. Today more than 60% of switching devices applied in the medium voltage range from 7.2 kV up to 50 kV are vacuum interrupters. In the past, the vacuum switching technology was first developed by American (General Electric) and English (Vacuum Interrupter Ltd.) manufacturers, followed by Japanese and Germans (Toshiba, Siemens, ABB).

The main reasons for such a long development time of the vacuum interrupters have been shortcomings in industrial vacuum technology and a lack of fundamental knowledge about the vacuum arc behaviour. Finally, long term basic research and development made the introduction of a new modern switching principle possible. Convincing the customer to move from proved switching principles to vacuum interrupters was not easy in the beginning. It was possible by giving information concerning the function principle, properties and reliability of vacuum interrupters.

At first the number of sold vacuum circuit breakers was not high, but since 1980 there has been a rapid increase in world wide demand. The global production (excluding China) in 2004 was approximately 1.2 million vacuum interrupters for medium voltage circuit breakers. Within Europe (including Russia) the estimated unit quantity was about 400 000 in 2004, e.g. ABB, Eaton Electrical, AREVA and Siemens together sold more than 800 000 units in 2005. In more than 35 years of experience a measure for reliability was obtained in the form of mean time to failure (MTTF) of 40 000 VI-years. This knowledge is an important base for further development of VI's.

The manufacturing technology and design of vacuum interrupters changed parallel with the increased output. In the beginning the tubes were produced in so-called many-fold technology. After pre-assembling and brazing of contact- and housing-parts the tubes were mounted, welded and evacuated via an exhausting pipe. Today the one-shot brazing technology is well established (Fig. 9.1). Here the complete vacuum interrupters are assembled in a dust-protected environment. In a batch of several tens or hundreds the bottles will then be evacuated and brazed simultaneously (one-shot) at 800–900°C in an ultrahigh-vacuum furnace in one process. This technology is an important premise for economical mass-production of vacuum interrupters.

To produce the vacuum in the range of 10^{-6} hPa or less, turbo-molecular pump systems are the best choice. During heating up in the vacuum furnace the tubes are out-baked and water vapour desorbs from the inner surfaces. After cooling down the

Fig. 9.1. One-shot-brazing technique (Siemens). In a batch of several tens or hundreds the bottles will be evacuated and brazed at 800–900°C in an ultrahigh-vacuum furnace in one process (one-shot)

tightness of the bottles has to be controlled. Normally, the PENNING-principle is used, in which the residual gas in the tube is 100% ionized by an impulse voltage in a magnetic field. The ion current then is a direct measure for the internal pressure. Multiple measurements within a certain time give precise information concerning the vacuum tightness.

In the middle of 1970s the first samples for the high voltage range (84 kV) had been developed in Japan. Since 1984 vacuum technology has been applied in the low voltage range (<1 kV) as well. But even in 2004 the vacuum circuit breakers are mainly used in the medium voltage range. New challenges have arisen from the higher ratings of voltages and currents. Even for power plants an increasing trend towards vacuum circuit-breakers is emerging in order to achieve a better system management. In low voltage applications high reliability is necessary too. Maintenance-free operations and high number of operations are to the best advantage to the users. Hermetically sealed housings guarantee the prevention of an external extinction arc and thus a high environmental compatibility.

9.2 Physical Fundamentals

9.2.1 Interrupting Capability

When contacts carrying current are separated, a metal vapour arc will be created. This arc, which consists exclusively of the vaporising contact material, is fed by the external supply of energy until the next current zero. At the instant this current zero takes place, the arc is finally extinguished, and the vacuum interrupter regains its insulating capability and is able to withstand the transient recovery voltage.

Charge carriers in the vacuum arc are metal ions from the anode and electrons emitted from cathode-spots. After current zero the free charge carriers recombine in a few microseconds resulting in a very fast dielectric recovery [1]. On the other hand, the concentration of the neutral metal vapour in the arc decreases in hundreds of microseconds.

At currents around 10 kA the vacuum arc begins to contract, being initially noticeable in the form of anode spots. One way in which the switching capability can be improved is to create a contact geometry with a self-generated magnetic field. Until today, spiral contacts and contrary slotted pot-shaped systems are used [2, 3]. These contacts generate a radial magnetic field (RMF), which causes an azimuthal electromagnetic force acting on the contracted arc. The contracted arc moves over the contact surface at a speed of up to 150 m/s. This high velocity ensures that there is less contact erosion significantly improving the current interrupting capability up to 50 kA.

The movement of the constricted burning arc (Fig. 9.2) is caused by a radial magnetic field component B_r due to the Lorentz force [4]. Because these contact systems also produce an azimuthal field B_φ, a radial force has an effect on the arc movement and arc stability. Hence, both magnetic field components B_r and B_φ have to be optimised in order to ensure a proper switching behaviour.

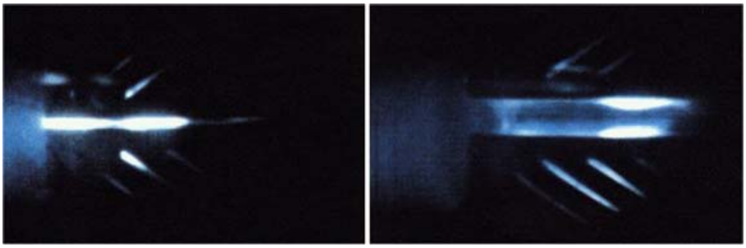

Fig. 9.2. Arc rotation. The movement of the constricted burning arc is caused by a radial magnetic field component B_r due to Lorentz force

For pot-shaped contacts we have some parameters like slot angle, slot number, pot depth and pot diameter which can be varied at a given contact diameter. Considering also manufacturing aspects, one set of optimised parameters results from the calculations. Typical values for the specific magnetic field B/I are:

$$\frac{B_r}{I} = 6 \ldots 12 \frac{\mu T}{A} \tag{9.1}$$

and

$$-5\frac{\mu T}{A} < \frac{B_\varphi}{I} < 0\frac{\mu T}{A}. \tag{9.1'}$$

Due to the negative sign of B_φ/I the radial component of the Lorentz force is directed from the contact centre to outwards. In case of a non-optimised system the rotating arc forms jets which can interact with the surrounding interrupter housing. This tendency increases depending on the contact stroke d. A limiting condition is given by

$$I \cdot d < C_L, \tag{9.2}$$

where C_L is a constant for a given contact material and I is the interrupting current. The arc movement is correlated with the radial magnetic field. For a given contact diameter D the number of arc rotations N is approximately

$$N = C_r \cdot I \cdot \frac{B_r}{I} \cdot \frac{d}{D}, \tag{9.3}$$

where C_r is a constant depending on the contact system. The arc movement in (9.3) results from simple thermodynamic considerations of heat dissipation on the contact surface due to the vacuum arc. For maximum ac-arcing times the interrupting current is limited due to overheating of the contact surface. In this case N_{max} is nearly constant, independent of contact diameter D and maximum current I_{max} [5]. This corresponds to the experience that maximum interrupting current I_{max} scales rather well with the contact diameter D for RMF-systems.

A physical measure for the interrupting capability is the maximum amount of electrical charge Q which can be carried by the arc, divided by an effective contact surface A_{eff} (molten area). In this case the experience is summarized by the following relation:

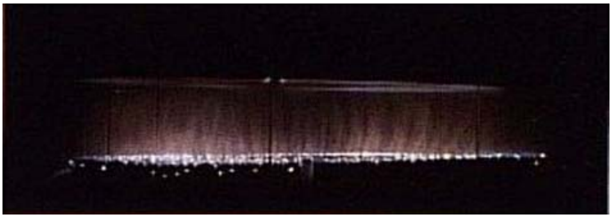

Fig. 9.3. Diffuse burning arc mode. Due to an inverse pinch effect (see below) the arc constriction is shifted towards higher currents

$$\frac{Q_{\mathrm{RMF}}}{A_{\mathrm{eff}}} = \frac{C_{\mathrm{RMF}}}{1 + \Gamma_{\mathrm{RMF}} \cdot d}, \tag{9.4}$$

where C_{RMF} is a constant depending on the contact material and Γ_{RMF} is approximately a constant term, which causes a strong dependence on the contact stroke, as shown in Fig. 9.4. However, in case of a small gap (i.e. less than 5 mm), relation (9.4) becomes independent on the contact stroke, respectively constant. A_{eff} is determined by the arc radius r_{arc} which is weak proportional to $I^{1/3}$ and the rotating orbit length $\pi \cdot D$. Therefore, (9.4) also indicates a linear dependence of the interrupting capability on D.

For a further increase of the switching capability (from 63 kA to 80 kA), e.g. for applications close to generator terminals, the contacts generating an axial magnetic field (AMF) are used. Thereby the contraction of the arc is shifted towards higher currents. The arc is diffuse (Fig. 9.3) and the supplies of arc-energy and the contact erosion are reduced drastically. The main parameters which have to be considered when dimensioning AMF contacts are the size, distribution and phase relation of the axial magnetic field [4]. The goal is to minimise the phase displacement between the high current and the magnetic field it generates.

Also in the case of AMF-contacts different geometries are known. Multiple armed coil systems [6] and identical slotted pot-shaped AMF-contacts [7] are well-established. Based on simple and cost effective manufacturing techniques, an axial field contact with plane slits running in the same direction was developed by Siemens [8]. Accurate magnetic field calculations were performed in order to optimise the contact system. The contacts were designed in such a manner that the axial component of the specific magnetic induction is in the range [4]

$$\frac{B_z}{I} = 2.5 \ldots 5 \frac{\mu\mathrm{T}}{\mathrm{A}}. \tag{9.5}$$

In case of pot-shaped AMF-contacts there are also some geometrical parameters like slot angle, slot number, pot depth and pot diameter which can be varied at a given contact diameter. Hence, it is advantageous to optimise both the axial magnetic field and the ohmic resistance of the contact system.

Considering the interrupting capability, the specific electrical charge is also limited by a relation similar to (9.4)

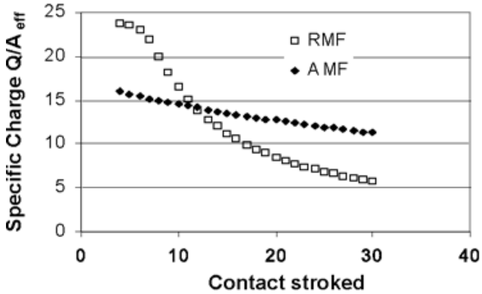

Fig. 9.4. Interrupting capability of RMF- and AMF-contacts. Experimental data in accordance to (9.4) and (9.6)

$$\frac{Q_{\mathrm{AMF}}}{A_{\mathrm{eff}}} = \frac{C_{\mathrm{AMF}}}{1 + \Gamma_{\mathrm{AMF}} \cdot d}. \tag{9.6}$$

Contrary to the strong dependence on the contact stroke in case of RMF, Γ_{AMF} is a weak constant, as shown in Fig. 9.4. C_{AMF} is a constant depending on the contact material.

The effective contact surface (molten area) A_{eff} for the AMF-systems is related with the axial magnetic induction. If we define a yield-factor η_{AMF} by

$$A_{\mathrm{eff}} = \eta_{\mathrm{AMF}} \cdot D^2 \cdot \frac{\pi}{4} \tag{9.7}$$

with D as the contact diameter, our experience gives a very good approximation for η_{AMF} in terms of B_z/I

$$\eta_{\mathrm{AMF}} \approx C_\gamma \cdot \sqrt{\frac{B_z}{I}}. \tag{9.8}$$

If we assume that $B_z/I \propto 1/D$ for this Helmholtz-like coil system, from (9.6)–(9.8) a well-known approximation results

$$Q_{\mathrm{AMF}} = C_{\mathrm{q}}(d) \cdot D^{1.5}. \tag{9.9}$$

Relation (9.9) fits Yanabu's experience [6] for the interrupting capability of AMF contacts very well. $C_{\mathrm{q}}(d)$ is weakly dependent on the contact stroke.

In a first order approximation, (9.4) and (9.6) reflect the energy balance in the vacuum arc. If we assume that the electrical arc energy

$$W_{\mathrm{el}} = \int u_{\mathrm{arc}} \cdot i_{\mathrm{arc}} \cdot \mathrm{d}t \approx u_{\mathrm{arc}} \cdot Q \tag{9.10}$$

is equal to the thermal energy loss at the contact surface

$$W_{\mathrm{th}} = \iint \lambda \cdot \nabla T_{\mathrm{S}} \cdot \mathrm{d}A \cdot \mathrm{d}t \approx \lambda \cdot \frac{\Delta T_{\mathrm{S}}}{\delta} \cdot A_{\mathrm{eff}} \cdot t_{\mathrm{arc}} \tag{9.11}$$

with the thermal conductivity λ, melting temperature T_{S} and penetration depth δ of the contact material, we obtain

$$\frac{Q}{A_{\mathrm{eff}}} \approx \lambda \cdot \frac{\Delta T_{\mathrm{S}}}{\delta} \cdot \frac{t_{\mathrm{arc}}}{u_{\mathrm{arc}}}. \tag{9.12}$$

Further, if the arcing voltage u_{arc} is a linear function in terms of the contact stroke d, (9.12) can be estimated by

$$\frac{Q}{A_{\mathrm{eff}}} \approx \frac{C}{1 + \Gamma \cdot d} \tag{9.13}$$

according to (9.4) and (9.6). Equation (9.8) is only a simple empirical relation fitting the experimental data. The diffuse burning mode of high-current arcs is correlated with the distribution and magnitude of the axial magnetic field [9]. A minimum value of B_z/I is obviously necessary as an existing criteria for the diffuse arc mode.

The arcing voltage also shows different behaviours, dependent on its state. In the diffuse mode, e.g. at low currents ($<$10 kA) or AMF-arc, the voltage is rather low (20–60 V) and smooth during burning time. At higher currents in case of the constricted mode, the voltage increases up to several 100 V and high-frequency oscillations appear. The arcing voltage is a combination of three parts: the cathode-fall, the anode-fall and the voltage at the plasma-column. Cathode- and anode-fall are in the range of 20 V (CuCr), while the plasma-column voltage increases with increasing current (ohmic behaviour).

In the high-current region ($>$10 kA) the diffuse AMF-arc is spread over the whole anode surface. Exceeding a certain current density a central arc-constriction appears accompanied with bright anode-spots. The arc mode changes into the diffuse columnar arc. This is regarded as a transition phase to the completely constricted arc at higher current densities [10]. Now the interrupting limit is reached.

A better knowledge about the physics of AMF-arcs is important to increase the interrupting capability. The magneto-hydrodynamic theory leads to the known generalised Ohm's law

$$\mathbf{E} = \frac{\mathbf{j}}{\sigma} + \frac{1}{n \cdot e} \cdot [(\mathbf{j} \times \mathbf{B}) - \nabla p] \tag{9.14}$$

with electrical field vector $\mathbf{E}$, magnetic field vector $\mathbf{B}$, current density $\mathbf{j}$, electrical conductivity σ, plasma density n, elementary charge e and plasma pressure p. If we presume

$$\mathbf{E} = (0, 0, E_z) \quad \text{and} \quad \mathbf{B} = (0, B_\varphi, B_z) \tag{9.15}$$

the Maxwell's equations require in general case non-cylindrical symmetry, which is in accordance to experimental experiences (Fig. 9.3).

Considering rotational symmetry, one obtains

$$\mathbf{j} = (j_{\mathrm{r}}, j_\varphi, j_z) \tag{9.16}$$

with current density components j_{r}, j_φ, j_z depending on B_φ, B_z and E_z. In order to minimise the radial current density component j_{r} and to obtain an optimised inverse pinch-effect, the following boundary condition should be realised:

$$\frac{\partial^2 (B_z)^2}{\partial r^2} < 0. \tag{9.17}$$

Obviously, the radial distribution of the axial magnetic flux between the contacts is also very important for AMF-systems [11].

9.2.2 Dielectric Properties

Approaching current zero in any case, RMF or AMF, the arc mode changes to a diffuse form determined by cathodic spots. Due to a starvation effect in carrier production the arc will chop just before current zero. Natural in case of vacuum arcs this chopping current is related with a steep $\mathrm{d}i/\mathrm{d}t$ which may cause over-voltages in inductive loads. The chopping current depends on the contact material. Therefore, this property has to be optimised during contact material development.

One of the best contact materials also taking this fact into account is a composition of Cu and Cr (Fig. 9.5). For example, CuCr50 has a chopping current below 5 A. Some other very important properties of CuCr are:

- high resistance to arc corrosion,
- high breaking capacity,
- high electrical conductivity,
- low tendency to contact welding,
- high dielectric strength.

After current zero the transient recovery voltage (TRV) imposed by the circuit appears at the contacts within some tens of microseconds. The dielectric strength of the contact gap, however, recovers in a few microseconds. This is correlated to the neutralization of the metal plasma in the arc. The contact gap is now insulating, and the current is successfully interrupted.

In principle, the vacuum stroke is an ideal insulator because there are no free electrical carriers. So the interrupter can withstand very high voltages, even light-

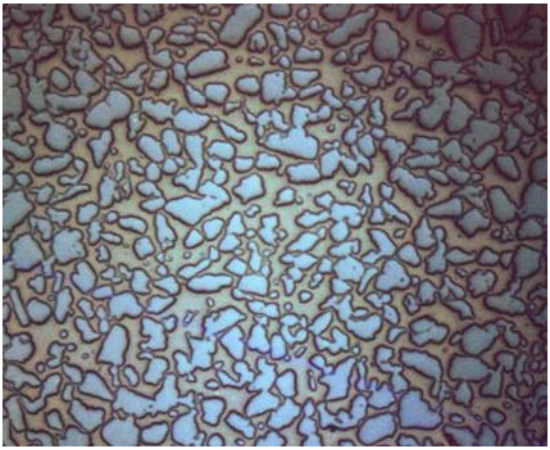

Fig. 9.5. CuCr contact material

ning impulse voltages. Limits are given by current emitting mechanism or particle discharges [12].

Micro-protrusions on the metallic surfaces will enhance the electrical field strength E locally by a factor β of the order of several hundreds, depending on the surface conditions. Due to the quantum mechanical tunnel-effect electrons will be emitted. According to the theoretical description given by Fowler and Nordheim [13], the field-emission current density j_{FE} is

$$j_{\mathrm{FE}} = C_1 \cdot (\beta \cdot E)^2 \cdot \mathrm{e}^{-\frac{C_2}{(\beta \cdot E)}}, \tag{9.18}$$

where C_1 and C_2 are coefficients in terms of the work function of the material and weakly dependent on the field strength. In practice they may be considered as constants. The field enhancement factor β can be determined experimentally by the current voltage analysis from the plot slope of $\ln(I_{\mathrm{FE}}/U^2)$ versus $1/U$. This Fowler–Nordheim analysis (FNA) gives important information regarding the surface condition and dielectric quality.

At a critical electrical field strength E_{crit} the field emission current density increases rapidly producing a discharge,

$$\beta \cdot E_{\mathrm{crit}} \approx 10^{10}\,\frac{\mathrm{V}}{\mathrm{m}}. \tag{9.19}$$

Field emission mechanisms limit the dielectric strength in vacuum depending on the local field enhancement, caused by micro-protrusions (surface structure). But there is also a FN-like electron emission from semi-conducting layers on metallic surfaces in vacuum (Shottky emission). These layers may be caused by metal oxides or other surface contaminations. Even the joint of ceramic and metal in the interrupter (triple-junction) produces Shottky emission under the influence of an electrical field. Hence, clean surfaces and field protected triple-junction areas are essential for high dielectrical properties.

The dielectric limits in vacuum due to emission effects are linearly correlated to the electrode distances, hence to the electrical field strength. With increasing contact gap d, however, non-linear relations between the discharge voltage U_{d} and d appear. This experience is of most importance for vacuum interrupters at rated contact gap. The dielectric strength is nearly square-root dependent from the gap [14]. This square-root law can be described with a particle discharge mechanism [15]. Micro-particles are charged under the influence of the local electrical field and accelerated. At a certain particle energy a discharge is initiated due to a secondary process, e.g. particle vaporization at impact. This model leads to the following relationship:

$$U_{\mathrm{d}} = C_{\mathrm{p}} \cdot \sqrt{d}, \tag{9.20}$$

where the constant C_{p} depends on the material, particle size and surface quality. Because of this it is obvious that a dust-protected environment in the interrupter production line is necessary.

In spite of the extremely clean production conditions a final high-voltage treatment of the tubes is needed. Between the contacts a voltage is applied which is higher than the internal dielectric strength. This causes powerful internal breakdowns just at the position of protrusions or particles where the electrical field is enhanced. Due to these breakdowns the dielectric disturbances vaporize (micro-explosion) and decrease the local field enhancement (β). With increasing applied voltage step by step and/or decreasing the contact stroke the final desired dielectric strength will be 'produced'. This process is called high-voltage conditioning. The voltage may be AC and/or impulse.

9.2.3 Current-Zero Effects

Approaching current-zero, the plasma burns in a diffuse mode rooting from plenty of cathode spots. Each cathode spot carries a limited amount of current in the range of 100 A, depending on the contact material. Correlated to the extinguishing of the last spot, arc-instabilities appear and the arc 'starves' just before current-zero. The current at this moment is called chopping-current i_{chop}. This chopping-current shows a statistical distribution around a main value, also depending on the contact material. Due to very fast dielectric recovery in vacuum the current chopping results in a steep $\mathrm{d}i/\mathrm{d}t$ in the range of 10^8 A/s.

In the case of an inductive network, these high-frequency phenomena may lead to over-voltages u_{surge} at the load-side of the circuit:

$$u_{\text{surge}} \approx \frac{\mathrm{d}i}{\mathrm{d}t} \cdot L \cdot 2 \cdot \sin\left(\frac{i_{\text{chop}}}{2 \cdot \frac{\mathrm{d}i}{\mathrm{d}t} \cdot \sqrt{L \cdot C}}\right), \tag{9.21}$$

where L and C are the circuit inductivity and capacity. In practice the sine-argument is very small, so the following approximation is sufficient:

$$u_{\text{surge}} \approx i_{\text{chop}} \cdot \sqrt{\frac{L}{C}}. \tag{9.22}$$

For medium voltage circuit-breakers CuCr is well-established with a maximum i_{chop} at 5 A. In the case of contactors WCu-based materials with 3 A and WCAg with 1 A are used as well [16].

9.2.4 Mechanical and Thermal Aspects

In order to realize the switching function in a vacuum-sealed interrupter a moveable contact is needed. A usual number of operations is between 10 000 and 30 000 during an interrupter's lifetime. The most reliable solution is moving via stainless steel bellows. The mechanical lifetime of these bellows is only a matter of dimensioning. If D_{a} and D_{i} are the outer and inner diameter, z the number of waves and s the material thickness, the mechanical life N_{mech} for a certain stroke d is approximately given by

$$N_{\text{mech}} \propto \left[\frac{(D_\text{a} - D_\text{i})^2 \cdot z}{s \cdot d} \right]^4. \tag{9.23}$$

This strong dependence on geometric parameters allows the designer to optimize the tube's dimensions.

Another demanding application is the making operation on a short-circuit current. Depending on the circuit conditions, a peak current I_{max} in the range of three times short-circuit current will appear, which may be 100 kA or more. Due to current loops in the contact path, repulsive forces F_c can lead to bouncing and at least to contact welding. To avoid this, a contact pressure is necessary which is higher than the repulsive force. Usually this is realized by the switching mechanism. The repulsive force F_c is approximately given by

$$F_\text{c} = K \cdot I_{\text{max}}^2, \tag{9.24}$$

where the constant K depends on the contact system. Due to attractive forces produced in an AMF-system, K is approximately 40% smaller for AMF than for RMF.

In the closed position, the interrupter must also be able to carry the short-circuit current for a few seconds without inadmissible warming or contact welding, according to the standards. The thermal energy loss is determined by the Ohm losses in the contact resistance R_c and narrowness resistance R_n on the contact surface. R_c depends on the surface cleanness and is in the range of a few μΩ for vacuum interrupters, while the narrowness resistance is of the order of

$$R_\text{n} = \frac{\rho_{\text{el}}}{D_\text{c}}, \tag{9.25}$$

where D_c is the diameter of the thermal contact area and ρ_{el} the specific Ohm-resistance of the contact material. In order to minimize the Ohm-losses $I^2 \cdot (R_\text{c} + R_\text{n})$, ultra-clean surfaces are needed and the thermal contact area has to be maximized.

The time-dependent temperature $T(t)$ related to the initial temperature T_0 on the contact surface can be estimated by

$$T(t) = T_0 + \frac{2}{\sqrt{\lambda \cdot \rho_\text{m} \cdot c \cdot \pi}} \cdot \frac{I^2}{D_\text{c}^2 \cdot \frac{\pi}{4}} \cdot \left(R_\text{c} + \frac{\rho_{\text{el}}}{D_\text{c}} \right) \cdot \sqrt{t}, \tag{9.26}$$

where λ is the thermal conductivity, ρ_m the mass density and c the specific heat of the contact material (Table 9.1). If $T(t)$ exceeds the melting temperature, welding occurs.

9.3 Present State-of-the-Art and Applications

9.3.1 Vacuum Interrupter Design and Technology

The vacuum interrupter is a switching component for ac-networks. But even in dc-circuits an interruption is possible due to forced current-zero by taking external measures. The principle properties of an interrupter are:

Table 9.1. Material values

Material		$Cu_{300\,K}$	$Cu_{1000\,K}$	$Cr_{300\,K}$	$Cr_{1000\,K}$	$CuCr50_{300\,K}$	$CuCr50_{1000\,K}$
Mass density	ρ_m (10^3 kg/m^3)	8.9	≈8,5	6.9	≈6,7	8	≈7,6
Spec. resistance	ρ_{el} (10^{-8} Ω m)	1.7	≈7	12.9	≈50	5.5	≈20
Therm. conductivity	λ (W/m/K)	400	≈350	100	≈60	200	≈150
Spec. heat	c (J/kg/K)	380	≈500	450	≈680	400	≈600
Melt. temperature	T_m (K)	1383		2203		1383	
Boil. temperature	T_b (K)	2895		2942		2895	

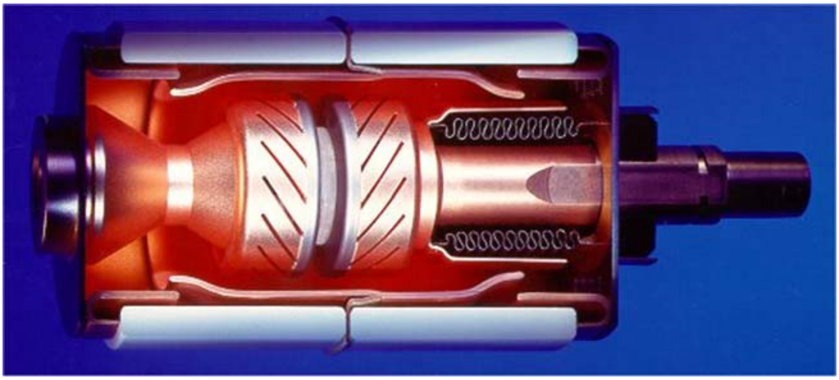

Fig. 9.6. Vacuum interrupter

- conduction of rated (permanent) and short-circuit currents (few seconds),
- interruption of rated and short-circuit currents,
- insulation of rated, power frequency and impulse voltages,
- making (closing) operations at rated and short-circuit conditions,
- mechanical switching operations.

To realize these functions, copper bolts, contact parts, ceramics, internal shields, bellows and a vacuum sealed envelope are necessary. There are many different tube designs depending on the application and "manufacturer's philosophy". For the lower ratings tubes with only one ceramic and one internal shield are sufficient. High-ranged interrupters have two ceramics and sophisticated shield systems (Fig. 9.6). Tubes with an arcing chamber in the middle are also advantageous.

These shield systems protect the inner ceramic surfaces against metal vapor and improve the dielectrical strength. Electrical field calculations and optimizations are state-of-the-art today. The insulators are made of Al_2O_3-ceramic which is metallized at the joint surfaces to the metal parts. Stainless steel bellows allow up to several million of mechanical operations without any loss of vacuum. All joints are absolutely vacuum-sealed for life cycle by brazing or welding technology. The product life is over 20 years. The brazing materials are based on copper–silver alloys with additions. Copper parts are oxygen-free (OFCu) and all internal materials have only low gas content. Especially the contact material, e.g. CuCr, is extremely outgassed and predominantly free of impurities. Thus, there are only a few suppliers for these high-tech materials word wide.

Knowing the parameters which determine the contact system properties, one is able to take into account the advantages and disadvantages of both worlds, RMF and AMF. One has to compare the switching behavior for different voltage ratings, the ohmic losses during operation with rated current, mechanical forces to keep the contact closed and, of course, the costs.

Looking at the switching behavior, there is a higher interrupting capability at smaller gaps for RMF than for AMF contacts (Fig. 9.4). In practice it is more useful to consider the interrupting capability in dependence on the contact diameter D. From (9.4) resp. (9.9) we get another graph in Fig. 9.7. Due to the condition according to (9.2), a saturation effect occurs for RMF and the interrupting capability is limited in contrast to AMF. Hence, AMF is used at higher voltages and higher interrupting currents.

The RMF arc-mode tends to form jets which may interact with the internal parts of the tube, while the AMF arc-mode has an effect like a magnetic cage. Thus, AMF systems make smaller tube designs possible. Considering the ohmic losses RMF is more advantageous than AMF. This is because of the rather long length of the current path in the AMF contact design. Of course, due to several geometrical parameters AMF systems can be optimized concerning the electrical resistance and the axial magnetic field. For making operations the force to keep the contacts closed is also an important parameter. In accord to (9.24) this force is approximately 40% smaller for AMF than for RMF.

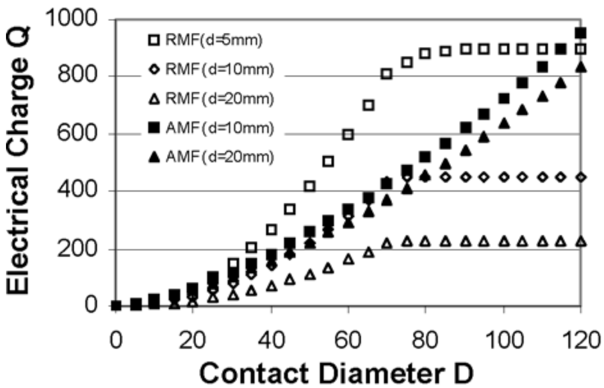

Fig. 9.7. Interrupting capability in dependence on contact diameter and stroke. Saturation effect for RMF due to the limiting rule (9.2)

Table 9.2. Contact system portfolio

	<20 kA	25 kA	31.5 kA	>31.5 kA
≤1 kV	RMF	RMF	RMF	RMF
12 kV	RMF	RMF	RMF	AMF
24 kV	RMF	RMF/AMF	AMF	AMF
36 kV	RMF	AMF	AMF	AMF
>36 kV	AMF	AMF	AMF	AMF

Finally, a more complicated AMF design often results in higher production costs compared to RMF. In view of the above mentioned facts it is obvious that the application of RMF is preferred at lower voltage ratings and AMF is preferred at higher interrupting currents. For the low voltage range, i.e. less than 1 kV, there is no alternative to RMF in order to interrupt proper short-circuit currents. On the other hand, at higher voltages (>24 kV) and higher currents (>40 kA) AMF is the best choice (Table 9.2). Of course, if there is a need for smallest interrupter design at lower ratings, e.g. at 12 kV level, sometimes AMF is used as well. In these cases it depends on customer's requirements.

9.3.2 Medium Voltage Circuit Breakers

Today the main applications of vacuum interrupters are in circuit breakers for the medium voltage range 7.2–50 kV. The rated currents are several hundreds or thousands of amperes. VCB's are able to interrupt the rated current some tens of thousand times without any significant reduction in dielectric strength. Also short-circuit current interruptions up to tens of kiloamperes will be managed properly. Even in the case of power generators more than 72 kA short-circuit currents with a high dc-component will be interrupted more than 30 times.

High dc-components are caused by an asymmetrical shift of the sinusoidal ac-current due to the network behavior after the short-circuit fault. Even the absence of current-zeros is possible during the first power-frequency cycles. After some tens of milliseconds – depending on the time-constant τ of the network – the first current-zero appears, which is essential for current interruption. Modern VCB's have a rather short response time t_o for opening after short-circuit occurs, thus rather high dc-components appear,

$$\text{dc} = \text{e}^{-\frac{t_\text{o}}{\tau}} \approx 0.3 \ldots 0.6. \tag{9.27}$$

Therefore, the inevitable interrupting capability for tubes is given by the electrical arc-charge carrying the asymmetrical current during the arcing-time t_arc,

$$Q_\text{dc} \approx Q_\text{sym} \cdot \left(1 + \frac{\pi}{2} \cdot dc\right). \tag{9.28}$$

The user likes to have rapid interrupters in order to shorten the fault time. Thus, at given ratings highest dc-components are demanded. On the other hand, this leads to larger contact and tube diameter. A balanced design will result in an optimized cost position for the interrupter.

9.3.3 Medium Voltage Contactors

In the medium voltage range vacuum contactors are in operation all around the world: switching transformers, capacitors, reactors, resistive loads or motor starters up to 12 kV. Recently designed vacuum contactors extend the supply range to 24 kV.

The switching frequency is much higher than for circuit-breakers; therefore, contactors and their vacuum interrupters have to exhibit much longer mechanical and electrical lifetimes. As a rule, the minimum required number of switching cycles over the life is one million. Usually the contact material consists of WCAg instead of CuCr commonly used in circuit-breakers. The hard-metal component, tungsten carbide (WC), ensures small erosion caused by arcing [17]. Also with WCAg the chopping current is below 0.5 A. This helps considerably in reducing possible over-voltages caused by the $\mathrm{d}i/\mathrm{d}t$ in high-inductance circuits. But contact materials based on CuCr or WCu are well-established in medium voltage contactors too.

The first use of contactors for the 24 kV level was in 1998 operating the drivers of the TRANSRAPID magnetic transportation system (Fig. 9.8). Here switching devices have to handle higher rated currents and voltages, and also up to one million operating cycles. This large number of operations in the 24 kV range is possible by innovative contactor designs with a special contact material used in the vacuum interrupter.

Fig. 9.8. 24 kV contactor. Switching device for the magnetic transport system TRANSRAPID

Fig. 9.9. Low voltage vacuum interrupter. First vacuum interrupter for 50 kA at 690 V; 80 mm tube diameter

9.3.4 Low Voltage Circuit Breakers

In 1990 the first vacuum interrupter for a low voltage range was introduced into the market (Fig. 9.9). With a lifetime of several 10 000 operations at 2500 A and a few tens of short-circuit current interruptions at more than 50 kA new trends were set in low voltage power engineering.

References are given in facilities with high demands like cranes for open-cast mining. Minimum standstill-times and maximum availability reduce the production costs considerably. Circuit breakers on ships should be maintenance-free and without exhausting systems. Furthermore, in the chemical industry hermetically sealed switching devices are desirable. Vacuum technology has improved itself in plenty of low voltage applications. There is no doubt that the vacuum technology will also be available for ratings higher than 100 kA in the future.

9.3.5 Low Voltage Contactors

The use of vacuum interrupters for low voltage is well-established for contactors. Starting with 630 A contactors in the early 1980s, the development now tends towards smaller currents.

Main problems are the production costs compared to air contactors. New designs and modern vacuum mass-production technologies are imperative in order to introduce economical products (Fig. 9.10). Contactors are available in vacuum technology with a significantly higher electrical lifetime (up to 3 million switching operations) than conventional devices. Besides the compact design and high mechanical and electrical lifetime, the hermetic capsulation of vacuum contactors is a further advan-

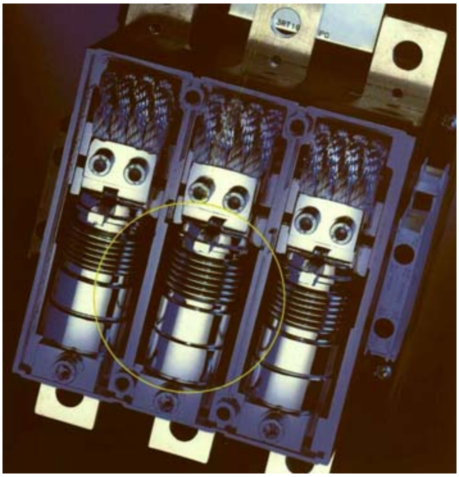

Fig. 9.10. Low voltage contactor: for 300 A at 690 V; 30 mm tube diameter

tage. Because of no interaction between the arc and the environment, applications in aggressive or explosive atmospheres are possible.

9.3.6 High Voltage Vacuum Breakers

By using series arrangements of two or more vacuum interrupters, it is basically possible to double or multiply the dielectric strength without increasing the operation energy substantially. Applications with two 24 kV or 36 kV standard vacuum interrupters in series for rated voltages of 52 kV or 72 kV are well known.

In addition, the rise of the dielectric recovery after current zero is steeper than for a single device. By this the interrupter is able to quench arcs successfully after shorter arcing times compared with a single interrupter [18]. In principle, there is no restriction on the medium voltage range for single vacuum interrupters. Tubes for 72 kV and even more than 125 kV applications are described by Japanese manufacturers [19]. However, due to the nearly square-root dependence of the dielectric strength on the contact stroke [see (9.20)] it is not trivial to find acceptable solutions. Optimized shield systems, excellent surface technologies and mellow contact systems for long-stroke interruption capability (e.g. AMF-system) are essential for high voltage interrupters.

Due to basic research and development high voltage interrupters in ‘medium voltage sizes’ are possible today (Fig. 9.11). The electrical field strength is minimized and is in the rage of medium voltage bottles. Even the X-ray emission under rated voltage (72 kV) seems to be no problem.

9.3.7 Load Breakers

Unlike the interrupters used in contactors, an interrupter in a load-break switch only has to interrupt currents in order of magnitude of the rated current. The maximum

Fig. 9.11. High voltage vacuum interrupter (prototype): for 72.5 kV and 31.5 kA; 150 mm tube diameter; 500 mm length

mechanical and electrical lifetimes are about 10 000 switching cycles. Switches must also be capable of disconnecting capacitor banks without re-striking. Capacitive switching, for which high dielectrically strength is essential, is also required for frequent disconnections of overhead lines and cables under no-load or low-load conditions. The highest demand on dielectric strength exists when the rated cable-charging breaking current has to be interrupted under earth-fault conditions.

Based on the considerable differences between the contactor and the switch applications, the challenge is to design an interrupter that is economically priced, compact and which can be used for different applications with the same external dimensions and the same internal construction. The difference is only in the contact material.

9.3.8 Transformer Tap Changers

A special application of vacuum interrupters is the use for transformer tap changers. Requirements are large numbers of operations like contactors with current-ratings as circuit breakers. Nevertheless, a very high reliability is essential. This was a great challenge for the tube developers and producers.

Fig. 9.12. Transformer Tap Changer (MR Germany). A special application of vacuum interrupters for transformer tap changers

In the early 1990s the world-wide leading manufacturer of transformer tap changers introduced vacuum switching interrupters successfully (Fig. 9.12). The tap changer operation is divided into three major functions:

- arc interruption and re-closing by use of the vacuum interrupters in conjunction with the associated by-pass switches;
- selection of the next position by a selector switch assemblies in proper sequence with the operation of a vacuum interrupter and by-pass switch;
- operation of reversing or coarse/fine switches in order to double the number of tap positions.

9.3.9 Other Applications

There are many other applications for vacuum switching devices, for example, circuit breakers for railroads in low-cycle networks (e.g. 16 Hz) and power-breakers for nuclear fusion reactors (ITER). In these cases rather long arcing-times compared to normal power frequency (50/60 Hz) and high interrupting currents (up to 80 kA) may appear. This requires tubes with highest interrupting capability.

Vacuum interrupters are not able to interrupt dc-currents. But with the help of current commutation an artificial current zero can be generated in order to extinguish the arc. A typical application is in Tokamak-devices for nuclear fusion experiments [20]. Best experiences were made with the use of vacuum interrupters, and maybe in future the ‘sun on earth’ will be switched on with vacuum bottles.

For special applications some types of interrupters must be able to operate properly at more severe stress, e.g.

- switches for arc furnaces operate frequently with high currents,
- switches for back-to-back capacitor banks that operate rather frequent inrush currents with high frequency and amplitude,
- switches for small inductive currents which may cause over-voltages at the load-side.

Highly sophisticated mechanical designs, excellent dielectrical performances and suitable contact materials are essential in order to realize these demands.

9.4 Future Aspects

Up to now most of the applications of vacuum interrupters are in the medium voltage range 7.2–52 kV with maximum short current interruption capability of 72 kA. World-wide the manufactures are working on a further increase of the switching capability, e.g. for power generators. The next level to reach is 80 kA according to ANSI standards. But also more than 100 kA seems to be possible. For this high-current interruption optimized AMF-contacts are necessary. A better knowledge about the physics of plasma-arcs is important to increase the interrupting capability. Calculated field distributions combined with plasma models have to reflect the experimental results. Plenty of investigations are focused on this [21].

Looking at the low voltage range a beginning was made with 690 V contactors for 300 up to 800 A. However, the lower the ratings the higher are the production costs. Hence economical limits are given. For the low voltage circuit breakers the situation is quite similar. Low cost solutions for ratings higher than 50 kA are needed. The question is, whether 200 kA interruptions are possible with common contact systems [22].

On the other side also the high voltage regime is ready for vacuum technology. Assuming vacuum interrupters for 125 kV rated voltage with a single contact gap are available in the future, the fiction is a 750 kV arrangement [25]. New technologies like magnetically driven switchgears open a wide field for innovations, e.g. phase-controlled switching just before current zero in order to minimize the arc energy. Intelligent electronics and vacuum electronics will melt together, leading to computer-controlled vacuum interrupters (CCVI).

Further tubes in cast-resin insulated poles allow compact switchgear designs and outdoor applications. Small dimensions and compatibility to older breakers allow a trouble-free replacement [23]. There is also a certain pool for vacuum interrupters in special cases mentioned before, like reclosers, nuclear fusion research (ITER) and high-speed transfer switches.

Increasing production quantities are reflecting the progressive trend of vacuum technique. For example, in China there is a clear decision for vacuum switching-technology [24]. Maintenance-free and large numbers of operations, high reliability of the vacuum chamber with mean time to failure (MTTF) of several tens of thousands of tube-years, proper switching performance and environmental compatibility predestine the vacuum switching principle for this millennium.

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