VACUUM SWITCHES

FUNDAMENTAL DESIGN OF THE VACUUM SWITCH

Components

The vacuum switch represents a family of devices ranging widely in different types and applications. However, despite the large variety, many common components can be identified. Figure 1 illustrates a schematic cross section of a generic vacuum switch. In the closed state the moving contact is pushed against the fixed contact by an external mechanism. The main current path is accomplished through (from left to right) the moving-contact stem (2); an arc-control contact (3), if any; the moving-contact tip (8); the fixed-contact tip (8); an arc-control contact (3), if any; and the fixed-contact stem (1). All these components are current carrying so they have to be made of low-resistivity materials. In the open state the moving contact is retracted from the fixed contact by applying an opening force to overcome outside atmospheric pressure and possible contact welding. The metallic bellows (9) provides the necessary motion in vacuum, tightly sealing against the atmospheric pressure. The ceramic or glass envelopes (6) serve as electrical insulation between the two end terminals of the switch as well as housing for all components of the assembly. When the switch is open under flow of electrical current an arc is drawn between the contact tips (8). This arc is commonly called a vacuum arc although in fact it is burning in the hot ionized vapors of the contact-tip material. Some literature refers to it as a metal vapor arc. The arc products, hot vapors, ions, electrons, and microdroplets of molten material are sputtered from the interelectrode area outward due to the pressure differential between the arc and surrounding vacuum ambient. In order to avoid coating the inside of ceramic insulators with conducting films of condensing vapors, the contacts are surrounded by an ion shield (4), typically made of metallic material. Notice that the shield is normally electrically floating, that is, not connected to either electrode. An additional shield (5) is often used to protect the bellows. Although coating of the bellow would not have any dielectric consequences, the exposure to high temperatures of the arc might damage the rather fragile component. The end plates (10) are holding the contacts in place and provide the seal and mechanical support for the bellows.

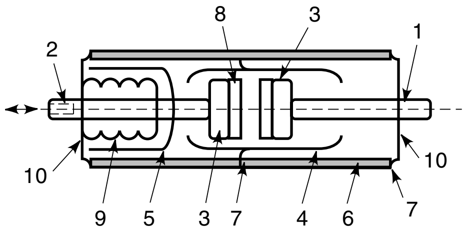

Figure 1. Vacuum switch components (shown in open state): (1) fixed contact stem; (2) moving contact stem; (3) contact–arc-control geometry; (4) ion shield; (5) bellows shield; (6) ceramic or glass insulators; (7) ceramic-to-metal junction; (8) contact tip; (9) bellows; (10) end plates.

Manufacturers of vacuum switches utilize their own designs with modifications to the basic schematic shown in Fig. 1. For example, in order to reduce the number of components and cost only a single ceramic or glass envelope is used. In this case the ion shield would typically be electrically connected to one of the electrodes. In other designs the inside surface of the ceramic is shaped with special grooves so even when the vapors are deposited onto the exposed ceramic surfaces, the remaining, shadowed grooves provide the necessary electrical clearance. Other solutions include mounting the bellows so it extends outside the vacuum bottle, thus providing better utilization of the full length of the ceramic insulation. Further reduction in the number of components can be achieved by combining the fixed-contact end plate with the ion shield by shortening the fixed-contact stem and placing the fixed contact right on the end plate or ion shield. Depending on the application the arc-control contacts are often omitted, especially for low currents. Sometimes the bellows shield could also be eliminated.

Materials

All components of the vacuum switch have to be vacuum suitable, that is, must be able to work in low pressures and be gas-free. This translates to the requirement that all metallic components be of highest purity and all ceramic and glass be resistant to high temperatures. This also includes the brazing materials used for connecting the parts together. Table 1 lists the commonly used materials and the components of the switch.

High-purity copper is often labeled as 5N, that is, 99.999% pure, or OFHC, that is, oxygen-free, high conductivity. Such copper is commonly available today but it is rather soft and ductile and therefore difficult to machine. The material for the contact tips is most often proprietary and specific to each manufacturer. Various alloys and sintered materials composed of copper or silver mixed with chromium, bismuth, tungsten, etc., are used. For high power switches a mixture of chromium and copper is now almost universally used. The main two functions of the contact tip are (1) to allow the arc to burn easily in its vapors so as to provide good conduction during the main current flow and (2) to ensure easy and rapid arc extinction during the dielectric recovery after the current reaches zero. Since these two functions are in direct conflict, the material for the contact tip is a compromise solution. In addition, the contact tips have to provide a good electrical con-

Table 1. Materials Commonly Used for Vacuum Switch Manufacturing

Material	Component or Its Function
High purity (5N) OFHC copper	Contact stems, arc control contact, end plates
Copper–chromium, copper–bismuth, silver–tungsten, etc.	Contact tip
Stainless steels	Bellows, ion shields, bellow shields, end plates, additional components of arc control contacts
Ferromagnetic steels (Nickel steels. . .)	Ion shields, bellow shields, end plates
Aluminum oxide-based ceramics and glasses	Envelopes, ion shield
Eutectic brazing materials (Silver-based)	All connections and junctions
Getters	Continuous pumping of sealed switch

nection in the closed state as well as the ability to close onto a fault current without welding to each other. In the last several years manufacturers put a great deal of research and development effort into the creation of suitable contact materials. Many of them have developed a few different materials depending on different switch applications and used small amounts of other additives (Te, Se, etc.) to alter the property of the final compound.

A variety of stainless steels is used for bellows and shields. These components do not carry any current so their electrical conductivity is of no importance unless eddy currents induced by magnetic fields become significant. The steels used for the bellows have to be durable enough so as to ensure typically of the order of 1,000,000 mechanical operations without fatigue. Some switches utilize ferromagnetic steel rather than stainless steel for their shields.

Today most vacuum switches use an AlO_2-based ceramic rather than glass as an insulating envelope. The ceramic is easy to braze with the metallic components of the switch which are selected to have very similar thermal expansion properties so the junctions do not crack under thermal stress. All components of the switch are assembled together by using Ag-based brazing. The brazing material melts easily, forms a good hemetic seal, and provides good electrical conductivity. Typically it is used in a form of thin washers or wires. Sometimes a small amount of getter, a special active material, is placed inside the switch before the final assembly is sealed off. The getter acts as a miniature chemical pump that can restore and improve the vacuum pressure even if a small amount of residual gas is trapped inside. Operating the switch under normal current conditions also results in an effective pumping action since the vapor jets from the burning arc capture the gas molecules and deposit them on the surrounding ion shield. The gas molecules bonded with the metal vapor molecules form a layer that can be safely stored on the surface of the shield. Chromium based materials are particularly effective at this self pumping action.

Manufacturing

The manufacturing process of vacuum switches resembles that used in the silicon wafer industry. A clean-room facility (typically class 100) is required. The assembly area has to be dust-free and the components have to be free of oxides and oil residues from machining. After chemical cleaning all the parts of the switch are dry-assembled together and placed on special jigs to be put into the vacuum furnaces for final processing. Modern vacuum furnaces allow a large number of devices to be processed simultaneously. With the load of dry-assembled bottles inside, the furnace is closed and the temperature is raised. At the same time the chamber is evacuated. This accomplishes two things. First, the residual gases and other volatile impurities are freed off all the surfaces and pumped out. Second, when the temperature exceeds the melting point of the brazing washers the braze melts and brazes the components together. The same principle is also used for the final sealing off of the device. In some designs both processes are performed in one operation called “one shot seal off.” Sophisticated computerized process-control technology is necessary to ensure the proper temperature control, duration of individual cycles, etc. Quality control and highest repeatability of the furnace operation are critical. A load of vacuum-switching devices is typically processed within 24 h to 36 h. Once cooled and removed from the furnace the devices are checked for proper vacuum pressure using a magnetron stand in which a strong external magnetic field is applied to the switch with contacts open and at high voltage. A small current resulting from the field emission from the electrodes is indicative of the amount of background gas inside the switch chamber. Then the devices are stored for several days, typically of the order of two weeks to one month, and the pressure is checked again using the same principle. Although the technique is not very accurate in terms of the absolute pressure reading, the comparison between the two readings gives an indication of the worst possible leak. The final operating pressure of the healthy switch could be as high as 10^{-5} Torr and as low as 10^{-10} Torr. Any pressure less than 10^{-5} Torr plays no part in the operation of the device.

Manufacturing of the material for the contact tips could be accomplished by either powder packing or infiltration. Powder packing requires the metallic ingredients Cu and Cr, for instance, to be mixed as powders and pressed together as disk-shaped wafers under very high force. Well-mixed powders form a matrix of Cu and Cr granules. CLR, the original material used in vacuum switches, is made by producing a pressed wafer of powdered chromium only. Then, a separate, smaller disk of solid OFHC Cu is placed on top of the Cr wafer and inserted in a special vacuum furnace. By controlling the temperature inside the furnace the copper disk is allowed to melt and infiltrate the matrix of Cr powder like a sponge soaked with water. This is an effective way of saturating the Cr matrix with Cu completely, without leaving any voids. The final contact material is machined without any wet lubricants to a required shape.

TYPES OF VACUUM SWITCHES AND THEIR APPLICATIONS

High-Current Interrupters

The primary functions of these devices are to carry normal load current when closed and to be able to interrupt very high short-circuit currents in the event of a fault in the power system. Therefore, they are of a larger size, employing heavy contacts with sophisticated arc-control geometries. The shield is

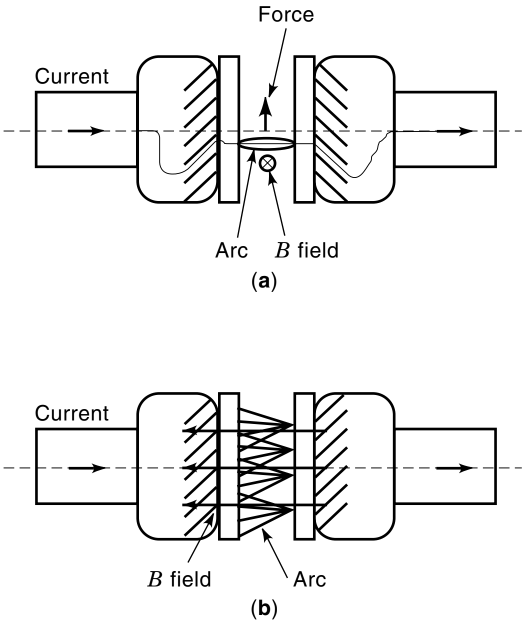

Figure 2. (a) Radial magnetic field arc control geometry (arc shown as constricted). (b) Axial magnetic field arc control geometry (arc shown as diffuse).

also thicker to withstand the heavy bombardment of plasma and vapor from the high current arc. These switches are expected to perform of the order of 10,000 mechanical operations but have a lower life expectancy for switching the faults (typically 50–100 operations). The high-current interrupters are commonly used in vacuum circuit breakers and are driven by either motor-operated spring mechanisms, solenoids, or special magnetic actuators.

In order to control the arc burning when the contacts separate under high current and to keep the arc in the diffuse mode for interruption at current zero (see the section entitled “Electrical Characteristics”), magnetic fields are employed inside the contacts. These magnetic fields are typically generated by the high current itself. There are two generic types of arc-control geometries, producing either radial magnetic field (RMF) or axial magnetic field (AMF). Both principles are shown in Fig. 2. In the RMF contacts parallel slots are cut around the circumference of both electrodes but in opposite directions, that is, one electrode clockwise, the other one counterclockwise. When the switch current passes through the contacts it forms a loop as shown in Fig. 2(a). This loop generates a radial magnetic field that in turn produces an azimuthal electromagnetic force according to the Lorenz force, $F = I \times B$. This forces the arc to rotate around the electrode perimeter typically 3–6 times per one-half cycle of power frequency current. The fast rotation of the arc cools the electrodes and uniformly distributes the arc products throughout the space. In Fig. 2(b) the cuts are in the same directions for both electrodes. The flowing current forms an azimuthal loop that produces an axial magnetic field, similar to a single turn of a solenoid around the contacts. Although the axial magnetic field does not move the arc roots, it causes the arc to spread evenly across the contact and keeps it in so-called diffuse mode, that is, as many separate small current arcs easily manageable during interruption.

Load Switches

Load switches are designed to carry and switch only normal load currents with limited fault-current-interruption capability. Thus they are lighter and less expensive to manufacture. Most of them do not have any arc-control geometries but their contact stems are suitable for providing good thermal conduction of heat from the contact area to the outside of the device. In all vacuum switches the heat dissipated as a result of I^2R power, where I is a current through the switch and R is a resistance of the contacts in closed state (5 $\mu\Omega$ to 50 $\mu\Omega$), has to be removed outside the device by thermal conduction through the stems since the convection and radiation of heat are insignificant. Load switches are expected to operate more frequently than the high-current interrupters.

Contactors

These switches are used for lower voltages and currents and very frequent operations. Typical applications would include motor control and capacitor bank switching. The insulators are therefore smaller in diameter and length; the contacts are also smaller with no arc control. The contact gap is typically of the order of 4 mm or less. The contactors are durable and often capable of 5,000,000 mechanical operations without maintenance. The contactors are primarily solenoid driven.

ELECTRICAL CHARACTERISTICS

The physics of vacuum discharge and vacuum insulation is still under heavy scrutiny, and scientists do not agree on many key principles of the vacuum-arc behavior. As a result many electrical characteristics of the vacuum discharge are either estimated analytically or obtained from experiments on specific devices. This implies that absolute limits of capabilities of the vacuum switches are not known and that the possibility for improvements and optimization exists.

Breakdown and Field Emission in Vacuum

It is generally agreed that breakdown in vacuum is a combination of field-emission processes according to the Fowler-Nordheim mechanism, Schottky emission, and thermal heating of the microscopic sites of the electrode surface. This section briefly describes the three mechanisms.

According to the Fowler–Nordheim theory, which draws on quantum mechanics, the electrons inside the metal electrode at room temperature have their energy below the potential barrier described as the work function (see Fig. 3). Figure 3

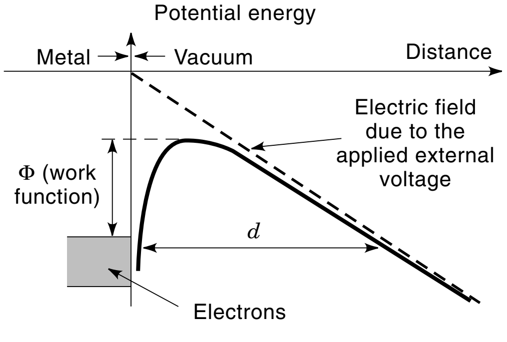

Figure 3. Potential energy distribution between the metal and vacuum.

illustrates the potential energy distribution across the interface of the metal and vacuum when an external electric field is applied, as shown by the dashed line. The energy of the electrons inside the metallic electrode (cathode) lies in the band as seen in Fig. 3, the highest energy being at the Fermi level. In such a case it is impossible, from the deterministic point of view, for electrons to escape from the metal into the vacuum and proceed to the right, in the direction of the applied field. However, quantum mechanics allows for a finite probability that the electrons can tunnel through the potential barrier even without having the required energy Φ. This tunnel effect depends on the width of the barrier, d. It is easy to observe that the width of the barrier is also dependent on the strength of the external field: the higher the field the narrower the barrier. The Fowler–Nordheim (FN) equation describes the relationship between the current density resulting from this effect and the applied electric field.

$$\log_{10}\left(\frac{J}{E^2}\right) = -\log_{10}\left(\frac{\Phi t^2(y)}{1.54 \times 10^{-2}}\right) - \frac{6.83 \times 10^9 \nu(y) \Phi^{3/2}(1/E)}{2.3026} \tag{1}$$

where J is the current density, Φ, the work function, E, electric field strength, and $y = 3.795 \times 10^{-3} E^{0.5}/\Phi$. $\nu(y)$ and $t(y)$ are functions of y and therefore E but do not vary significantly with the values of the field and are often assumed as constants. If one defines the current density as $J = I/A$, where I is the emission current and A is an effective emission area of the electrode, and the electric field strength as $E = \beta V/l$, where β is a so-called field enhancement factor, V is the voltage applied between the electrodes, and l is the distance between the electrodes (gap), Eq. (1) can be applied experimentally and a curve of I versus V plotted for a given experimental arrangement. If plotted on a logarithmic scale the FN curve is a straight line, the slope of which is related to the β factor and Φ. The β field enhancement factor is a very important indicator of the conditions of the surface microstructure of the cathode and therefore sought after by designers and users of high-voltage vacuum devices. Since all practical metallic surfaces have a certain amount of roughness (Fig. 4) it is likely that at the peaks of the surface microdisturbances, or protrusions, the effective electric field will be greater than V/l by a certain factor (β) greater than 1. To use the FN equation for estimation of β it is necessary to know the value of Φ. For copper and similar materials $\Phi =$ 4.5 eV. The intercept of the FN logarithmic curve with the ordinate can also be used to calculate A, the effective emission area of the surface. It should be understood that A is not a geometric surface area of the cathode, especially for the flat electrodes since the emission current density is higher at the tips of the protrusions, where β is high, and lower or zero in the valleys. In actual vacuum switches the tips and protrusions are the results of machining the contacts and mechanical opening and closing operations as well as arcing. Moderate arcing of the contacts actually conditions the contacts and improves the surface structure (lower β). As an example, two flat electrodes in vacuum 2 mm apart might withstand ~25 kV in the first trial but might support in excess of ~70 kV after a few tens of repeated arcs. This conditioning effect of arcs is often used in the manufacturing of vacuum switches. The worst microprotrusions can be created by opening the vacuum contacts under no current.

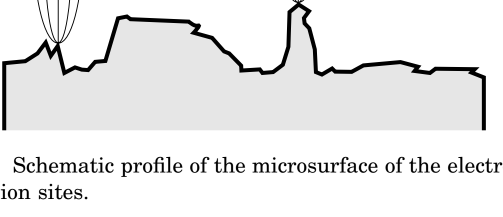

Figure 4. Schematic profile of the microsurface of the electrode with two emission sites.

Breaking the microwelds between the two contacts in the absence of a smoothing action of the arc produces extremely sharp surface structures of the order of 10–20 μm in size. Of course, any current switching operation would tend to remove these protrusions.

The Schottky theory proposes another mechanism for the emission of electrons from the cold (room-temperature) cathode. It states that with certain probability some electrons within the metal at the higher end of the energy distribution will have enough energy to jump over the potential barrier rather than tunnel through it. The required energy is, of course, Φ, the work function. As in the case of FN theory the potential barrier also depends on the external field E. The higher the field, the lower the barrier height.

The most obvious mechanism for emitting the electrons from the surface is the thermal energy that can be delivered to the electrons to increase their kinetic energy and therefore allow them to jump more easily over the potential barrier. Although thermal energy alone is not sufficient to produce appreciable emission, the temperature of the surface plays a very important role in other emission processes and can greatly enhance both Fowler–Nordheim and Schottky mechanisms. In such cases the process is described as thermionically enhanced field emission.

Extensive experimental and analytical studies indicate that for lower electric fields the Schottky mechanism tends to dominate whereas the high E field results in FN emission. In either case the current densities from the emission sites can reach values as high as 10^9 A/m^2 to 10^{10} A/m^2 or more. Some evidence exists that the anode electrode also plays some role in the vacuum discharge; however, the exact explanation of this phenomenon is still under scientific dispute.

In practical vacuum switches the possible breakdown scenario is as follows. When the applied electric field is high the combination of Schottky and FN emission causes the electrons to escape from the tips of the microprotrusions (Fig. 4). This electron current triggers intensive Joule heating of the tips and possible melting, thus enhancing the emission even further. As a simple rule of thumb one can assume that for a typical, conditioned vacuum switch, the electrode gap can support electric fields of the order of 30 kV/mm to 40 kV/mm. This value could be much less if the temperature is high, if the profile of the surface is rough, or if the gap is still filled with plasma residues from the previous arcing. Freshly conditioned and polished surfaces can support higher values. Typical breakdown is very fast and takes of the order of single-digit nanoseconds to precipitate. One has to realize that the full collapse of the voltage during breakdown also depends on the external electrical circuit, especially its characteristics at high frequencies.

Vacuum Arc

If the external power circuit can provide sufficient current, the breakdown between the open electrodes will initiate the arc. This is often the case during closing prestrikes of the vacuum switch. The arc could also be established by drawing the two electrodes apart from the closed position under current. This is the situation during opening of the switch.

The vacuum arc is actually a misnomer. Since vacuum does not contain any molecules the vacuum arc is, correctly speaking, a metal vapor arc. The molten metal of the cathode and sometimes anode provides the necessary vapor for ionization and conduction of current. There are two modes of existence of the vacuum arc: diffuse and constricted. Both of these forms are briefly described in the following.

The diffuse arc is characterized by a number of cathode spots, small areas, just above the cathode surface, where intensive ionization and pressure exist. These 10–30 μm size zones [Fig. 5(a)] provide the sole source of plasma that makes up the arc. Neutral metal atoms, positive ions, and electrons found in the arc discharge all have to pass through the cathode spots in the diffuse arc. The area under the cathode spot resembles a crater of a molten metal from which electrons are emitted. It is interesting to note that both the positive ions and negative electrons are ejected hemispherically outward from the cathode spot toward the anode. Since both species originate from the neutral atoms there is approximately an equal number of them in the diffuse arc at any given time. The plasma is quasineutral. To establish a net current flow between the contacts the electrons travel much faster than the ions. The difference in the effective velocities of the two species results in the net current density $j = ne(\nu_e - \nu_i)$, where n is a density of the plasma (both electrons and ions, $n_e = {\sim}n_i$), e is an electronic charge, ν_e is a drift velocity of the electron cloud, and ν_i is velocity of the ion flux. Since the electron mass is much lower compared to the ion mass (several tens of thousands times) it is the electrons that respond to the fluctuations of the external arc current, ions being almost unaffected. Typically the ion current constitutes about 10% of the total current of the arc; therefore it is necessary that the electrons provide 110% of the net current. A single cathode spot can carry about 75 A to 100 A for copper but could be as low as few amperes for mercury and as high as 200 A to 300 A for tungsten. When higher current is required the number of spots increases proportionally. The cathode spots are highly mobile and are in continuous motion over the surface of the electrode. The anode plays a very minor role in the diffuse arc discharge only as a passive collector of the ions and electrons. The diffuse arc is characterized by a very low arc voltage of the order of 15 V to 20 V for copper, with high-frequency, short-duration spikes superimposed on the steady-state value. These spikes can cause an instantaneous voltage reaching 100 V or more and are indicative of the microinstabilities in the arc. The more stable the arc, the less high-frequency noise observed in the arc voltage. A diffuse arc is very easy to interrupt when the current reaches zero. At this time the last existing cathode spot extinguishes. The remaining plasma quickly disperses to the interelectrode vacuum, and the remaining metallic ions deposit on the anode and shield surfaces. This period (postarc period) lasts a few microseconds. The successful operation of any vacuum switch strongly depends on how diffuse the arc is prior to the current reaching zero. If the arc is diffuse the proper interruption at current zero is likely.

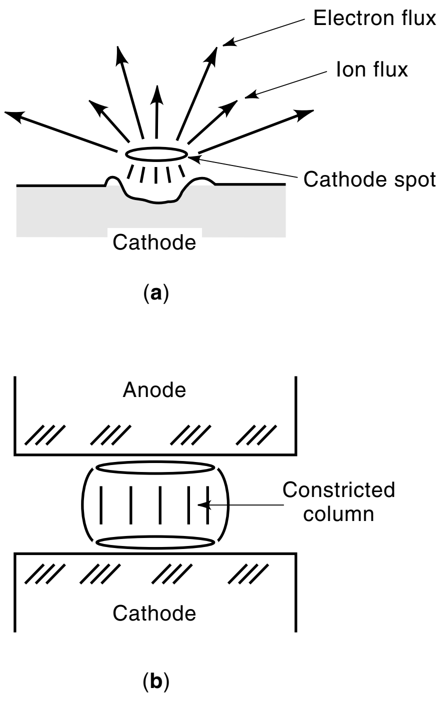

Figure 5. Two modes of vacuum arc existence. (a) Diffuse arc (only one cathode spot is shown); (b) constricted arc.

Under high current conditions, a large number of cathode spots merge together in the constricted arc mode. Not only does the resulting cluster of spots cause intensive localized cathode heating but the concentrated flux of ions melts the anode surface and initiates an anode spot [Fig. 5(b)]. The anode spot is much larger and hotter and contributes a significant amount of its own plasma to support the discharge. To summarize, both electrodes are active in the discharge and both have localized, anchored large hot spots producing plasma and metal vapor. If this is the case, the interrupting performance of this columnar arc at zero current is very poor and typically, for power system applications, failure to interrupt results unless the arc is made to move by means of radial magnetic field geometry as described previously. The arc voltage is higher than that in the diffuse mode, of the order of 100 V or more. This causes more power dissipation ($V_{arc}I_{arc}$) and magnifies the constriction effect even further.

Current Chopping

At very low currents the arc tends to become unstable, that is, thermodynamic processes inside the cathode spot are not balanced. This is often the case when switching an unloaded transformer or a high-impedance load, for example. When the current in the last existing cathode spot drops below the critical minimum value the arc could spontaneously extinguish itself. This would abruptly terminate the flow of the remaining current and cause a steplike transient. This current chopping is a function of the contact material, that is, the

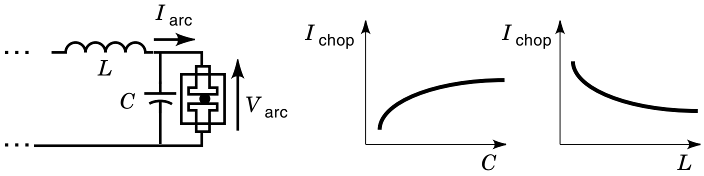

Figure 6. Effect of L and C of the external electrical circuit on current chopping.

composition of the metal vapor of the arc, as well as capacitance and inductance values of the external circuit immediately adjacent to the switch. Electrodes made of refractory metals (molybdenum or tungsten) tend to exhibit higher chopping currents (8 A to 20 A range) due to their low vapor pressures and inability to support the arc at low currents. High-vapor-pressure materials, such as bismuth, have much lower chopping currents (1 A to 3 A range). The influence of the electrical circuit capacitance and inductance can be explained with the help of Fig. 6. When the current flows through the arc the parallel capacitance C tends to keep the arc voltage constant. At low currents the stability of the cathode spot is in jeopardy and the arc tries to raise its voltage to increase the power input ($V_{arc}I_{arc}$) to regain the production of the plasma. The parallel capacitance restricts the voltage increase; therefore the higher the capacitance, the higher the chopping current. On the other hand, the series inductance L tends to keep the arc current constant. When the current tries to cease spontaneously the inductance helps maintain the current flow, so the higher the inductance the lower the current chop.

In the early days the current chop was a potential serious problem for the users and designers of vacuum switches and so contact materials, such as Cu–Cr and Cu–Bi were developed. These modern materials have low current chopping and unless the application of the switch is particularly sensitive the chopping is not considered a problem. In special cases either a different, extra-low chop contact material is employed, such as tungsten carbide silver (chop of $\sim$0.5 A), or additional surge-suppressing devices are installed in the power circuit.

Unique Electrical Properties of the Vacuum Switch

It should be pointed out that all of the properties mentioned previously of the vacuum breakdown and arc set the vacuum switches apart from all other switchgear technologies. Vacuum is a unique insulating and interrupting medium very different from air, oil, or SF_6 (sulfur hexafluoride). These unique properties can be utilized successfully if properly recognized, but could also result in misapplications and potential switching problems. The list below summarizes these properties.

1. Vacuum switches can interrupt very high currents in a small volume. The comparable SF_6 and air technologies require larger interrupting chambers and more components.
2. Vacuum switches can interrupt currents with very high rates of change, dI/dt, and therefore are applicable for switching higher frequencies. It is not unusual for the switch to be able to interrupt at a dI/dt of up to 1000 A/μs.
3. The dielectric recovery process after current interruption is extremely fast. Typically it is of the order of a few microseconds as compared with several tens of microseconds or even milliseconds for other technologies. This is related to the fact that the “memory” of the vacuum arc is very short.
4. Vacuum breakdown is fast, of the order of a few nanoseconds.
5. The power dissipation of the vacuum switch is low since for any given current the arc voltage is low, provided that the arc is kept in the diffuse mode. Other switches (SF_6, air, oil) have much higher arc voltages.
6. Because of the low arc power dissipation, vacuum switches fail in a benign fashion when overstressed. They do not explode or create a fire hazard. Often even after such failure, a vacuum switch “heals” itself and is capable of continuing its normal operation.
7. The vacuum gap can withstand very high electric fields ($\sim$30–40 kV/mm); therefore only short gaps are required to support high voltages.
8. Vacuum interrupters can be used in parallel for higher continuous current ratings due to the positive slope of the arc voltage-current characteristic.
9. Because of their excellent dI/dt interrupting capabilities and fast dielectric recovery, vacuum switches can also interrupt high-frequency transient currents and cause potential for multiple reignitions and voltage escalation. These high-frequency events might be harmful to other power equipment such as motors, generators, or transformers.

TYPICAL CAPABILITIES OF COMMERCIAL VACUUM SWITCHES

Table 2 summarizes the representative electrical characteristics and ratings of commercial vacuum switches available today. Technical literature on the subject reports trends of increasing ratings, and manufacturers are announcing new products. It is expected that the new vacuum-switch products will soon include voltage ratings of 145 kV and above and current interruption ratings of 120 kA and above. The experts predict that vacuum-switch technology will be able to compete

Table 2. Typical Electrical Characteristics of Commercial Vacuum Switches

Voltage	Continuous 50/60 Hz	From 600 V to 38 kV
	BIL (Basic Impulse Level)	Up to 100 kV to 200 kV impulse
	TRV (Transient Recovery Voltage)	Depending on the frequency of the TRV, up to two times the peak system voltage
Current	Continuous at closed state at 50/60 Hz	Up to 2000 A for single interrupters per phase and >2000 A for multiple units per phase
	Current chopping	1 A to 15 A depending on contact material
	Short-circuit interruption	Up to 56 kA at 50/60 Hz

successfully with the SF_6 switching technology not only, as at present, in the power distribution systems (0.4 kV to 38 kV) but also, in the future, in power transmission applications (69 kV and above).

POWER SYSTEM AND INDUSTRIAL APPLICATIONS

A wide variety of vacuum switches is available on the market today. The commercial names for these devices are manufacturer-specific. The different categories of devices include vacuum circuit breakers, load switches, reclosers, sectionalizers, circuit switchers, and fault interrupters. The different applications might include capacitor bank switching, load switching, fault interruption, sectionalizing distribution feeders during faults, generator load current switching, and motor starting. The devices are available for both indoor and outdoor use.

The indoor applications are primarily metal-clad enclosed gear that can be utilized in distribution substations, motor control centers, etc. The indoor vacuum circuit breakers are typically of a size of a substation cubicle with metal railings and rollers at the bottom of the unit so they can be withdrawn from their cubicles for interchangability and quick maintenance. In most cases the actual vacuum interrupters are mounted vertically in the rear portion of the circuit breaker. The outside of the vacuum interrupters is either air-insulated for standard applications but could be SF_6 insulated or solid insulated for compact, space-saving designs. In some countries retrofit designs of vacuum switches are offered to fit older oil switches in which current-interrupting oil units can be replaced with vacuum interrupters but the oil is still used as an insulating dielectric medium. Vacuum retrofits are also available for air-magnetic circuit breakers as well.

The outdoor-type vacuum switchgear can be either pad mounted or pole mounted. For pole top mounted units low weight, low operating energy (a simple mechanism), and no maintenace of vacuum interrupters are the primary advantages of the technology. The interrupters could be mounted horizontally, vertically, or at an angle within the main switch assembly.

In some countries vacuum switches have been widely applied in the railway transportation industry: on rooftops of railway locomotives for hard-duty switching of traction current of motors as well as in railway trackside service in rather inaccessible substations along the track. In both cases the capability of frequent switching and virtually no maintenance of vacuum switches contributed to the success of the application.

OTHER APPLICATIONS

Vacuum can also be used for specialized applications for which no commercialized, off-the-shelf devices are available. One such application is for the tokamak fusion machines in which a high-magnitude transient current has to be switched on and off the magnetic coil of the machine. Although the voltage requirements for the tokamak are usually low, the currents can easily reach 100 kA. This presents no problem for the vacuum switch. It can switch this current many times during its lifetime with a high repetition rate.

Another interesting application is interrupting dc current. Normally, a dc current will not be interrupted when the contacts are pulled apart, unless the current magnitude is minute and below the level of a stable arc operation (current chopping). If no other means are taken, the device will continue arcing until it self-destructs. However, it is possible to bring the dc current to zero artificially by means of injecting a countercurrent that is equal and opposite to the main dc current. This is done with a circuit as shown in Fig. 7. When the device is called to operate the contacts of the vacuum switch VS are drawn apart and at the same time the switch S closes. The capacitor C discharges through L and S into the main switch VS, producing transient countercurrent I_{com}. When $I_{com} + I_{dc} = 0$ the net is zero, giving the arcing VS opportunity to interrupt and recover. The frequency of the commutating current is often high in order to reduce the size of the L and C components. The vacuum switch can handle these high frequencies well, as described in the previous sections.

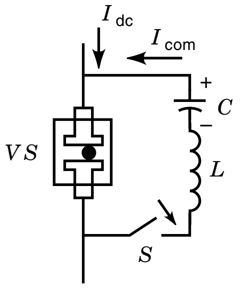

Figure 7. Principle of the dc switch commutation. *C* is charged before the switch *S* closes. VS is the vacuum switch, *L* and *C* are part of the commutating circuit and S is the auxiliary closing switch.

TRIGGERED VACUUM GAP AND TRIGGERED VACUUM SWITCH

A vacuum discharge can be initiated by either separating the contacts under current or overstressing the open contact gap with a high voltage and causing a breakdown. In either case it is difficult to predict and control the instant of arc formation and current conduction exactly. In some applications it is desired to initiate the conduction of the switch very fast and with very precise timing. A triggered vacuum gap (TVG) or triggered vacuum switch (TVS) contains, besides the two main contacts, an additional electrode(s) that can serve as a trigger lead. A sketch of such a device is shown in Fig. 8. A trigger electrode can initiate a microdischarge to help ignite, or trigger, the main arc. The trigger electrode is typically embedded inside one, or both, of the electrodes. The insulating sleeve tubing holding the trigger is coated with a special material, such as titanium hydrate, that can serve as a miniature source of hydrogen atoms. When a low-voltage (300 V to 500 V) pulse is applied between the trigger and the main electrode the microarc is ignited along the surface of the titanium hydrate, which releases a small amount of hydrogen atoms. The atoms are immediately ionized and the resulting microplasma diffuses rapidly to the main interelectrode gap. This in turn precipitates the main breakdown and the arc. The whole process takes only a few microseconds.

Both TVG and TVS operate on the same principle. The main difference is that in the TVG all electrodes are fixed and therefore there is no means of establishing metallic contact between the main terminals. There are at least two major designs of TVGs. Figure 8 illustrates a flat electrode design in which the two main contacts are of the same general shape as the conventional vacuum switch (Fig. 1). In the other type, the two electrodes are in the form of two sets of parallel rods extending above the end plates, opposing each other and overlapping like fingers. The second design is believed to have a higher current rating, lower contact erosion, and better useful life.

In the TVS one of the contacts is moveable, similar to the conventional vacuum switch as shown in Fig. 1 with the exception of the additional trigger. In TVS it is possible to ignite the arc precisely in the switch with the trigger and then during arc conduction close the contacts, thus establishing a solid connection. Although today there are only a few isolated TVG or TVS products available on the market and the demand for such devices is rather low, the future trend in power systems might call for greater utilization of this unique technology.

VACUUM FUSE

A vacuum fuse is essentially a device with two fixed contacts bridged together by a fusable element. This filament will melt and likely explode under high-current conditions, similar to a conventional fuse. When this happens the arc is drawn and the main electrodes take over the action. By utilizing the same arc-control principles (RMF or AMF) as described earlier the arc can then be extinguished at the first available current zero. Vacuum fuses are not popular because of their price which is typically higher than conventional air or sand fuses. Also, vacuum fuses, unlike other fuse technologies, do not have any current limiting capability. In isolated cases the application of a vacuum fuse might be justifiable.

OPERATIONAL SAFETY

When high voltage is applied between two electrodes in a vacuum environment a small electron emission current results. The cathodic electrons bombarding the surface of the opposite anode can generate a small amount of x-ray emission. Under normal circumstances, that is, within the voltage rating of the device and at the full open gap, the x-ray emission is zero or minimal. However, when the device is tested or operated at a fractional gap distance the same voltage may cause measurable X-rays. In such special cases manufacturers of vacuum switches warn the users of the potential exposure and recommend that a protective lead shield, or equivalent means, be used if any personnel are working close to the vacuum chamber. Normally, standard safety distances for electrical reasons are sufficient.

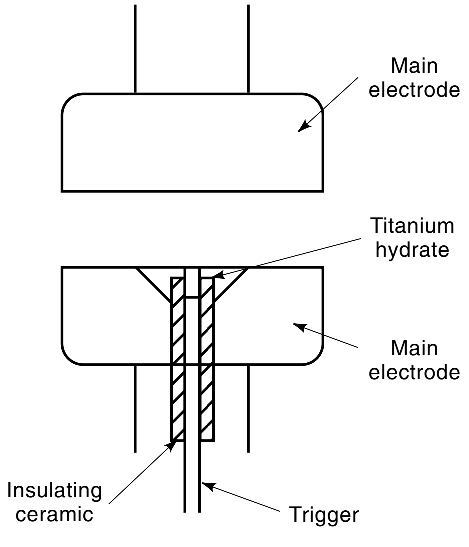

Figure 8. Triggered vacuum gap.

Mietek T. Glinkowski
ABB Electric Systems Technology Institute

VACUUM TUBES. See Gyrotron; Traveling wave tubes.

VALIDATION, MODEL. See Modeling and simulation.