Chapter 2
Current Interruption Basics

In this chapter, the principle of current interruption in power switching devices with mechanically separating contacts is presented. The interruption is associated with initiation and extinction of a switching arc. First, a qualitative description of current interruption in power networks with various load types is given, and important parameters and concepts are introduced.

In the second part, the switching arc as the key element in current interruption in mechanically opening switches is considered in detail. Relevant physical phenomena of the switching arcs in different types of interrupting media, as well as methods for arc modelling are discussed comprehensively.

2.1 A Phenomenological Description of Current Interruption in an AC Power System

2.1.1 Contact Separation and Switching Arc

A switching device contains one or more pairs of contacts in each phase. Under normal service, these are in closed position and current passes through the switch. When an opening command signal is sent to the switchgear, its driving mechanism will set the contacts in motion so that they start moving away from each other. As explained earlier, the current is not interrupted at the time of mechanical separation of the contacts, but continues to flow through an electric arc that ignites in the gap between the opening contacts. The electric arc consists of a mixture of electrons, neutral particles, and positive and negative ions. The temperature of the arc is very high due to the energy dissipated in the arc by the current flow, making it a reasonably good electrical conductor. The key task of a power switch is to control the energy losses during arcing, as well as to provide appropriate measures to make the arc unstable and cause the current to be interrupted near its zero crossing.

K. Niayesh and M. Runde, *Power Switching Components*, Power Systems,
DOI 10.1007/978-3-319-51460-4_2

The voltage drop along the arc through most of a current half cycle is approximately constant and much lower than the rated voltage of the power network. As the current passes zero, the input power to the arc also becomes zero, and the processes responsible for generation of electrical charge carriers in the arc cease. The working principle of a switching device is essentially to get rid of the available charge carriers between its contacts so efficiently that the gap becomes virtually insulating as the current reaches its zero crossing, and then to quench the arc and to interrupt the current at this instant. In case of switching arcs in gaseous interrupting medium, this process is associated with the cooling of the electric arc.

After the arc has been quenched at current zero, a voltage generated by the surrounding power network arises across the contact gap of the switching device. This is called the *recovery voltage*, and its amplitude and steepness determine whether a new arc ignites after current zero, that is, whether or not the interruption has been successful.

A simplified single-phase circuit diagram where a short circuit has occurred close to the breaker is shown in Fig. 2.1. Figure 2.2 shows the current through the

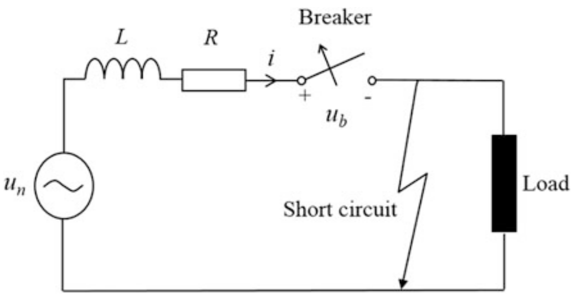

Fig. 2.1 Single-phase system, short circuit close to the breaker

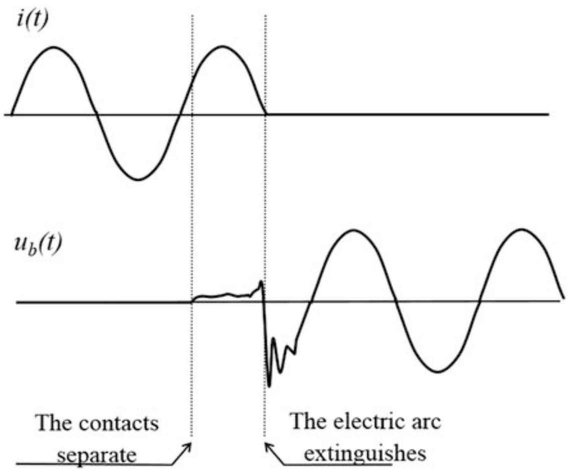

Fig. 2.2 Current and voltage during a current interruption

breaker and the voltage drop across the contacts during the interruption process as described above.

The following factors play a major role in the success or failure of an attempted current interruption:

- **Arc current**: The larger the amplitude of the current, the higher becomes the arc temperature and the density of electric charge carriers generated in the arc. This makes it much more difficult for the contact gap to become insulating after current interruption at current zero. In addition to the current amplitude, the current steepness (*di/dt*) near current zero is of crucial importance for the current interruption process. A higher *di/dt* means that the switching gap has less time to change from conducting to insulating state, before the gap is exposed to the transient recovery voltage.
- **Arcing time**: Since there is no control on the mechanical opening and closing moment of most switching devices, the instant when the contacts of a switching device separate is a random variable. If the contacts separate just before the current zero crossing, the current will not be immediately interrupted but continues to flow until the next current zero crossing. Therefore, the arc duration is typically in the range of 0.5–1.5 times the length of a current half cycle. By longer arc durations, the energy dissipation in the breaker increases, and interruption of the current usually becomes more difficult.
- **Arc voltage**: The input power required for an arc to remain stable depends on the medium in which the arc is burning. This defines the arc voltage that is observed. The arc voltage is dependent on the design and the materials—including the type of interrupting medium—of the switching device itself and not on the rated voltage of the power grid.
- **Transient recovery voltage (TRV)**: After current zero crossing, in case of a successful interruption, a voltage is generated from the network onto the terminals of the switching device as the result of energy oscillations between the energy storage elements of the network. This is called the recovery voltage, and it normally has an initial transient part, the Transient Recovery Voltage (TRV), This voltage can accelerate the remaining electric charge carriers present in the contact gap, increasing the chance of getting charge carrier multiplication by impact ionization and finally lead to a breakdown of the switching gap and formation of a new arc. Thus, the TRV is one of the key factors determining a switching device ability to interrupt a current. In particular, the *Rate of Rise of the Recovery Voltage (RRRV)* is of great importance. The TRV and short-circuit current are determined by the network where the switching device is installed, and differ for different switching applications, see Chap. 3.

The switching arc should have a very high electrical conductance, so that the current can flow through it from the moment of contact separation to current zero, without dissipating excessive amounts of power in the interruption chamber. After current zero, its conductance has to go rapidly to zero, so that no current will flow through the arc causing the current to be interrupted. The total energy dissipation during arcing in a switching device E_{loss} can be expressed as follows:

$$E_{loss} = \int_{t_{sep}}^{t_{cz}} u_{arc} \cdot i_{arc} \cdot dt \tag{2.1}$$

where t_{sep} is the moment of contact separation and t_{cz} the current zero crossing. u_{arc} and i_{arc} are arc voltage and arc current, respectively.

Consequently, the key processes for achieving a successful current interruption are to control the dissipated energy in interruption chamber during arcing as well as to rapidly decrease the arc conductance from very high values to near zero at current zero crossing.

The breaker is said to *re-ignite* or *re-strike* if a new arc is formed after a current zero crossing. A re-ignition occurs immediately after current zero, while a re-strike is defined to occur at least a quarter of a power cycle later. Re-ignitions are divided into two categories: thermal and dielectric re-ignitions.

The temperature of the electric arc channel is still high as the current passes through zero, and thus some electrical conductivity remains. When the recovery voltage then builds up, some power dissipation takes place in the arc path. If the cooling is efficient, the temperature nevertheless drops, conductivity reduces, and the current goes towards zero. However, the cooling might not be sufficient, and the temperature and conductivity may then rise and a new electric arc is formed. This is referred to as a *thermal re-ignition* as it is caused by a thermal instability in the electric arc. The temperature in the contact gap is closely correlated to the amplitude of the current that is being interrupted. Thermal re-strike occurs immediately (up to a few microseconds) after current zero and is greatly dependent on the recovery voltage shape, especially its steepness, during this period.

If a thermal re-ignition is avoided, the voltage across the contacts increases. Even if there is practically no electric conductivity left in the contact gap, this area is dielectrically stressed. A re-ignition will occur if the recovery voltage at any time exceeds the dielectric strength of the gap. This is referred to as a *dielectric re-ignition*.

The dielectric strength increases with time as the contact members move apart. However, as the dielectric strength of a gas is inversely proportional to its absolute temperature, the condition of the gas in the gap also plays a role. The gas may still be warm due to the electric arc that has been burning in the gap. Often it is found that the most critical time as to whether a dielectric re-strike will occur is a few milliseconds after current zero. Thus, the possibility of having a dielectric re-strike is influenced by the shape and amplitude of the recovery voltage in this period.

Interruption of an alternating current can therefore be seen firstly as a race between heat generation and cooling in the contact gap (risk of thermal re-ignition);

and then secondly as a race between voltage build-up and dielectric strength in the contact gap (risk of dielectric re-ignition).

2.1.2 Recovery Voltage

As mentioned above, the recovery voltage is determined by the properties of the power system in which the switching device is installed, in particular the type of load being interrupted. Idealised examples of recovery voltages in single-phase systems, after interruption of a resistive, capacitive and inductive load are shown in Fig. 2.3. The voltages u_l and u_r are the voltages at the left and right side of the breaker, respectively. The arc voltage is assumed negligible compared to the system voltage and the voltage across the switchgear before the arc extinguishes at current zero is $u_{breaker} = u_l - u_r = 0$.

Current and voltage are in phase when the load is resistive (Fig. 2.3a), and the voltage drop across the breaker follows the source voltage. In this case, the recovery voltage has no transient part and $u_{breaker}$ never becomes greater than the source voltage.

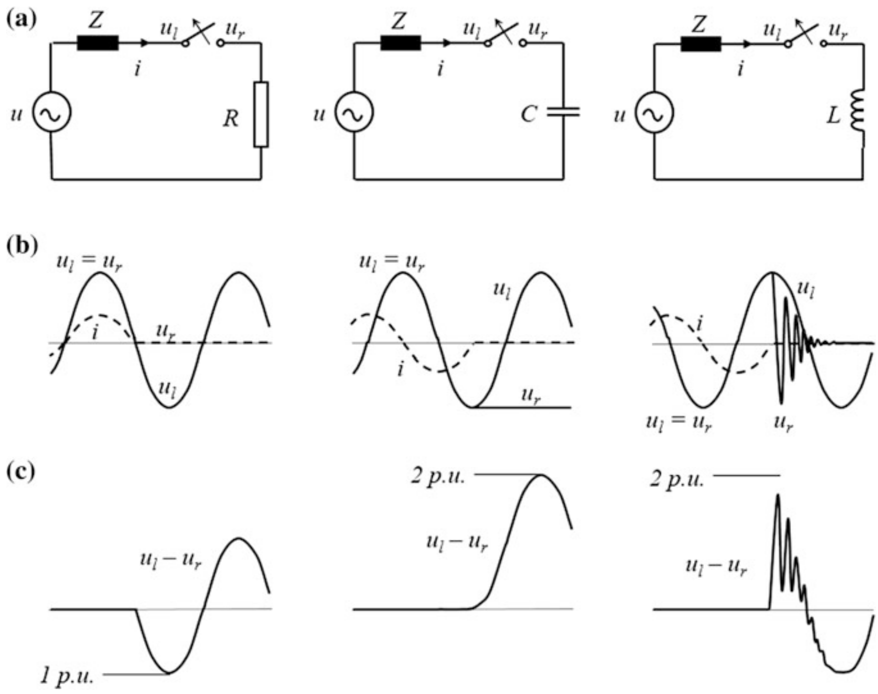

Fig. 2.3 Current and voltage waveforms (schematic) during interruptions of resistive (**a**), capacitive (**b**) and inductive (**c**) loads. The impedance on the source side of the breaker is ignored

When the load is purely capacitive (Fig. 2.3b), the current is interrupted when the source voltage is at its maximum. The voltage at the left side of the switchgear follows the source voltage, while u_r remains at its maximum value due to the capacitive charging at the load side. The maximum amplitude of the voltage across the contacts thus becomes twice the source voltage amplitude.

The idealised cases with resistive and capacitive loads give easy current interruption, as there are no voltage transients following the current zero crossing. Inductive load (Fig. 2.3c) in combination with stray capacitances (not included in the figure), on the other hand, gives an oscillatory circuit at the load side. Hence, u_r quickly goes to zero, but with a high frequency transient voltage component. If the damping in the circuit is low, the maximum amplitude of $u_{breaker}$ becomes twice the source voltage amplitude. Consequently, the chance for having a re-ignition is greater in this case, due to both the steepness and the amplitude of the TRV.

These simple and idealised examples serve as illustrations and an introduction to a more thorough treatment of different switching duties and the associated recovery voltages that will follow in subsequent chapters.

2.2 Switching Arcs

When gases or metal vapour are heated to very high temperatures a large part of the molecules decompose and break down into a mixture of atoms and other neutral particles, free electrons and positively and negatively charged ions. This mixture is called a *plasma* and is the main ingredient of the electric arc, which always is formed when the contacts of an energized switchgear separate. The properties of arcs burning in gases at atmospheric pressure and above (known as high pressure switching arcs) are treated in Sect. 2.3, while physical foundations of the arcs burning in very low pressure (vacuum) environments are discussed briefly in Sect. 2.4.

2.2.1 Arc Initiation

Sending an opening command signal to a power switching device causes its contacts to separate soon after and a *switching arc* is formed. Different stages of this process may be explained as follows:

- When the contact is closed current flows from one contact member to the other one, not through the entire apparent contact interface, but through a limited number of contact points (see Fig. 2.4a). The number and resistance of these minute conducting areas depend on the contact material and the force pressing the two metallic contact members together.

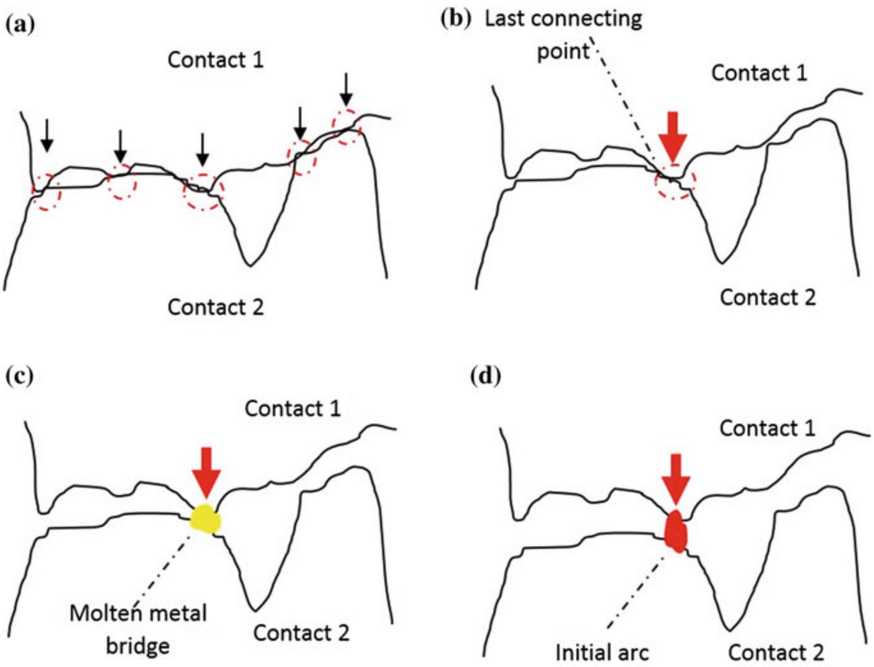

Fig. 2.4 Various stages of initial arc formation by separating current-carrying contacts **a** contacts in the closed position **b** contacts are connected only at the last point **c** a molten metallic bridge is formed at the last connecting point **d** the initial arc formed by evaporation and ionization of the molten metallic bridge (Note that the contacts surface roughness is exaggerated in this figure to better explain the concept)

– The very high current density in the last connecting point results in formation of a liquid metallic bridge between the contacts. By parting the contacts from each other, its cross-sectional area decreases and the current density further increases. Eventually, the liquid bridge evaporates and is ionized. This process leads to formation of the so-called *initial arc*.
– From now on, motion of charge carriers generated in the arc makes it possible to keep the current flowing from one contact to the other one. If the formation of the initial arc happens in the vicinity of an ionisable medium (like gas or oil in switching devices), this medium is also ionized. The arc characteristics are then determined by the material properties of the surrounding medium. If no ionisable medium surrounds the initial arc (like in vacuum switchgear), electric charge carriers can only be supplied from the contacts, and therefore, the arc characteristics are determined solely by the contact material.

Figure 2.4 shows the various stages of the arc initiation during separation of current-carrying contacts. After formation of an electric arc between the two contacts, the current flow will continue until the arc becomes unstable. The switching arc remains stable as long as the dissipated energy from the arc (e.g. in form of heat radiation and light emission) is compensated for by the energy input to the arc. Since the input energy to the arc is determined as time integral of the input power to the arc (the product of arc current and arc voltage), the arc usually remains stable until the current approaches zero. Hence, the current flows through the arc during the period from the time of contact separation, where the switching arc initiates, until current zero crossing, where the arc becomes unstable.

2.2.2 Charge Carriers Balance

The electrical conductivity of gases is under normal temperatures and pressures almost zero. This is because very low number of free electric charge carriers are present. The current flow through a gas can only be realized if a significant number of free charge carriers are generated. In this section, we will review all relevant mechanisms contributing to generation and loss of charge carriers in a switching arc.

The various mechanisms for the generation of electric charge carriers in gases are also referred to as *ionization mechanisms*. When sufficient amount of energy is transferred to a neutral particle, an electron may detach and a free electron and a positive ion are created. The energy may be transferred by interactions (impacts, collisions) with electrons, neutral atoms or positive ions, or may be acquired by absorbing radiation. It is also possible for electrons within the metal contacts of a switching device to overcome the energy barrier and be emitted the gas (*electron emission mechanisms*). These two types of generation mechanisms of charge carriers are shown schematically in Fig. 2.5.

The generated free electrons may recombine with the ions and this decreases the number of available charged particles. Another important process is the attachment of the electrons to atoms and formation of negative ions, which have by far much higher masses. During this process, very mobile charged particles are converted into charged particles with very low mobility, which do not significantly contribute any more to the current flow through the switching arc.

2.2.3 Ionisation Mechanisms

In ionisation processes due to impacts and collisions, it is common to distinguish between *thermal ionisation* caused by random impacts in a gas at high temperature, and *impact ionisation* caused by acceleration of the electrons in an electric field in the time interval between two impacts. In the first process, the energy is solely associated with the high temperature, whereas the energy in the last process comes from the electric field, at least partly.

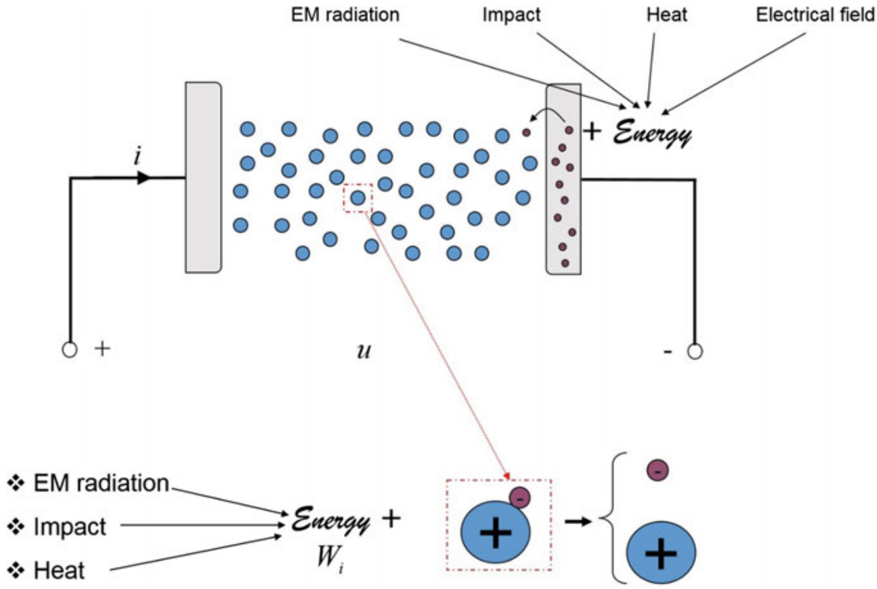

Fig. 2.5 Schematically shown different charge generation mechanisms in a switching arc including ionization and electron emission processes

2.2.3.1 Thermal Dissociation and Ionisation

Occurrence of arc in switching devices is associated with generation of heat. By increasing the temperature of the gas, the gas molecules begin to decompose to their building atoms. Decomposition or splitting of a molecule into two or more smaller neutral particles is referred to as dissociation, such as the dissociation of a nitrogen molecule into two nitrogen atoms ($N_2 \rightarrow 2N$).

Dissociation occurs when a gas is heated to temperatures where the kinetic energy of the particles exceeds the binding energy of the molecules. The dissociated fraction, x_d, of the gas molecules at a given temperature T and pressure p is [1]:

$$\frac{x_d^2}{1 - x_d^2} p = K_1 T^{3/2} e^{-\left(\frac{W_d}{kT}\right)} \tag{2.2}$$

where K_1 is a constant and W_d is the dissociation energy of the gas.

Dissociation is a far more complicated process for a gas molecule consisting of many atoms, e.g. SF_6, compared to a simple diatomic gas as nitrogen. The dissociation of SF_6 takes place through several steps where the molecule is gradually split into smaller fragments. Finally, when the temperature has reached a sufficiently high level a complete dissociation into fluorine and sulphur atoms occurs.

If the gas temperature continues to rise further, electrons will gradually leave the atoms and free electrons and different positive ions in the gas are generated (this process is known as *thermal ionisation*).

Thermal ionisation is closely correlated to the kinetic energy of the particles in the gas. The mean kinetic energy W_k is given by:

$$W_k = \frac{1}{2}m\overline{v^2} = \frac{3}{2}kT \tag{2.3}$$

where $\overline{v^2}$ is the mean value of the velocity squared. According to the Maxwell theory, the velocity of each particle statistically distributes around a mean velocity.

At a given temperature, some of the particles have sufficiently high kinetic energy to cause ionisation through electron detachment. The detailed process of ionisation depends on the gas temperature and is not discussed here, but the dominating process at high temperatures is collisions between free electrons and neutral particles. The free electrons that take part in the impact have acquired most of their kinetic energy thermally, and not by acceleration in an electric field. Thus, the density of generated charge carriers in a gas at a certain pressure under thermal equilibrium is solely determined by its temperature. This fact is described in plasma physics by the so-called *Saha equation* [2]. Consequently, the specific conductivity of any gas and its degree of ionization are strongly dependent on its temperature. The fraction of the particles in a gas that are thermally ionised are, similarly as for dissociation, given by:

$$\frac{x_i^2}{1 - x_i^2}p = K_2 T^{5/2} \mathrm{e}^{-\left(\frac{W_i}{kT}\right)} \tag{2.4}$$

where K_2 is a constant, and W_i is the energy needed for single ionization of a gas molecule. The ionisation energy is also often expressed as

$$W_i = eV_i \tag{2.5}$$

where e is the elementary charge, and V_i the ionisation potential. The variation of x_i due to variations in temperature and ionisation energy is shown in Fig. 2.6, and the ionisation energies for some particle types are listed in Table 2.1. It can be seen that at normal temperatures, the number of ionized atoms is very small, so that the gas has very low electrical conductivity. As the temperature increases above a certain level, the number of ions increases abruptly. By further increase of temperature, the gas becomes fully ionised.

The energy needed to detach one or two electrons is W_{i1} or W_{i2}, respectively. The table also contains the ionisation energies for single atoms. This is of interest since some gases dissociate before they are thermally ionised. Consequently, the ionisation potential for the dissociation products is more relevant than that of the complete gas molecule.

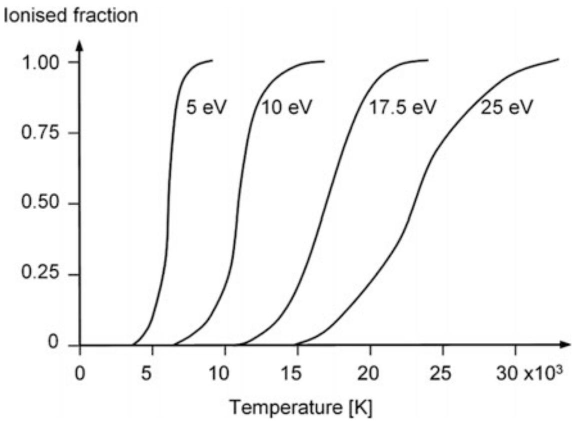

Fig. 2.6 The fraction ionised by thermal ionisation as a function of ionisation energy and temperature. The value of K_2 in (2.4) is set to 3.16×10^{-7}

Table 2.1 The thermal ionisation energy for some gases [3]

Particle type	W_{i1} (single ionisation) (eV)	W_{i2} (double ionisation) (eV)
N_2	15.6	
N	14.5	44.1
O_2	12.5	
SF_6	16.2	
S	10.4	33.8
F	17.4	

2.2.3.2 Impact Ionisation and Excitation

Collision or impact ionisation generally refers to ionisation due to an impact between a gas particle and an electron that has gained energy through acceleration in an electric field. This is not a precise definition as the kinetic energy obtained from the field adds to its thermal energy. The electron energy has to be equal to or greater than the ionisation energy of the particle it collides with in order for the impact to cause ionisation. As mentioned earlier, it is only just after current zero crossing, where the electric field is strong enough and temperature low enough for collision ionisation to be of any importance.

In gases and arcs with high pressure and/or low electric fields, the electron may experience many elastic collisions between each inelastic (which may cause ionisation). Due to these elastic impacts, the velocity of the electron along the field will have a randomly directed component, much in the same way as the thermal movement. In strong electric fields, it is said that the *electron temperature* is greater than the heavy particle/gas temperature, and it is thus difficult to separate between thermal and collision ionisation in an arc.

In principle, an ion accelerated in a field could also cause impact ionisation, but this is far less probable as an ion, in contrast to an electron with much lower mass, would lose a great part of its "extra" energy in elastic impacts. Therefore, very strong fields are needed in order to "heat" the ions to temperatures above the neutral particle temperatures.

2.2.3.3 Generation of Charge Carriers at the Anode and Cathode (Electron Emission Mechanisms)

Metallic contacts are full of free electrons, which can move freely within the metallic body. Under normal conditions, they cannot leave the contacts, because there is an energy barrier between metal and vacuum, which is called the *work function of the metal*. If some energy is transferred to the electrons, e.g. by heating up the contact (*thermionic emission*), or the barrier is reduced, e.g. by application of an electrical field (*field emission*), or a combination of both (*thermo-field emission*), the electrons can leave the contact surfaces and contribute to the flow of current through the arc from one electrode to the other.

Richardson-Schottky equation formulates the thermionic emission of electrons from a metallic surface [4]:

$$J_{TE} = AT^2 \exp\left(-\frac{e\varphi - \alpha E^{1/2}}{kT}\right) \tag{2.6}$$

where $A = 120.4$ [A/cm^{2}K^2], $\alpha = 3.8 \times 10^{-4}$. φ, k, E and T are the work function of the contact material [eV], Boltzmann constant, the electric field at the contact surface [V/cm] and the cathode temperature [K], respectively. J_{TE} [A/cm^2] is the thermionic emitted current density.

In case of field emission, the electrons tunnel through the energy barrier (*tunnelling effect*). If the barrier is reduced by application of an electric field, the probability of presence of electrons outside the metallic body increases and so does the emitted current density. The field emission current density is quantitatively described by Fowler-Nordheim equation [5]:

$$J_{FE} = 1.41 \times 10^{-6} \frac{E^2}{\varphi} \exp\left(-\frac{6.85 \times 10^7 \varphi^{\frac{3}{2}}}{E} \theta(y)\right) \tag{2.7}$$

where J_{FE} [A/cm^2] is the field emission current density and E [V/cm] the electric field on the contact surface, respectively. $\theta(y)$ is a function of $y = 3.62 \times 10^{-4} E^{1/2} \varphi^{-1}$ and it is approximately equal to 0.95 − 1.03 times of y^2 [6].

In many cases, the cathode surface is hot and at the same time, an electric field is applied. The current densities are much higher than both thermionic and field emission currents. A method proposed by Murphy and Good [7] can be used to calculate the thermo-field emission current densities.

Electrons are mainly supplied to the arc column by the cathode. If the cathode is made of a metal with a high boiling point, e.g. tungsten, molybdenum or zirconium, the cathode surface may reach high enough temperatures for thermal emissions to occur. Thermal emission becomes important for temperatures greater than 3500 K, and a typical current density is 100 A/mm^2. Other mechanisms work for cathode materials with boiling points lower than the arc's temperature. In such cases, it is believed that field emission or a combination of thermal emission and field emission are the most important mechanisms.

The anode may be either active or passive. A passive anode does not supply electrons to the arc. As the arc temperature decreases towards the anode, the number of thermal ionisations in the arc decrease and the number of recombinations increase. This leads to a decrease of the electron density. To maintain the electric current, the electrons are accelerated to greater velocities. Consequently, there is an increased possibility for impact ionisations. In order to accelerate the electrons, a stronger electric field is needed. This is created by the net negative charge density in the anode region and the associated anode voltage drop V_a, see Fig. 2.9.

In an active anode, the surface temperature is so high that material evaporates. The metal vapour may then be ionised resulting in an arc burning in a mixture of gas and metal vapour.

The electron emission mechanisms are the main charge carrier generation mechanisms in case of low pressure (vacuum) switching devices as explained in Sect. 2.4.

2.2.3.4 Formation of Negative Ions

Negative ions are created when neutral particles capture and combine with free electrons. Such a process takes place for some molecules and atoms where the total potential energy of the electron and neutral particle becomes lower when they are combined. Consequently, energy is required to separate them. This energy is called the *electron affinity* and is generally measured in electron volts (eV). The electron affinity varies from zero for the inert gases to 3.9 eV for fluorine. It is greatest for elements lacking one electron in their outermost shell. These elements form electronegative gases, as is the case with sulphur and fluorine in SF_6.

The probability of forming a negative ion decreases with increasing electron velocity, i.e. with increasing temperature and electric field. The average time it takes before a free electron becomes attached is referred to as the *attachment time.* At room temperature, it is infinite for inert gases, about 6×10^{-7} s for air and about 4×10^{-9} s for SF_6.

2.2.3.5 Recombination

When a gas or plasma contains a mixture of negatively and positively charged particles, these can recombine to form neutral particles. They then have to reduce their combined energy, either as kinetic energy (collisions with solid surfaces, three-particle-impacts) or by radiation. Exchanging energy with the surroundings takes some time, and the recombination probability is therefore greater when particle velocities are low (i.e. low temperatures).

Among the many possible recombination processes are:

- Recombination at solid surfaces (of less importance in high pressure arcs, important in vacuum arcs).
- Recombination of positive and negative ions (high probability as both types of particles have relatively low velocities).
- Recombination of electrons and positive ions (relatively low probability as the electrons move much faster than the ions).

The recombination rates are very sensitive to changes in pressure and temperature.

2.2.4 Charge Carrier Dynamics

In the previous subsection, the relevant generation and loss mechanisms of the charge carriers were discussed. The generated charge carriers are subjected to different motion mechanisms due to the external applied forces (e.g. by an electrical field) or because of their internal energy. The directional motion of charged particles (*drift*) results in a net current flow through the switching arc, while their random motion cause them to spread or redistribute (*diffusion*).

2.2.4.1 Motion of Charged Particles in an Electric Field (Electrical Conductivity)

As previously explained, charge carriers for carrying the current in an electric arc are mainly generated in three different ways:

- Electrons are emitted from the cathode.
- Electrons and positive ions are formed by ionisation of gas molecules or atoms, i.e. one or more electrons are detached and the gas molecule or atom becomes a positive ion.
- Negative ions are formed in electronegative gases through electron capture.

When such a mixture of positive and negative charge carriers exists in an electric field, the carriers will in average move parallel to or in opposite direction of the field, depending on their polarity. The mean velocity is called the drift velocity u and can be expressed as:

$$u = \mu E \tag{2.8}$$

where μ is called the mobility of the charge carrier and E is the electric field. This movement of charge leads to an electric current density J given as:

$$J = eE\left(\mu_e n_e + \sum_{k=1}^{N} k\mu_k n_i^k\right) = \sigma E \tag{2.9}$$

The electrical conductivity of the gas can be expressed based on the densities of charge carriers and their mobility as:

$$\sigma = e\left(\mu_e n_e + \sum_{k=1}^{N} k\mu_k n_i^k\right) \tag{2.10}$$

where σ is the electrical conductivity, μ_e and n_e are mobility and density of electrons, μ_k and n_l^k are mobility and density of the k-fold ionised ions.

The arc column is generally approximately charge neutral, i.e. $n_e \approx \sum_{k=1}^{N} kn_i^k$. The mobility of ions is very much smaller than that of electrons (typically a factor of 10^3), because their mass is much larger than the electron mass. This implies that the electron density of the ionised gas mainly determines its electrical conductivity:

$$J \approx eEn_e\mu_e = \sigma E \tag{2.11}$$

where the electric conductivity σ is:

$$\sigma = e \cdot n_e \cdot \mu_e \tag{2.12}$$

e is the elementary charge. In strongly electronegative gases, the electrons quickly form negative ions with approximately the same low mobility as the positive ions. The conductivity then becomes:

$$\sigma = 2e \cdot n_i \cdot \mu_i \tag{2.13}$$

2.2.4.2 Diffusion and Ambipolar Diffusion

Concentration gradient of a certain particle type in the arc causes a flow of particles from regions of high concentration to regions of low concentration; this phenomenon is called *diffusion* (see Fig. 2.7).

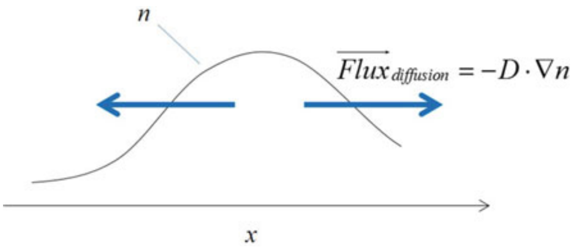

Fig. 2.7 Schematically shown flux of particles from high density to low density regions

In systems containing many particle types, each type diffuses with a flux proportional to the concentration gradient of that particle type:

$$i_a = -D_a \text{ grad } N_a \tag{2.14}$$

where i_a is the flux per volume and time of particles of type a, D_a is the diffusion coefficient for particle type a in the relevant medium, and N_a is the particle concentration.

When considering electron and ion transport in a cylindrical arc, the contributions from the electrons to the electric current density in radial direction can be expressed as

$$j_e = eD_e \text{grad } N_e + eN_e\mu_e E \tag{2.15}$$

and in a similar way for the positive ions

$$j_i = -eD_i \text{grad } N_i + eN_i\mu_i E. \tag{2.16}$$

The total current density in radial direction must be equal to zero under stationary conditions

$$j_e + j_i = 0. \tag{2.17}$$

Furthermore, $N_e \approx N_i = N$ *(for singly ionized atoms)*. By inserting this into (2.14) and (2.15), E is eliminated and the following equation is found:

$$j_i = -j_e = -eD_{am} \text{ grad } N \tag{2.18}$$

where D_{am} is called the ambipolar diffusion coefficient, given as:

$$D_{am} = \frac{D_i\mu_e + D_e\mu_i}{\mu_e + \mu_i}. \tag{2.19}$$

The Einstein relation gives the relationship between the mobility and the diffusion coefficient:

$$\frac{D}{\mu} = \frac{kT}{e}. \tag{2.20}$$

In a high pressure arc an equal particle temperature is generally assumed, thus $T_e = T_i$. The electron mobility is usually far greater than the ion mobility because ions are much heavier, i.e., $\mu_e \gg \mu_i$. By inserting this into the (2.19), the ambipolar diffusion coefficient becomes:

$$D_{am} \approx 2D_i. \tag{2.21}$$

This expression shows that the diffusion coefficient of the heavy and slow ions determines the speed at which the radial transport of heat and charge carriers from the arc core occurs. The movement of the normally faster electrons is in this case greatly influenced by a radial electric field in such a way that the particle flux (and the associated radial heat and charge transport) is mainly determined by the drift velocity of the ions.

Depending on the medium, in which the arc is formed, only some of the mechanisms explained in Sects. 2.2 and 2.4 are dominant. In power switching devices, the current carrying contacts are normally surrounded either by insulating liquids like oil or by insulating gases like air or SF_6 or even by vacuum.

By initiation of a switching arc in insulating liquids, the liquid quickly evaporates and the arc burns in a gas bubble, so that the behaviour of the switching arc in devices with insulating liquids is very much like as in those with insulating gases. Thus, as far as the arc behaviour is concerned, all switching arcs in power switchgear can be divided into the following two categories:

– **High pressure arcs**: this includes all switching devices with insulating liquid or gas (oil breakers, gas breakers).
– **Low pressure arcs**: this is related to vacuum switching devices, where the switching arc is a metal vapour arc.

The properties and characteristics of these two arc types will be discussed in more detail in the following sections.

2.3 High Pressure Switching Arc

When considering high pressure switching arcs, it is common to distinguish between *static* and *dynamic* arcs. A static arc can be established by using a DC circuit. A DC source is connected in series with a resistance and a pair of contacts. At first, the contacts are in closed position and current passes through the circuit. By separating the contact members, an arc ignites and burns across the contact gap. When all transient phenomena have faded out and stationary conditions have been reached, a static arc is obtained.

In cases, where the current or the cooling of the arc varies with time, the arc is said to be dynamic. The voltage drop in a dynamic arc at a given time does not only depend on the instantaneous value of the current, but also of the history, e.g., the magnitude of the current and environmental conditions as they were just prior to the voltage measurement. As it will be seen later, the reason is that the electrical conductivity of the arc is highly dependent on the arc temperature and cross-section. If the temperature is to be changed instantaneously, a certain mass has to be heated or cooled, and this cannot be achieved unless infinite amounts of power are transferred. In practice, the cooling is approximately constant over a short period of time, whereas the current of the circuit determines the input power. Consequently, the thermal inertia causes the arc to "remember" for a short time the amplitude of the current that just has passed.

AC switchgears are always dealing with dynamic arcs. However, the physical properties and conditions of the dynamic arc are very complex, and in simplified descriptions, it is generally assumed that the arc, within a time interval, behaves as a static one. Static arcs are, therefore treated first.

2.3.1 Static Arc Characteristic

The relation between the current in the arc and the voltage drop between the contacts in a static arc generally has a characteristic shape. This is called the *static arc characteristic* and is shown in Fig. 2.8.

The relation shown in Fig. 2.8 applies to a freely burning arc, i.e. an arc burning in a gaseous medium where there is no interaction or influence with the walls or other parts of the interruption chamber. Vacuum arcs show a very different current–voltage relationship.

The static arc characteristic is highly nonlinear. At low currents, i.e. tens of amperes, the voltage drop across the arc decreases with increasing current. For

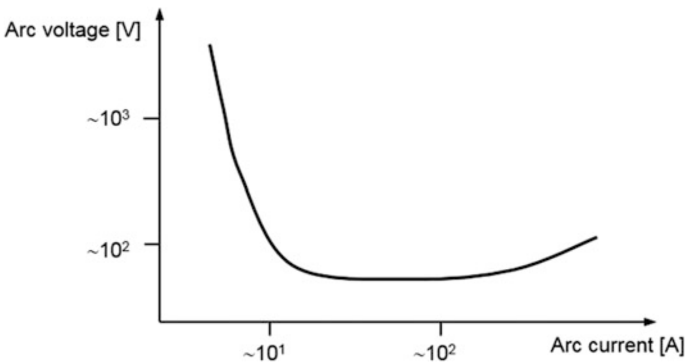

Fig. 2.8 The static arc characteristic for an arc burning in a gas gap at atmospheric pressure or greater (schematic). The scaling of the axes is approximate and varies greatly with gas type and electrode material

somewhat higher currents, the voltage across the arc is fairly constant and independent of the current amplitude. At high currents, the voltage increases somewhat with increasing current.

The arc voltage varies quite a lot from one gas to another and is also dependent on the electrode material and the arc length. Typical values for the flat part of the characteristic are from a few hundred to a few thousand volts.

Figure 2.9 shows a schematic drawing of the longitudinal cross-section and electrical potential distribution of an arc.

The electric arc is divided into three main regions:

- The cathode region with a cathode voltage drop V_c. A typical value of V_c is 20 V.
- The arc column with an approximately constant electric field, typically 10 V/cm, and thus with a relatively low contribution to the total voltage drop if the arc is short.
- The anode region with an anode voltage drop V_a, typically 3 V.

The cathode side has more distinct arc foot points than the anode. In short arcs most of the voltage drop occurs close to the electrodes, as shown in Fig. 2.9; the increase in potential is substantially smaller along the arc column.

The electric current in a burning arc is carried partly by electrons and partly by positive ions, with the direction of movements as shown in Fig. 2.9. Most of the current is carried by electrons, which in part are generated by ionisation of gas molecules in the cathode area and in part emitted from the cathode surface. The space charge distribution in the electric arc can be found by considering the distribution of the electric potential along the arc. The relationship between electric flux density $\boldsymbol{D}$ and the space charge density ρ is:

$$\mathrm{div}\boldsymbol{D} = \rho. \tag{2.22}$$

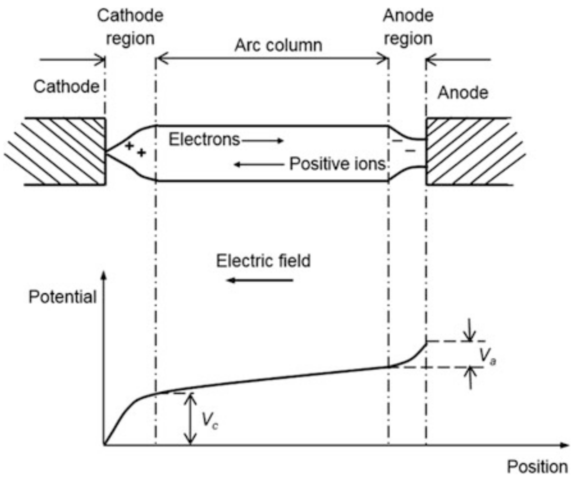

Fig. 2.9 A cross-section of a stationary arc (*top*) and the corresponding potential distribution (*bottom*)

Electric flux density can be expressed by the electric field $\boldsymbol{E}$ and the electric potential ϕ by the following equations:

$$\boldsymbol{D} = \varepsilon_r \varepsilon_0 \boldsymbol{E} \quad \boldsymbol{E} = -grad\,\phi. \tag{2.23}$$

Combining (2.22) and (2.23), and assuming constant permittivity, $\varepsilon_r \varepsilon_0$, gives:

$$\frac{d^2\phi}{dx^2} = -\frac{\rho}{\varepsilon_r \varepsilon_0} \tag{2.24}$$

This implies that there is a net negative space charge in areas, where the second derivative of $\phi(x)$ is positive (i.e. where $\phi(x)$ curves upwards). Figure 2.9 shows that this occurs in the anode region. Similarly, it is evidently a net positive space charge close to the cathode.

The second derivative in the arc column is zero ($\phi(x)$ is approximately linear), which indicates that there is no net space charge in this region. In other words, the density of electrons and (singly charged positive) ions is equal. Thus, the plasma contains many free charge carriers, but when observed as a whole from the outside it appears uncharged or neutral.

2.3.1.1 Particle Density

In switching devices with high pressure arcs, thermal ionisation is the most important charge generation process. Impact ionisation can be of relatively greater importance near current zero crossing. Ionisation due to radiation plays normally only a minor role. In a gas or an arc at stationary conditions, there is an equilibrium between the dissociation, ionisation and recombination processes. These processes determine the concentrations of the different particles. By only considering dissociation and thermal ionisation processes, various particle densities can be calculated using (2.2) and (2.4). The outcome of such a calculation is presented in Fig. 2.10 for nitrogen at constant pressure.

SF_6 decomposes in several steps (SF_4, SF_2 etc.). The processes and conditions then become very complex, and the calculated particle densities are not very accurate, particularly at higher temperatures.

The charge carrier concentration in nitrogen varies strongly with temperature as shown in Fig. 2.10. Similar conditions are found in other gases being used in switching equipment. Hence, the electrical conductivity of an arc varies over a huge span. Figure 2.11 shows the electric conductivity of air as a function of temperature.

As shown in Fig. 2.11, the arc is an excellent electric insulator (comparable to glass and porcelain) for temperatures less than a few thousand kelvin. By increasing the absolute temperature one decade, from 500 to 5000 K, the conductivity increases with as much as 14 orders of magnitude [9], approaching the conductivity

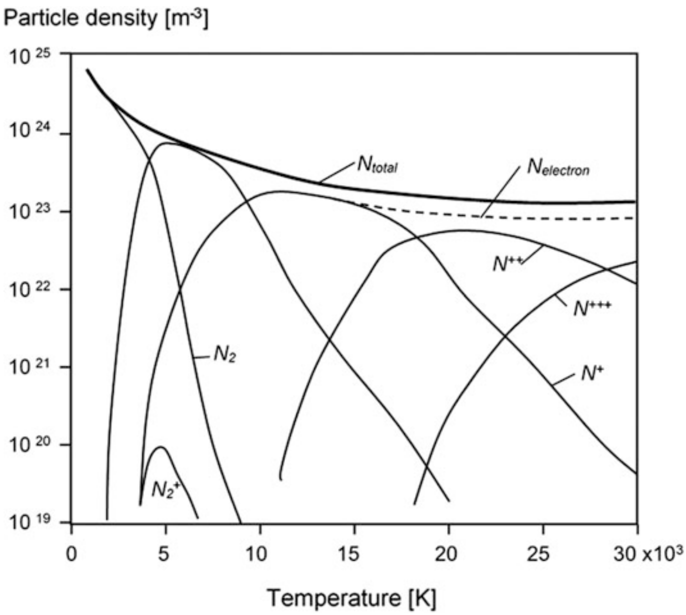

Fig. 2.10 Particle densities for nitrogen at different temperatures and atmospheric pressure [8]

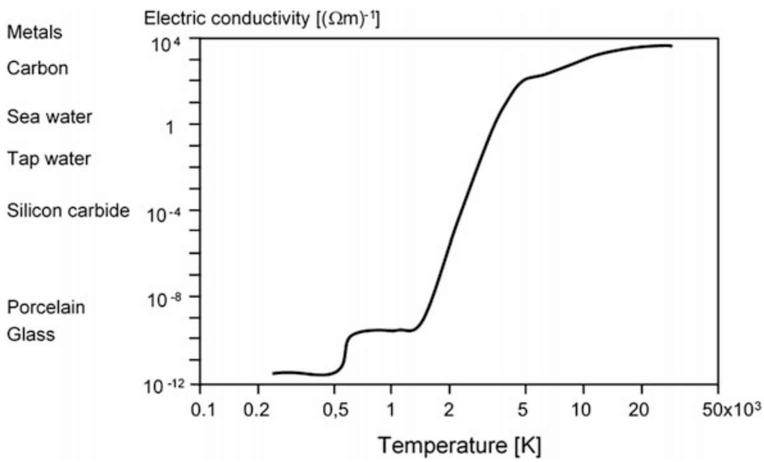

Fig. 2.11 Electrical conductivity of air at atmospheric pressure as a function of temperature. Note that both axes have logarithmic scales. Examples of materials at the different conductivities are given along the vertical axis

of metals. No other substance is capable of changing its electric conductivity this much. The conductivity span of semi-conductors in thyristors and diodes is considerably less, at most 8–9 orders of magnitude.

Moreover, the change in the arc conductivity can occur very fast. These two properties are the most important reasons behind the electric arc being such an excellent medium for interrupting electric current.

To be able to change the electrical conductance of a high-pressure switching arc abruptly near current zero, its temperature has to be reduced drastically. Therefore, *cooling* of the arc channel is realised in different ways in various power switching components with liquid or gas interruption media. This shows the importance of heat transfer mechanisms in high pressure switching arcs; these are discussed in detail in the next section.

2.3.2 Heat Transport in Electric Arcs

2.3.2.1 Heat Conductance

A temperature difference in a system implies that particles in the warmer regions have higher kinetic energy than those in the colder regions. The system seeks to level out these differences in kinetic energy through interactions (e.g. impacts). This is how heat or energy transport due to *heat conduction* from warmer to colder areas in an arc occurs.

Moreover, in case of diffusion of particles with different temperatures, such a process leads to an energy transport in the direction of particle movement, or opposite, depending on the direction of the temperature gradient. If the particles flow from a warm to a cold region, heat or energy transport by *particle diffusion* thus occurs.

The temperature is highest in the centre or core of the arc column. Dissociation and ionization processes occurring here create particle types not found in the colder regions at the outer edge of the arc column. A concentration gradient is thus present and causes a flux of these particles (ions, electrons, molecule fragments) in the radial direction. When these particles reach the colder areas, they recombine and emit their dissociation energy and/or ionisation energy. In this way particle diffusion causes radial energy transport in the arc.

Concerning charged particles (electrons and ions) certain restrictions apply for such a particle flux. If differences in the concentration of positive and negative charge carriers exist, the resulting space charges generate an electric field. This field yields Coulomb forces acting in opposite direction on positive and negative charge carriers. The direction of these forces is such that they seek to prevent space charge formation, i.e. to maintain charge neutrality.

Based on the descriptions of the different heat conduction mechanisms in the arc plasma, it is obvious that the thermal conductivity varies strongly with temperature. Without consideration of dissociation, ionisation and chemical reactions, the thermal conductivity coefficient of a gas increases slowly with temperature, but as discussed in Sect. 2.2.2, in a high pressure arc many reactions like dissociation and ionisation take place. This results in a very non-linear temperature dependent behaviour of the

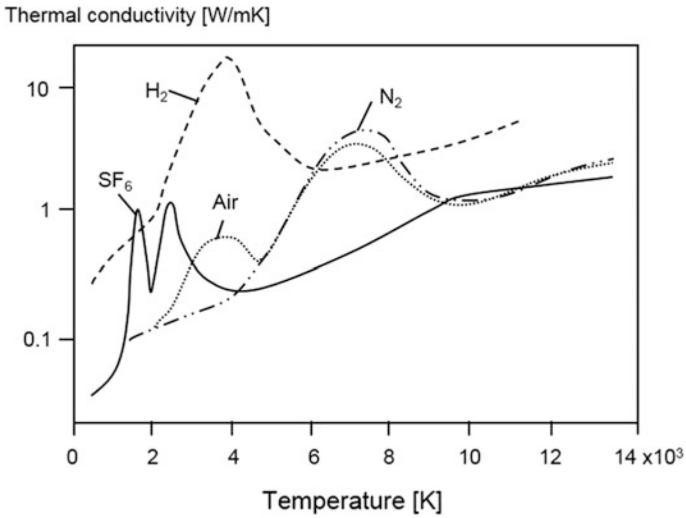

Fig. 2.12 Thermal conductivity as a function of temperature for gases at elevated temperatures [10]

thermal conductivity. This relationship is shown in Fig. 2.12 for a few relevant gases. In case of gas mixtures, e.g. air, or complex molecules with different dissociation stages, a number of peaks at different temperatures can be identified.

The extremely high thermal conductivity of molecular gases near their dissociation temperatures can be simply explained by considering the schematics depicted in Fig. 2.13. The diffusion of molecules to the higher temperature region results in increased dissociation, i.e. consumption of dissociation energy W_D, and in an accompanying large heat flux ($\boldsymbol{q_D}$) [11]:

$$\boldsymbol{q_D} = -W_D \cdot D_m \nabla n_m \tag{2.25}$$

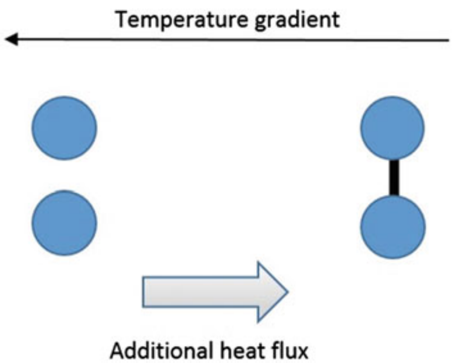

Fig. 2.13 Contribution of dissociation process to thermal conductivity

Here, n_m and D_m are the molecules density and the diffusion coefficient, respectively. This can be interpreted as an enhancement of thermal conductivity at those regions. Hence, higher dissociation energies may enhance the heat conduction in high pressure switching arcs.

2.3.2.2 Radiation

Electromagnetic radiation is of great importance for the energy transport within an arc. Moreover, radiation may also provide clues with regard to the physical processes occurring in the arc, and a great deal of the existing knowledge about the physics of the electric arc comes from studying the radiation.

Plasma in an arc can emit or absorb radiation through several different processes. These can be grouped into two categories:

- Radiation from atoms going from one energy level to another.
- Radiation from charged particles that are accelerated.

When analysing the light emitted from an arc, it is generally found that it consists of a *line spectrum* superimposed on a *continuous spectrum*.

The line spectrum is due to transitions between fixed energy levels in the atoms, ions or molecules, and is directly related to excitation processes. With the particle densities normally seen in high pressure switching arcs (not vacuum arcs), practically no radiation is emitted from the arc for transitions from an excited level to the ground state. In such transitions, the absorbing atoms will enter into the same energy state, as was the original emitting atom. The light quantum therefore diffuses around in the plasma and has a low probability of escaping. This is called *optical trapping*. This radiation may be of considerable importance for the energy transport internally in the arc if the photons diffuse from regions of high radiation intensity to regions of low radiation intensity.

The continuous spectrum originates in several processes, which can be divided into "free-bound" and "free-free" transitions. "Free-bound" transitions are transitions where a free electron of a certain kinetic energy recombines with an ion and the combined particle enters a discrete energy state. In "free-free" transitions an electron leaves one free state and enters another free state, for example by being accelerated by a nearby ion.

The continuous radiation is not associated with optical trapping and can rather easily escape the plasma.

2.3.2.3 Convection

Heat can be taken up by a flowing gas at one location and released at some other colder location (by heat conduction). Such a heat transport is referred to as *convection* and is, in contrast to heat conduction, associated with a transport of mass. The gas flow may origin in heating of the gas, since the density of a warm gas is

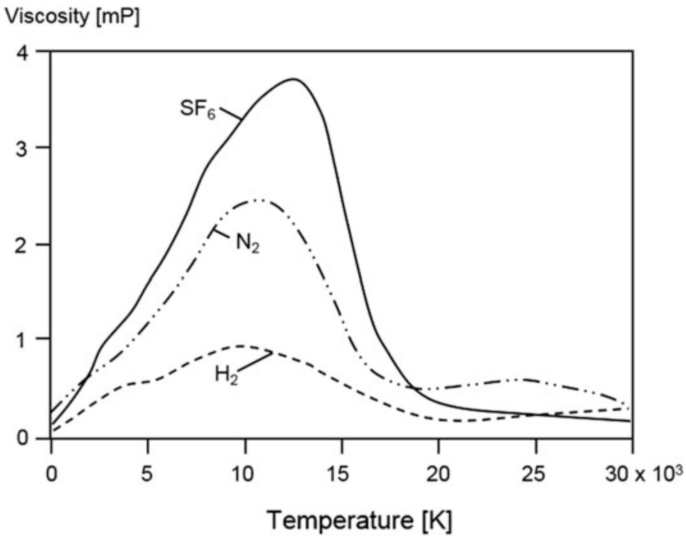

Fig. 2.14 Viscosity as a function of temperature for some gases [12]

lower than for a cold gas, and warm gas will rise and be replaced by gas flowing from colder areas. This is called *self convection*. However, in switching equipment the convection is generally due to a blowing of cold gas from an external location onto the arc. This is called forced convection or forced cooling, and is in many switchgear designs essential in extinguishing the arc at current zero.

Hence, convective cooling is closely related to flow of gases. The flow is laminar at low gas velocities and turbulent at higher velocities. The turbulence has two important aspects. It causes an increased flow resistance, but also a more efficient cooling. Whether a flow is laminar or turbulent depends, among other things, on the viscosity of the gas. The viscosity is very temperature dependent, as shown in Fig. 2.14.

Due to the temperature dependency of viscosity, the flow inside an arc can be laminar whereas the flow around the arc can be turbulent. This plays a significant role in air blast and SF_6 circuit breakers where the arc is cooled by a gas flow.

2.3.3 Temperature Distribution in an Electric Arc Column

The detailed knowledge concerning temperature distribution inside the arc of a switching device is still far from complete, but a good semi-quantitative understanding exists. The temperature profile through the arc cross-section is approximately bell-shaped at low currents (the declining part of the static arc characteristic) with a maximum in the centre. As long as the currents are relatively low, the

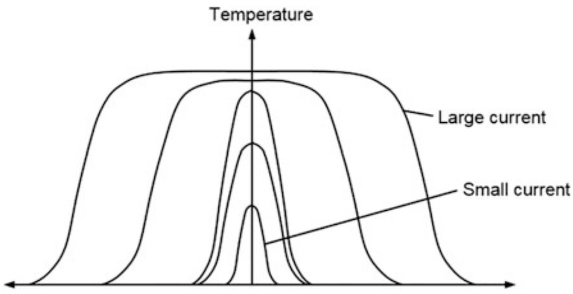

Fig. 2.15 Radial temperature distribution in the arc column for increasing currents (schematic)

maximum temperature, and thereby the conductance of the arc, follows changes in the amplitude of the current during a power cycle.

If the current is increased to several thousand amperes or greater, the temperature does not rise without limits. At $20 - 30 \times 10^3$ K, the radiation losses from the arc core are so great that the temperature (and the electric conductivity) varies relatively little with the radial distance. Increasing the current even further only increases the arc cross-section.

Hence, in general terms, at low currents the arc temperature changes in line with changes in the current, whereas at large currents the maximum temperature is fairly constant across the cross-section. This is shown schematically in Fig. 2.15.

The arc diameter may reach a few centimetres for very large currents. The arc cross-section plays a role when designing nozzles for large circuit breakers. Here the arc is drawn through a nozzle in presence of an intense gas blast.

2.3.4 Dynamic Arcs

When the current in the arc changes rapidly, the arc voltage no longer follows the static characteristic. This is because the arc temperature and cross-section are not able to adjust instantaneously to the values corresponding to the new current value. The arc has a certain thermal inertia since a change in current leads to heating or cooling of matter. If, for example, the current follows a step function, the arc voltage will at first take a higher value, and then gradually decrease to the value corresponding to the static arc characteristic. This is shown schematically in Fig. 2.16.

The arc resistance is mainly determined by the temperature, which cannot be abruptly changed. Initially, the voltage drop is therefore directly proportional to the step in the current. The voltage waveform can be approximated by an exponential decay. The arc *time constant* can be defined as the time constant of the exponential change in arc voltage following from a step in current. Measured values for such a time constant for some gases are listed in Table 2.2.

Studies show that the arc time constant is far from a constant. It not only depends on the test conditions and the method of measurement, but also on the magnitude of the current [13].

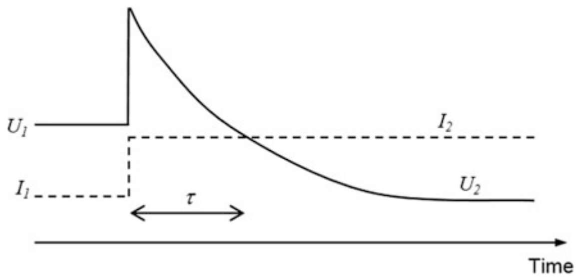

Fig. 2.16 Voltage drop (*solid*) of an arc exposed to a current that follows a step function (*dashed*)

Table 2.2 Time constants measured in a 1 A arc burning in a 19 mm tube [13]

Gas	Time constant (µs)
SF_6	0.8
O_2	1.5
CO_2	15
Air	80
N_2	210
H_2	1

The thermal inertia causes the current–voltage relationship to depend on how fast the current is changing. Figure 2.17 shows arc characteristics for the static case and for two dynamic cases.

As Fig. 2.17 shows, the current–voltage relationship has a course similar to a hysteresis loop where the loop narrows as the frequency increases.

For interrupting currents, it is advantageous to have a small arc time constant. This makes it easier to quickly change the arc temperature and thereby its electric conductance. However, the time constant is not an unambiguous measure of whether or not a gas is well suited as an arc quenching medium. SF_6 is, for example,

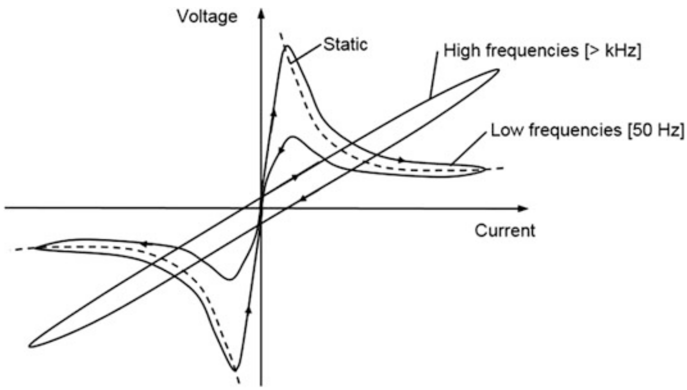

Fig. 2.17 The static arc characteristic, the arc characteristics for low frequencies (typically 50 Hz) and for high frequencies (several kilohertz)

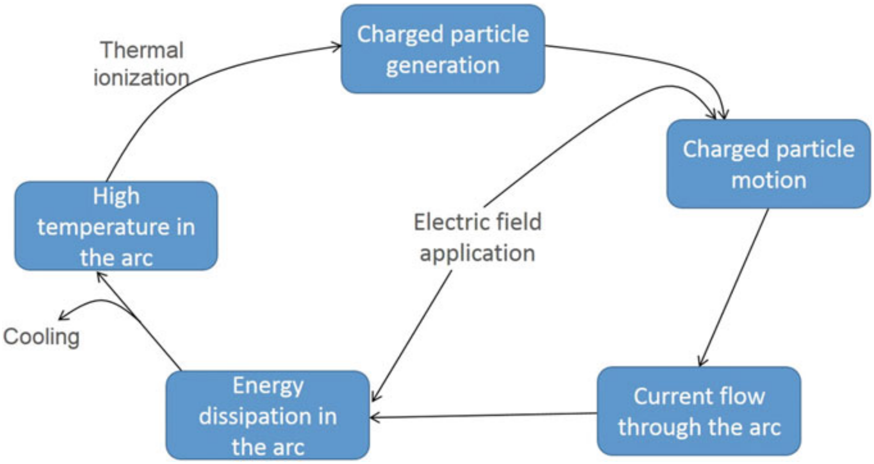

Fig. 2.18 Interrelation between important mechanisms at work in high pressure switching arcs

a far better interrupting medium than H_2 although their time constants are approximately equal, as shown in Table 2.2.

Important mechanisms in high-pressure switching arcs and their interrelations are summarized in Fig. 2.18. Charged particles responsible for current flow after opening the contacts are mainly produced by thermal ionization of the gaseous medium (see Sect. 2.2.3). The charged particles are accelerated by the electric field within the arc, and as the result of their motion a current is generated. The energy dissipation in the arc is proportional to the current flowing through the arc. The dissipated energy partly contributes to the temperature increase of the plasma. If the cooling mechanisms are so efficient that much larger amounts of power are drawn out of the arc than generated by the current flow, the temperature and consequently the conductivity of the medium decrease, and current can be successfully interrupted.

2.4 Low Pressure (Vacuum) Switching Arc

In certain switching devices, the switching arc is formed in an environment of very low pressure. In those cases, there are almost no gas atoms present and therefore, ionization of the very few gas atoms does not provide enough charge carriers to carry the electric current across the contact gap. In these devices, electron emission mechanisms at the metal contact surfaces are supplying the necessary charge carrier.

The electron current emitted from the contact surface may locally produce very high temperatures, which in turn contribute to further increase of current density. If the temperature of the contact surface in small areas exceeds its melting temperature, these areas eventually explode and a mixture of electrons, ions and metallic neutral atoms are injected into the contact gap. This mechanism is known as *explosive electron emission*. By generation of a plasma near the contact surface, the work function is reduced to zero, so that the electrons can easily flow outwards from the contact. This is mainly valid for formation of emission centres in an open contact arrangement. During contact separation of vacuum switching devices, as explained in Sect. 2.2.1, excessive thermal losses lead to formation of a first emission centre. As the electrodes are moving further apart, the initial, single arc foot point quickly splits into several foot points. This only occurs at the cathode and these micrometre-sized foot points are called *cathode spots*.

As shown schematically in Fig. 2.19, the metal atoms are explosively accelerated from the cathode spots into the switching gap. They are ionised during the first few 100 nm by the emitted electrons. Each cathode spot has a cone-shaped structure. Near the cathode surface a positive space charge region (*cathode sheath*) is formed. In a distance of a few micrometres from the cathode surface, a metal vapour plasma is formed; its density distribution is very non-homogenous and reduces strongly in the direction towards the anode (*inter electrode plasma*). The number of emission centres is very much dependent on the current amplitude and the contact material. The average current per cathode spot is in the range of some tens to 100 A depending on the cathode material (see Table 2.3). In case of low current arcs, the anode is passive and acts only as a sink of electrons and there are many cathode spots on the cathode surface, which are moving very fast all over the contact surface. The cathode spots are the only powerful light source in the gap between the contacts. There is no confined or well-defined arc column, and there is no visible foot point of the arc on the anode side. A characteristic weak, diffuse light is emitted from the arc between the electrodes, and this type of arc is thus usually called *diffuse mode vacuum arc*.

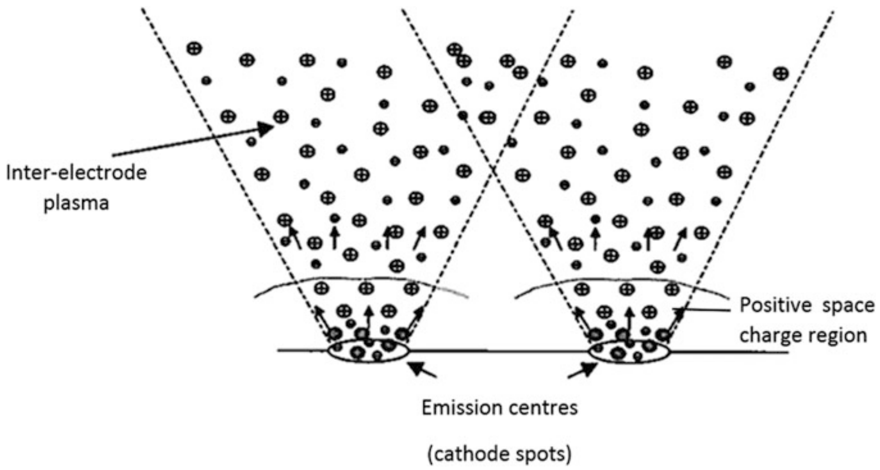

Fig. 2.19 Schematics of emission centres structure on the cathode surface

Table 2.3 Cathode spot erosion rate, average cathode spot current, arc voltage in diffused mode and chopping current level for different cathode materials [14]

Cathode material	Cathode spot erosion rate (μg/C)	Average current per cathode spot (A)	Arc voltage (V)	Average and maximum chopping currents (A)
Cu	140, 150	75–100	20	15, 25
Cr	115, 130	30–50	18	7, 16
Ag	22–27, 40	60–100	18	3.5, 6.5
W	55, 62, 64	250–300		16, 350

This arc mode is associated with low contact erosion (see Table 2.3), and the switching gap recovers very fast after current zero, making an interruption of the current easy.

As the radiation from the cathode spots is the dominating loss mechanism and an increase in current simply leads to formation of more cathode spots, the arc voltage in a diffuse mode vacuum arc is almost independent of both the distance between the contacts and of the current magnitude, see Fig. 2.21. Typical values of current per cathode spot and arc voltage as well as cathode spot erosion rates for different materials are listed in Table 2.3. The arc voltage is very low in comparison to that of high pressure switching arcs. Consequently, the energy dissipation during an interruption becomes relatively small, which is a clear advantage.

In case of vacuum (metal vapour) arcs, the recovery process of the switching gap takes place mainly by diffusion of the generated charge carriers out of the switching gap. As explained in Sect. 2.2.4.2, the diffusion dominated particle flux is very dependent on the gradient of its concentration. The gradient of particle concentrations is extremely high in case of metal vapour arcs, and consequently the flux of the particles out of the switching gap becomes large. It results in an almost complete removal of charge carriers from the contact gap within a few microseconds after cease of supply of new charge carriers at current zero crossing.

If the current exceeds a threshold, typically around 10–15 kA depending on the contact material and geometry, the arc behaviour changes drastically. The cathode spots gather in one point, a well-defined arc forms in the gap and there is also a distinct foot point on the anode, an *anode spot*. This is called a *constricted mode vacuum arc*, and it has an appearance that is quite similar to a high pressure gas arc. In this mode, large areas of the anode and cathode surface melt and both contacts can provide some metal vapour to the switching gap. The molten and very hot contact surfaces continue to release metal vapour to the switching gap even after current zero crossing. This results in very high contact erosion and slow recovery of the switching gap. Therefore, entering into this arc mode is clearly undesirable, and should preferably be avoided during the operation of vacuum switching components.

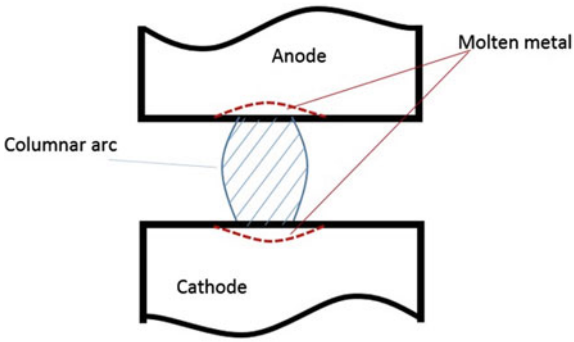

Fig. 2.20 Schematically shown structure of a constricted vacuum arc

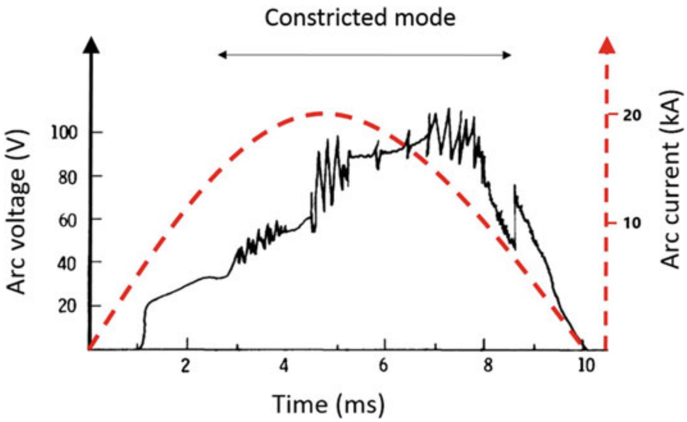

Fig. 2.21 Arc voltage of a vacuum interrupter at different currents

Figure 2.20 shows the constricted vacuum arc schematically. Dissipations contributing to the melting of large area on the anode and cathode surfaces are partly due to the radiation losses of the constricted mode arc, but mainly due to the losses occurred by current flow through the arc near electrode regions. A significant voltage drop exists near cathode and anode. This implies that energies of $\int i(t) \cdot V_c dt$ and $\int i(t) \cdot V_a dt$ are dissipated close to cathode and anode surfaces.

Due to establishment of new arc foot points, the arc voltage changes sporadically, but is in average much higher than that of a vacuum arc in diffuse mode, as illustrated in Fig. 2.21.

When the current decreases towards the end of the half cycle, the arc returns to its more harmless diffuse mode. The cathode spots die one by one, and finally, there is only one spot left. This abruptly ceases to exist just before the natural current zero crossing, and the current is cut off. This is called *current chopping* and is a typical vacuum interrupter phenomenon, although it can occur under certain conditions in other types of switchgears as well. The contact material determines the chopping current level in a vacuum interrupter (see Table 2.3). Current chopping is an unwanted phenomenon since such a rapid change in current may lead to overvoltages. A low chopping current is therefore favourable when choosing contact materials for vacuum interrupters.

Thus, the control of arc in vacuum switching devices means to distribute the dissipated energy homogenously over the whole surface of the contacts to prevent large area melting of contact surface. In Chap. 4, it will be described how magnetic fields can be utilized to accomplish this.

2.5 Modeling of Switching Arcs

The switching arc is the key element, which enables interruption of currents in mechanical switching devices. Therefore, methods contributing to a better understanding its behaviour have received considerable attention. Depending on the perspective and goals of the research, numerous models with different complexity levels and for various applications have been developed for switching arcs.

In some cases, e.g. if the switching transients are to be modelled and the rated voltage of the network is much higher than the arc voltage of the switching component, the switching arc can be modelled as an ideal switch opening at current zero, i.e. zero resistance in closed and arcing state, and zero conductance in open position.

In case the interaction between the switching arc and components of the surrounding network is of importance, the simplest models describe the arc as a two-port element with a nonlinear interrelation between arc voltage and arc current. H. Ayrton suggested one of the most famous arc models of this kind [15], when she investigated the characteristics of the arcs burning between carbon electrodes. She postulated:

$$u_{arc} = a + b \cdot l + \frac{c + d \cdot l}{i_{arc}} \tag{2.26}$$

where u_{arc} and i_{arc} are arc voltage and arc current, respectively; *a, b, c* and *d* are constants and l is the length of the arc. This equation fits to the behaviour of static arcs for currents less than a few tens of amperes (see Fig. 2.8). However, no time dependency is included, so this model cannot be used to describe dynamic arcs as those in power switchgear.

2.5.1 Detailed Physical Models

To be able to develop applicable switching arc models, physical phenomena taking place in the arc have to be considered. The most accurate but complex models are the so-called *detailed physical models*. Here, all the physical mechanisms are described by their governing equations and those equations are solved simultaneously using numerical methods to determine the time and space resolved physical parameters, such as density, velocity and temperature of different particle types present in the arc. This in turn is used to calculate the integrated, measurable quantities like arc voltage and arc current.

Depending on the interrupting media, the governing equations for the arc plasma could be very different.

2.5.1.1 High Pressure Switching Arc

For high pressure switching arcs, it is normallyassumed that a local thermodynamicequilibrium exists, and therefore all particle types are supposed to have the same temperature. In this case, a plasma is assumed being a fluid with high electrical conductivity, capable of interacting with electromagnetic fields. Hence, the governing equations of fluid dynamics, e.g. Navier-stokes equation, are solved together with the electromagnetic field equations. This formulation is known as magneto-hydrodynamic (MHD) model. Three sets of equations, namely fluid dynamic equations, electromagnetic field equations and material equations of state are considered:

- Fluid dynamic equations: These include mass, momentum and energy conservation equations.

$$\begin{aligned} &\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \boldsymbol{v}) = 0 \\ &\frac{\partial (\rho \cdot \boldsymbol{v})}{\partial t} = -\nabla(\rho \boldsymbol{v}\boldsymbol{v}) - \nabla p + \eta \nabla^2 \boldsymbol{v} + \boldsymbol{j} \times \boldsymbol{B} \\ &\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \boldsymbol{v} H) - \nabla(\lambda \nabla T) = \frac{\partial p}{\partial t} + \boldsymbol{j} \cdot \boldsymbol{E} - E_{rad} \end{aligned} \tag{2.27}$$

Here ρ and v are mass density and velocity of the fluid (i.e. the plasma). H, p and T are the total enthalpy, pressure and temperature, respectively. The total enthalpy H can be expressed as:

$$H = \frac{1}{2} v^2 + h \tag{2.28}$$

where h is the specific enthalpy of the material and is a function of its density and temperature. The viscosity coefficient and the specific thermal conductivity are denoted η and λ. E_{rad} is the radiation losses. $\boldsymbol{E}$, $\boldsymbol{B}$ and $\boldsymbol{j}$ are the electric field, the magnetic flux density and the current density, respectively.

- Maxwell's equations:

These are in general form expressed as:

$$\begin{aligned} \nabla \times \boldsymbol{E} &= -\frac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \times \boldsymbol{H} &= \boldsymbol{j} + \frac{\partial \boldsymbol{D}}{\partial t} \\ \nabla \cdot \boldsymbol{E} &= \frac{\rho_{elec}}{\varepsilon_0} \\ \nabla \cdot \boldsymbol{B} &= 0 \end{aligned} \tag{2.29}$$

In a switching arc (plasma), as mentioned earlier, there is almost no net charge and therefore, $\rho_{elec} \approx 0$. In addition, the impact of the time derivative of the magnetic flux density ($\frac{\partial \boldsymbol{B}}{\partial t}$) is in many cases negligible, because the frequency range of interest is not so high. This implies that the electrical field is rotational free and therefore, an electrical potential φ may be defined within plasma arc. The electric potential is calculated by solving the Laplace's equation. The current density can then be expressed as:

$$j = -\sigma \nabla \phi \tag{2.30}$$

- Material equation of state:

(2.27) contains thermodynamic quantities of the interrupting medium. These are in general not constant, but functions of the arc density and temperature, as discussed in Sect. 2.2. The set of equations is only complete if these interrelations are taken into consideration.

The governing equations of the high pressure arc are solved together with appropriate boundary and initial conditions. Normally, numerical methods and commercial CFD (computational fluid dynamics) software are used. The output of such simulations is the spatial distribution of the gas temperature and pressure (density) at different times. Based on the gas temperature and pressure, the conductance of the switching device at different times, especially near current zero can be calculated.

2.5.1.2 Low Pressure (Vacuum) Switching Arc

In one extreme case, when considering the switching arc in low-pressure switching devices with diffuse plasma, there is no local thermodynamic equilibrium and therefore different species, like electrons, ions and neutral particles may have different temperatures. For this case, either two flow plasma models [16] or Boltzmann equation based plasma models [17] are used to describe its behaviour. In constricted mode, where an arc column exists, magneto-hydro dynamic models like those applied to model high-pressure arcs are used [18]. The output of these simulations is the current density and energy flux distribution to the contact surfaces at different times.

Contrary to high-pressure arcs, the electrodes play the dominant role in recovery process of low-pressure (vacuum) switching arcs. The energy flux to cathode and anode may result in temperature increase of the contact surfaces and consequently to metal vapour supply to the switching gap after current interruption. This is the main reason for thermal re-ignition in vacuum interrupters. The temperature distribution at the contact surface may be modelled by considering the heat conduction through the bulk of the metallic contact.

2.5.2 Qualitative Physical Models

In order to reduce the complexity of the governing equations, one simplification would be to integrate (2.27) in one or more spatial dimensions (e.g. radial $\boldsymbol{r}$ and axial z directions). From a physical perspective, this means to divide the arc in many zones with different simplified governing equations. Those equations can then be solved using appropriate boundary conditions between adjacent zones. One of the simplest qualitative (integral) models is the so-called two-zone model [19]. In this model, the arc is split into two zones, arc column and arc surroundings, see Fig. 2.22. It is assumed that all current flows through the arc column (zone 1) and that the energy dissipation takes place in this zone. The second zone is only important for the radial transport of the generated heat out of the arc column. This method has been successfully applied to describe switching arcs in high voltage gas circuit breakers.

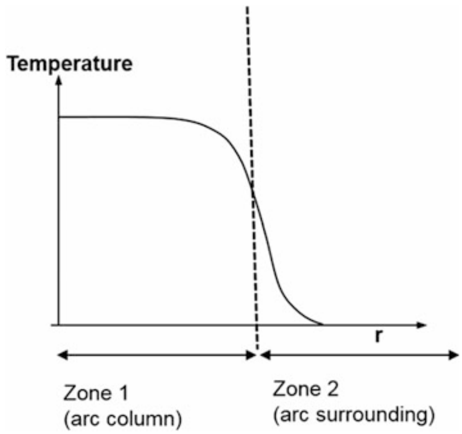

Fig. 2.22 Temperature profile of a high pressure arc with indication of two distinct zones

In terms of computational requirements, the qualitative methods are much more efficient than the detailed physical models and are therefore applied for arc-network interaction, in simple electrical circuits, and for simple current interruption investigations.

2.5.3 Black Box Models

In the two categories of arc models described above, the physics of the arc stands in the foreground, but in many cases, there is no need to delve into the physical behaviour of the arc. The only important fact is how the arc interacts with other components of the power network. For such cases, it is sufficient to find a relationship between arc voltage and arc current. So-called b*lack box modelling* is a way to describe voltage–current characteristics of power switching devices during their arcing time, regardless of the physical parameters of the switching arc. The scope of these three different approaches used for modelling of high pressure switching arcs is shown schematically in Fig. 2.23.

The foundation of all black box models is the fact that the energy stored in the arc Q strongly influences its conductance. Under the assumption that all cooling mechanisms of the arc contribute to reduction of the energy stored in the arc with an equivalent cooling power $P_{cooling}$, and considering the input power to the arc due to the current flow through it, the following expression can be derived:

$$Q = \int \left(u_{arc} \cdot i_{arc} - P_{cooling}\right) dt \quad (2.31)$$

The difference between different black box methods is how the dependency of the conductance of the arc (g) on the energy stored in it (Q) is expressed:

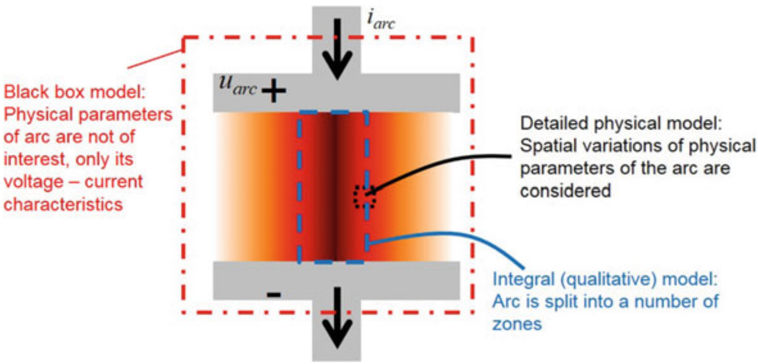

Fig. 2.23 Different approaches to modelling of switching components with high-pressure arcs

$$g = f(Q) \tag{2.32}$$

After differentiation of (2.32) and using (2.31), the following general expression is found:

$$\begin{aligned} \frac{dg}{dt} &= \frac{dg}{dQ} \cdot \frac{dQ}{dt} \\ \frac{dg}{dt} &= f'(Q) \cdot \left(u_{arc} \cdot i_{arc} - P_{cooling}\right) \end{aligned} \tag{2.33}$$

The latter equation is the basic equation for all black box models. Note that, no assumptions are made with regard to how the arc conductance varies.

2.5.3.1 Cassie Black Box Model

If the behaviour of the arc under high currents is considered, the arc can be simply modelled as a cylindrical column with a radius dependent on the energy stored in it, see the temperature profile of the arc in Fig. 2.15. This means that the electrical conductivity of the arc column is assumed to be constant, and a change of the arc current leads only to a change in the arc column radius (i.e. the arc current density is constant as well). In this case, the relationship between arc conductance and the energy stored in arc is linear ($g = kQ$). In addition, it is assumed that the cooling power is proportional to the conductance of the arc ($P_{cooling} = U_C^2 \cdot g$). So by replacing $f'(Q) = k = \frac{g}{Q}$ and considering that $g = \frac{i_{arc}}{u_{arc}}$, the general equation of the black box models can be written as:

$$\frac{1}{g}\frac{dg}{dt} = \frac{P_{cooling}}{Q}\left(\frac{u_{arc}^2}{U_c^2} - 1\right). \tag{2.34}$$

The ratio of the energy stored in the arc to the cooling power has the dimension of time and describes how fast the arc reacts to change of its input/output power. It is almost identical to the arc time constant introduced in Sect. 2.3. As a second simplification, this ratio is assumed constant and denoted τ_c. The resulting differential equation for what is known as the Cassie black box model [20] can then be expressed as follows:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau_c}\left(\frac{u_{arc}^2}{U_c^2} - 1\right); \quad g = \frac{i_{arc}}{u_{arc}} \tag{2.35}$$

Thus:

$$\frac{1}{i_{arc}}\frac{di_{arc}}{dt} - \frac{1}{u_{arc}}\frac{du_{arc}}{dt} = \frac{1}{\tau_c}\left(\frac{u_{arc}^2}{U_c^2} - 1\right) \tag{2.36}$$

In this way, a closed mathematical relationship between arc voltage and arc current is derived. The resulting model contains two parameters U_c and τ_c, both independent of time.

2.5.3.2 Mayr Black Box Model

As discussed in Sect. 2.3.3, at lower arc currents, the temperature of the arc core is very much dependent on the current amplitude. This corresponds to the temperature range where the electrical conductivity of the arc is strongly dependent on its temperature; see Fig. 2.15. As a simplification, the arc column can in this regime be modelled as a cylinder with constant diameter, and with a conductivity depending on the energy stored in the arc. In Mayr black box formulation [21], the arc conductance is assumed to be an exponential function of the stored energy in it:

$$g = g_0 \cdot \exp\left(\frac{Q}{Q_0}\right) \tag{2.37}$$

where g_0 and Q_0 are constants. The cooling power is assumed to be constant, $P_{cooling} = P_0$. Replacing $f'(Q) = \frac{g_0}{Q_0}\exp\left(\frac{Q}{Q_0}\right) = \frac{g}{Q_0}$ in (2.33), this yields the following differential equation:

$$\frac{1}{g}\frac{dg}{dt} = \frac{P_0}{Q_0}\left(\frac{u_{arc} \cdot i_{arc}}{P_0} - 1\right) \tag{2.38}$$

As in case of Cassie black box model, the ratio $\frac{Q_0}{P_0}$ has the dimension of time and represents the arc time constant. Also in Mayr formulation, this ratio is replaced with a constant τ_m. In this way, the final differential equation of Mayr black box model becomes:

$$\begin{gathered} \frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau_m}\left(\frac{u_{arc} \cdot i_{arc}}{P_0} - 1\right) \\ or \\ \frac{1}{i_{arc}}\frac{di_{arc}}{dt} - \frac{1}{u_{arc}}\frac{du_{arc}}{dt} = \frac{1}{\tau_m}\left(\frac{u_{arc} \cdot i_{arc}}{P_0} - 1\right) \end{gathered} \tag{2.39}$$

The Mayr formulation is very useful for describing the behaviour of a high-pressure switching arc near current zero, where the current amplitude is rather low and heat conduction is the dominating cooling mechanism.

The parameters of the black box models can be obtained from experimental measurements of the arc voltage for a given arc current. The parameter values are determined as those minimizing the difference between simulated and measured arc voltage.

In many cases, two parameters are not enough to give a satisfactory modelling of the arc behaviour for all current ranges. It is possible to combine Mayr and Cassie formulations, e.g. by considering the total arc conductance as the sum of partial arc conductances found by Mayr and Cassie models [22]. It is also possible to introduce new parameters, e.g. by taking into account the dependency of the arc time constant and/or cooling power on different quantities such as arc conductance and arc energy [23, 24].

2.5.3.3 Application of Black Box Model for Simulation of Arc—Network Interaction

The mathematical relationship between arc voltage and arc current, established by black box models, can be used together with circuit equations to simulate the arc voltage and arc current as functions of time in a switching device installed in a power network.

As the differential equations of black box models are nonlinear, it is in most cases not possible to find a closed form solution for the arc voltage or the arc current. Numerical methods are used to solve the set of equations. The classical Mayr and Cassie black box models are implemented in many scientific software packages like as Matlab/Simulink, and numerical methods such as finite difference method may be directly applied to solve the equations in an iterative manner.

The following example demonstrates how the differential equations of black box models can be transformed into a set of algebraic equations using the finite difference method. The resulting set of algebraic equations can then be solved numerically.

Consider the simple circuit of Fig. 2.24, where a circuit breaker is used to clear an inductive short circuit fault current. The equations of this circuit can be expressed as follows (note that the Mayr formulation of (2.39) is used to describe the voltage–current relationship of the arc):

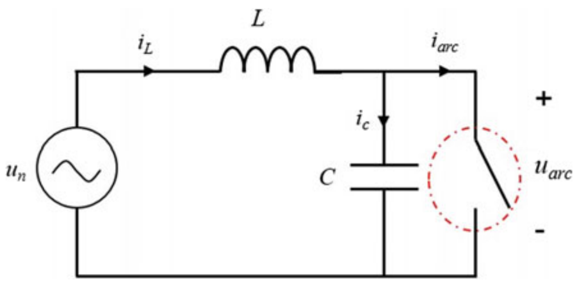

Fig. 2.24 An exemplary circuit to study arc—network interaction using black box models

$$
\begin{aligned}
&\frac{dg}{dt}=\frac{1}{\tau_m}\left(\frac{i_{arc}^2}{P_0}-g\right) \qquad g=\frac{i_{arc}}{u_{arc}}\\
&i_L=i_C+i_{arc}\\
&L\frac{di_L}{dt}=u_N-u_{arc}\\
&i_C=C\frac{di_{arc}}{dt}
\end{aligned}
\tag{2.40}
$$

Replacing the time derivatives by finite difference (e.g. $\frac{dg(t)}{dt}\approx\frac{g(t+\Delta t)-g(t)}{\Delta t}$ if $\Delta t\rightarrow 0$), the above set of differential equations can be transformed to the following set of algebraic equations:

$$
\begin{aligned}
&i_{arc}(t+\Delta t)=u_{arc}(t)g(t+\Delta t)=\frac{\left(\frac{i_{arc}(t)^2}{P_0\cdot\tau_m}+\frac{g(t)}{\Delta t}\right)\cdot u_{arc}(t)}{\left(\frac{1}{\Delta t}+\frac{1}{\tau}\right)}\\
&i_L(t+\Delta t)=\Delta t\cdot\frac{(u_N(t+\Delta t)-u_{arc}(t+\Delta t))}{L}+i_L(t)\\
&i_c(t+\Delta t)=i_L(t+\Delta t)-i_{arc}(t+\Delta t)\\
&u_{arc}(t+\Delta t)=\Delta t\cdot\frac{i_C(t+\Delta t)}{C}+u_{arc}(t)
\end{aligned}
\tag{2.41}
$$

Using (2.41) and starting with the initial conditions of four variables i_L, i_C, i_{arc} and u_{arc} at t_0, it is possible to calculate all circuit variable values for the times $t_0+\Delta t$, $t_0+2\Delta t$, etc. In this way, all circuit variables are determined for all times steps.

In case of complex networks, the number of circuit variables and equations increase, and implementing black box models directly into circuit analysis software is a more convenient approach than manually establishing the algebraic equations.

Exercises

Problem 1—Switchgear Introduction

What are the main requirements for a switching device?

What are the main differentiators between different types of switching devices?

Problem 2—Energy Dissipation in Arc

Assume a constant arc voltage of 600 V and a sinusoidal current with the frequency of 50 Hz peak value of 50 kA. The arc burns for a half period before it is extinguished.

Calculate the total energy dissipated in the arc.

What is the maximum and mean power dissipation?

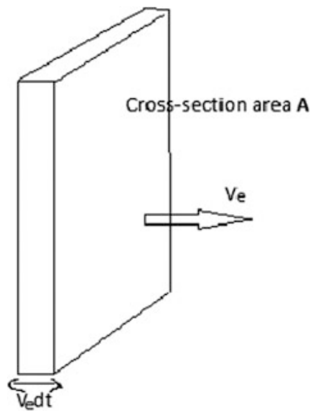

Fig. 2.25 Figure of problem 3

Problem 3—Derive Current Density Equation for Moving Charge Carriers
Consider the arc cross-section in Fig. 2.25.

The charge carriers in the arc with the charge q_e and the density n_e move with a velocity, v_e. Show that the current density, J, can be expressed as:

$$J = q_e n_e v_e$$

Problem 4—Conductivity in Gaseous Media
Figure 2.11 shows the relation between temperature and conductivity (in air). Why is there such a big difference in conductivity at different temperatures?

Explain in your own words the process of transition (a) from insulating to conducting state and (b) from conducting to insulating state by explaining the role of different physical processes including dissociation, ionization, recombination and heat transport.

Problem 5—Thermal Conductivity
Considering Fig. 2.26, please explain why H_2 and SF_6 have distinct peaks at in their thermal conductivity in contrast to the inert gas Argon.

Computer Exercises

In the following computer exercises, MATLAB/Simulink is used to model a switching arc and the resulting transient recovery voltage. A demonstration model that exists in the MATLAB package (power_arcmodels) will serve as the starting point for this exercise.

Problem 1
Implement the circuit of Fig. 2.27 in Simulink. Use existing Cassie and Mayr arc models to simulate the current interruption process. The parameters of the Cassie

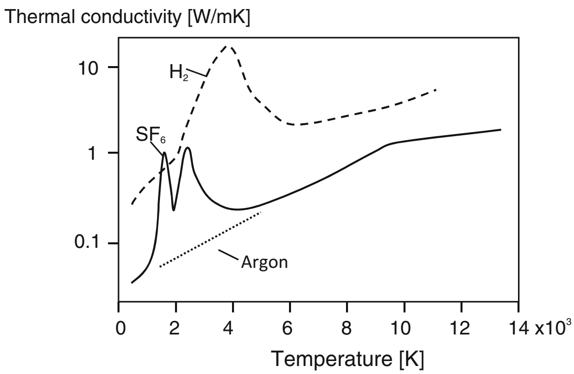

Fig. 2.26 Figure of problem 5

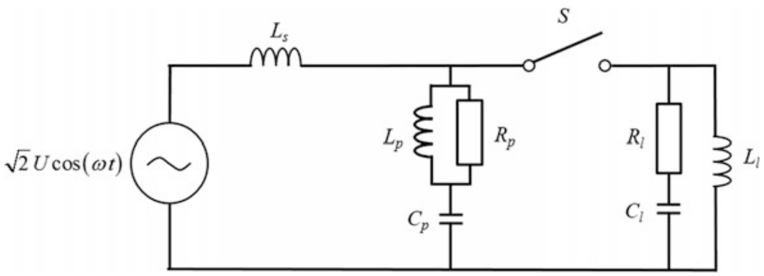

Fig. 2.27 Figure of problem 1

and Mayr models are set to, tau = 1.2 μs and Uc = 2 kV, and tau = 0.3 μs and P = 30.9 kW, respectively. The following starting values are used for different parameters:

$$L_s = 3.52\,\text{mH}, L_p = 5.28\,\text{mH}, L_l = 0.625\,\text{mH}, C_p = 1.98\,\text{mF}, C_l = 1.93\,\text{nF},$$
$$R_p = 30\,\text{W}, R_l = 450\,\text{W} \quad \text{and} \quad U = 60\,\text{kV}.$$

Explain the difference in arc voltage and current resulting from the two models. Which one is able to model a successful interruption? Which gives a more realistic arc voltage before current zero? Which one gives a realistic voltage after current zero?

Problem 2—Cooling Power and Time Constant in the Mayr Model
In this problem, only the Mayr model is considered. By double-clicking the breaker model, you can set new values to the parameters:

- Arc time constant, tau
- Cooling power, P

If the cooling power is reduced, the interruption capability of the breaker is reduced.

- Find the minimum cooling power needed to interrupt this circuit.

If the arc time constant is increased the recovery of insulation medium is slower, and the interruption capability is reduced.

- Set P back to the original, 30,900 W. Find the critical arc time constant.

Problem 3—Transient Recovery Voltage, TRV (Using the Mayr Arc Model)

(a) In this problem, a terminal short circuit fault is investigated. The short circuit is simply generated by reducing the value of the load impedance (the arc model does not allow for zero impedance between its output and ground). Replace the load RLC combination in Fig. 2.27 by a 1 mΩ resistor.

- Set cooling power, *P*, to 10,000 W
- Set arc time constant, *tau*, to 0.6e−6
- Run the model and find:
  - Peak of the TRV U_{peak}
  - Approximate rate of rise of recovery voltage, RRRV (given in V/μs)

(b) In a case like this, the RRRV is very dependent on the capacitance of the supply circuit (left side)

- Adjust the supply side capacitance to increase the RRRV.
- What is the maximum RRRV that this breaker can interrupt at this given current?

Problem 4—Current Limiting Circuit Breakers

The Mayr arc model gives a good description of the arc behaviour near current zero. In this problem, a series combination of Cassie and Mayr arc models as shown in Fig. 2.28 is used to model the arc voltage during the entire arcing time. The parallel resistor R_p is used to avoid numerical instabilities; its value can be set 100 kΩ, so the current flowing through this path is negligible.

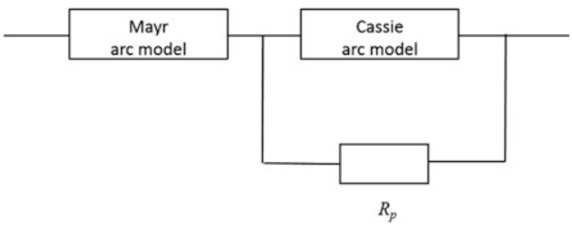

Fig. 2.28 Figure of problem 4

(a) Set the value of the capacitance C_p back to the original 1.98 μF.

- Run the model and find:
  - The peak current
  - The arcing time
  - The TRV amplitude and RRRV (approximate)

(b) Reduce the source voltage and the value of the source side inductor L_s by a factor 10.

- Run the model and find:
  - The peak current
  - The arcing time
  - The TRV amplitude and RRRV

(c) Change the circuit breaker separation time to 0.017 (in both models). Run the model and find:

- The peak current
- The arcing time
- The TRV amplitude and RRRV

(d) Compare the results of (a), (b) and (c) in terms of interactions between the arc voltage and the short circuit current. In which switching components are high arc voltages desirable, what are drawbacks of high arc voltages? Explain.

References

1. Chen FF (1984) Introduction to plasma physics and controlled fusion. Springer, Berlin
2. Bittencourt JA (2004) Fundamentals of plasma physics, 3rd edn. Springer, Berlin
3. Friedman A, Kennedy LA (2004) Plasma physics and engineering. Taylor & Francis Books Inc, New York, p 18
4. Richardson OW (1921) The emission of electricity from hot bodies. Longmans Green Co., London
5. Fowler RH, Nordheim LW (1928) Electron emission in intense electric fields. Proc R Soc 119:173–181
6. Bhattacharya S, Ghatak KP (2012) Fowler-Nordheim field emission. Springer, Berlin
7. Murphy EL, Good RH (1956) Thermionic emission, field emission and the transition region. Phys Rev 102(6):1464–1472
8. Lindmayer M (ed) (1987) *Schaltgeräte: Grundlagen, Aufbau, Wirkungsweise*, Springer, Berlin, p 7
9. Rieder W (1970) “Circuit breakers” In: IEEE spectrum, pp 36–43
10. Lindmayer M (ed) (1987) *Schaltgeräte: Grundlagen, Aufbau, Wirkungsweise*, Springer, Berlin, p 8
11. Friedman A, Kennedy LA (2004) Plasma physics and engineering. Taylor & Francis Books Inc, New York

12. Lindmayer M (ed) (1987) *Schaltgeräte: Grundlagen, Aufbau, Wirkungsweise*, Springer, Berlin, p 9
13. Frind G (1960) Über das Abklingen von Lichtbögen: II. Prüfung der Theorie an experimentallen Untersuchungen. Z angewandte Physik 11:515–521
14. Slade PG (2008) Vacuum interrupters: theory, design and applications. CRC Press, Boca Raton
15. Ayrton H (1902) The mechanism of the electric arc. Philos Trans R Soc Lond Ser A, pp 299–335
16. Callen JD (2006) Fundamentals of plasma physics. University of Wisconsin
17. Jenkes K, Heil B, Schnettler A (2002) Simulation of vacuum arcs in circuit breakers based on kinetic modelling. In: Proceedings of 20th international symposium on discharges and electrical insulation in vacuum, pp 634–637
18. Schade E, Shmelev L (2003) Numerical simulation of high current vacuum arcs with an external magnetic field. IEEE Trans Plasma Sci 31(5):890–901
19. Keidar M, Beilis I (2013) Plasma engineering: applications from aerospace to bio- and nanotechnology. Elsevier Inc., Amsterdam
20. Cassie AM (1939) 'Arc rupture and circuit severity: a new theory.' Report no. 102, CIGRE
21. Mayr O (1943) 'Über die Theorie des Lichtbogens und seine Löschung'. ETZ-A 64:645–652
22. Habedank U (1988) On the mathematical description of arc behavior in the vicinity of current zero. etz Archiv 10:339–343
23. Guardado J et al (2005) An improved arc model before current zero based on the combined Mayr and Cassie arc models. IEEE Trans Power Deliv 20:138–142
24. Shavemaker P, van der Sluis L (2000) An improved Mayr-Type arc model based on current-zero measurements. IEEE Trans Power Deliv 15:580–584

http://www.springer.com/978-3-319-51459-8

Power Switching Components
Theory, Applications and Future Trends
Niayesh, K.; Runde, M.
2017, X, 249 p. 162 illus., 43 illus. in color., Hardcover
ISBN: 978-3-319-51459-8