CHAPTER 1

FUNDAMENTALS OF ELECTRICAL DISCHARGES

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1.1 INTRODUCTION

Natural phenomena, such as gamma rays produced by radioactive decay processes in the soil and cosmic radiation originating from solar flares and other galactic objects, can ionize the air molecules and give rise to free electrons and positive and negative ions. Under normal conditions of temperature and pressure, the conduction in air at low field ranges from 10^{-16} to 10^{-17} A/cm^2 in proximity to the Earth's surface, so normally air could be considered an excellent insulating material. When in an air-filled volume the electron concentration increases, an electrical breakdown process takes place and this gas becomes conductive.

1.2 IONIZATION PROCESSES IN GASES

As defined in IEEE Std. 539 (2005), the term "ionization" indicates "the process by which an atom or molecule receives enough energy (by collision with electrons, photons, etc.) to split it into one or more free electrons and a positive ion." This kind of collision is called *inelastic* because all the kinetic energy of the colliding particle or only a part of it is converted into potential energy of the atom or molecule. On the contrary, a collision is *elastic* when the total kinetic energy of the

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colliding particle is conserved during the collision. In this case the neutral atom or molecule does not acquire energy from the colliding particle and no excitation or ionization takes place. In a neutral gas at ambient temperature, almost all the collisions are elastic. On the contrary, the plasma formation includes several inelastic collisions (such as recombination, charge transfer, attachment, detachment, and dissociation) in addition to excitation and ionization of the atom. If an inelastic collision with an electron occurs, the neutral atom or molecule may become excited but not ionized by the acquired energy, so the same excited molecule may become ionized by a subsequent inelastic collision. The effectiveness of the ionization depends on the kinetic energy gained by the colliding electron along the free path between two successive collisions. Slow electrons or very fast electrons are poor ionizers because the amount of energy is insufficient for ionizing the atom or the period of interaction is too short in order to transfer the energy, respectively. Ionization processes may occur in either the absence or presence of an electric field. In the absence of an electric field, the behavior of electrons, atoms, and molecules inside a gas can be well represented by the kinetic theory. The macroscopic properties, such as pressure, temperature, distribution of particle velocities, and energies, are related to the average values of the velocities of the particles and of the mean free path. In the absence of an electric field, the heating of the gas at ordinary temperatures results in an equilibrium between the ionization and deionization processes. Gas heating at a very high temperature (thermal ionization) may change this equilibrium and promote an ionization process, as does application of a sufficiently high electric field. We will deal with the thermal ionization later on. Now we will consider the presence of an electric field.

Charge particles (electrons or ions) acquire kinetic energy from the field between each pair of collisions, so that the effectiveness of ionization depends on the amount of energy gained along the mean free paths λ in the direction of the applied electric field $\mathbf{E}$ and on its strength. All things considered, the average kinetic energy acquired by a particle carrying a charge q is $w_k = qE\lambda$. Incidentally, the velocity v given to the particle in the direction of an unitary field is called mobility: $k = v/E$.

The main processes considered here are:

- Ionization by electron and photon impact
- Attachment and detachment, which are important in electronegative gases
- Recombination

1.2.1 Ionization by Electron Impact

The ionization by electron impact is the principal collision process in electrical discharge phenomena. If a free electron acquires under the action

of an applied field **E** a kinetic energy equal to or larger than the ionization energy w_i of the atom it collides with, an ionization process occurs and results in another electron and in a positive ion, which become accelerated and acquire kinetic energy. If the energy transferred to the atom during the collision is lower than w_i, then some electrons in the atom can acquire a quantum of energy and rise to a higher energy level without leaving the atom. The atom switches from a normal state to an excited state, and the quantum of energy required for this change is known as excitation energy w_e. These collisions are called *inelastic*.

Normally, the excited state of an atom lasts about 10^{-8} s. Moreover, some group II elements of the periodic table, as well as the inert gases, could present a metastable state—that is, a lifetime in some of their excited electronic states extended to seconds. This relatively high potential energy makes the metastables able to ionize neutral particles. When an electron drops to a lower energy level, the atom releases the quantum of energy in the form of a radiated photon having a wavelength $\lambda_p = h\,c/w_e$, where c is the free-space light velocity and h is the Planck constant. A radiated photon could transfer its energy to another atom or molecule, causing their excitation (photoexcitation) or ionization (photoionization) before vanishing. Note that a photon has neither mass nor electrical charge, which implies that it is unaffected by the background field. Positive ions result from an ionization process involving, for example, an energized electron and a neutral atom or molecule. The ion mass is comparable to the mass of the gas molecule, therefore each collision with other atoms causes a loss of about 50% of energy. Under the action of an applied field, the velocity acquired by the electron is largely greater than one acquired by the positive ion. The probability of a successive ionization determined by a positive ion is much lower than the ionization probability of an electron accelerated by the same applied field.

1.2.2 Townsend First Ionization Coefficient

The electric field distribution in the gas is the physical consequence of a voltage applied between two electrodes. Provided that the voltage is sufficiently high, a current will flow between the electrodes. Townsend (1910) first studied this current as a function of the applied voltage. In his experiment he used two conducting parallel plates located in a vacuum tube. An external ultraviolet radiation has been used to illuminate the cathode and to cause electron emission from the cathode surface. By reducing the pressure of the gas, it was possible to set the ions in motion at a sufficient velocity to ionize other molecules of the gas, even when the voltage employed has been of the order of magnitude of a few hundred volts. Townsend measured the current I

flowing across the plate gap as a function of the applied voltage V and found that the $I = I(V)$ curve initially increases linearly with the applied voltage. The rate of increase diminishes as the voltage increases further, and the current tends to attain a maximum value. This can be explained by considering that some electrons are emitted by the cathode and some positive ions diffuse in the tube and are lost by recombination on the tube walls. Diffusion, recombination, and losses on the walls decrease when the voltage increases until the voltage level exceeds, say, the value V_1 and all the electrons are collected on the anode. In a given region V_1–V_2 the current remains practically constant and approaches a saturation value. As the voltage increases further ($V > V_2$), there is a large increase in conductivity, presumably because new ions are produced by electron impact. The involved electrons gain sufficient energy from the electric field for ionizing the neutral gas molecules. The growth of the current in an even greater region V_2–V_3 obeys an exponential law, while in the extreme V_3–V_b region delimited by the breakdown voltage V_b the current increases faster than the exponential growth. This departure from the exponential law can be attributed to a secondary ionization process that generates new electrons (and then new avalanches) from the cathode by the impact of energized positive ions. In order to explain this current increase, Townsend defined an ionization coefficient α as the number of electron–ion pairs produced in the gas by a single electron which moves through a unit distance in the direction of the applied field. It is a matter of general knowledge that the coefficient α is referred to as Townsend's first ionization coefficient. This coefficient varies in function of the electric field for different gases. The related phenomenon is also called a primary ionizing process.

Townsend derived also the following expression:

$$\frac{\alpha}{p} = A_T \exp\left(\frac{-B_T}{(E/p)}\right) \tag{1.1}$$

for evaluating the primary ionization coefficient α in the function of the electric field. The constants A_T and B_T in Eq. (1.1) depend on the gas under examination and ambient conditions [see, for example, Table 1.2 in Abdel-Salam and Stanek (1988) where experimentally validated values of the coefficients A_T and B_T for air under standard conditions are reported]; p is the ambient pressure.

Additionally,

$$\frac{\alpha}{p} = A_T \left[\left(\frac{E}{E_0}\right)^2 - 1\right], \qquad E \geq E_0 \tag{1.2}$$

where E_0 is the critical electric field (namely, the voltage gradient on that confined surface area of an electrode on which a continuous corona is first detected when the applied voltage is gradually increased) and A_T is a constant [see Loeb (1939)]. Equations (1.1) and (1.2) are used in numerical procedures for simulating corona discharges (see Chapter 2).

1.2.3 Electron Avalanches

Consider a free electron positioned, say, on the cathode surface ($x = 0$) under the influence of an uniform electric field. If the electron acquires enough energy, it can ionize a gas molecule by collision and produce another electron. These two electrons, in turn, acquire energy from the electric field and repeat the process. In this way, the number of electrons increases with x. Let n_0 be the initial number of electrons emitted from the cathode and let n_x be the increased number of electrons at distance x from the cathode. After denoting by α_e the number of ionizing collisions per unit length, made by an electron traveling along the x-direction of the electric field, the formula giving the elementary increase dn_x of the number of electrons increasing across the length dx can be written

$$dn_x = \alpha_e n_x dx \tag{1.3}$$

By integrating Eq. (1.3) across the cathode-to-anode distance d,

$$n_d = n_0 e^{\alpha_e d} \tag{1.4}$$

is obtained. The exponential growth $e^{\alpha_e d}$ of electrons represents the electron avalanche. In terms of current, if I_0 is the current leaving the cathode, then Eq. (1.4) becomes

$$I = I_0 e^{\alpha_e d} \tag{1.5}$$

Even though the distribution of charge carriers in an avalanche influences the applied uniform electric field E, Eq. (1.4) is obtained by assuming, in combination, that such an influence is negligible and the probability of an electron ionizing a gas molecule is constant and independent of the distance traveled in the electric-field direction. Because the velocity of electrons is larger than the velocity of positive ions, the electrons build up the head of the avalanche oriented toward the anode, whereas the positive ions form a long tail between the avalanche head and the cathode. Indeed, this charge distribution can significantly affect the local electric field.

1.2.4 Photoionization

A neutral gas atom A_0 colliding with an electron of energy lower than w_i may pass from the normal state to an excited state, according to the reaction $A_0 + e + w_k \rightarrow A^* + e$, with w_k and A^* respectively being the kinetic energy of the electron and the atom in an excited state. On recovering from the excited state within a short time ranging from about 10^{-10} to 10^{-7} s, the atom radiates a quantum of energy of a photon. Formally, $A^* \rightarrow A_0 + h\nu$ where the quantum of energy $h\nu$ in turn may ionize another atom whose ionization potential energy is equal to or lower than the photon energy. Accordingly, the process $A_0 + h\nu \rightarrow A^+ + e + w_k$ stands for photoionization. The excess of the quantum $h\nu$ over w_i may be converted into the kinetic energy of the released electron. Photoionization is a secondary ionization process and may act in Townsend's breakdown mechanism, in the streamer the breakdown mechanism, and in corona discharge. If $h\nu < w_i$, then the photon may be absorbed from the atom that passes to an excited state, so that the process is in this case called *photoexcitation*.

1.2.5 Other Ionization Processes

Ionization by Interaction of Metastables with Atoms Some group II elements of the periodic table, as well as the inert gases, could present a metastable state—that is, a lifetime extended to a few seconds in some of their excited electronic states. This relatively high potential energy makes the metastables able to ionize neutral particles. If W^{**} is the energy of a metastable, the latter denoted by A^{**}, and w_{iB} the ionization energy of another atom B_0, then the following are the resulting reactions:

- If $W^{**} > w_{iB}$: $A^{**} + B_0 \rightarrow A_0 + B^+ + e$ (collision or Penning ionization)
- If $W^{**} < w_{iB}$: $A^{**} + B_0 \rightarrow A_0 + B^*$ (excitation of atom B_0)

Denoting with w_{iA} the ionization energy of the atom A, in the case of high-density metastables, and provided that $2W^{**} > w_{iA}$,

$$A^{**} + A^{**} \rightarrow A_0 + A^+ + e + w_k$$

is the presumed reaction. Moreover, a metastable atom may be ionized by photon absorption

$$A^{**} + h\nu \rightarrow A^+ + e$$

before returning to its ground state.

Thermal Ionization The velocities of the atoms of a gas in thermal equilibrium are distributed according to Boltzmann's distribution. If a gas is heated to sufficiently high temperature, many of the gas atoms acquire sufficiently high velocity to cause ionization by collision with other atoms or molecules. Thermal ionization is the principal source of ionization in flames and high-pressure arcs. Saha (1920) claimed that the thermal ionization in air is significant only at temperatures above about 4000 K. Thermal-ionization reactions are of particular importance for describing the behavior of plasmas created via electric discharge, such as arc discharges.

Autoionization This is a process by which atoms or molecules spontaneously emit one of the shell electrons so that the atom passes from an electrically neutral state (metastable) to a singly ionized state.

1.3 DEIONIZATION PROCESSES IN GASES

1.3.1 Deionization by Recombination

When groups of positively and negatively charged particles coexist in a gas, processes of recombination

$$A^+ + B^- \rightarrow A_0B_0 + h\nu$$

may take place. Here, B^- may be an electron or a negative ion. Radiative recombination, which may be considered as the reverse of photoionization, occurs only when electrons are involved. Recombination of positive and negative ions consists of two phases: In the first phase, two ions in random motion perform elliptic or hyperbolic orbits, under the action of Coulomb forces, around their common center of masses. In the second phase, a charge transfer takes place during the orbital encounter with consequent charge neutralization. The difference between the ionization energy of the positive ion and the electron affinity of the negative ion gives rise to a kinetic energy increase for the neutralized particle.

1.3.2 Deionization by Attachment

After a number of collisions with neutral atoms, or when the field strength is reduced, the kinetic energy of the electron becomes insufficient to excite the atom and then the electron could get attached to the atom to form a negative ion. Some atoms or molecules lacking one or two electrons in their outer orbits tend to capture free electrons to become negative ions. This process forming a

negative ion is known as *electron attachment* ($A_0 + e \rightarrow A^-$). Gases prone to exhibit such a behavior are called *electronegative gases*, and the energy required to remove an electron from a negative ion for restoring neutrality is called the *electron affinity* of the atom. The attachment of electrons to neutral molecules may be taken into account by an attachment coefficient η (analogous to the ionization coefficient α), thus representing the number of negative ions created by a single electron moving through a unit distance in the field direction.

Some elements of the periodic table (for example, F, Cl, Br, O, S) are lacking one or two electrons in their outer shell and tend readily to acquire a free electron to form a stable negative ion. This physical property is called *electronegativity*. The so-formed negative ion remains stable until its total energy is lower than that of the neutral atom. The excess energy upon attachment can be released as a radiative photon

$$e + A_0 \leftrightharpoons A^- + h\nu$$

or as the kinetic energy of a colliding third body

$$e + A_0 + B_0 \leftrightharpoons A^- + (B_0 + w_k)$$

The reverse process, namely, the electron detachment, requires energy, termed the electron affinity of the atom, for removing the electron and restoring neutrality.

Other processes of negative ion formation are:

- *Dissociative attachment*, in which the excess energy is used to separate the molecule into a neutral particle and an atomic negative ion:

$$e + A_0B_0 \leftrightharpoons A^- + B_0$$

  Alternatively, the excess energy is released to a colliding particle as kinetic and/or potential energy after forming the molecular negative ion:

$$e + A_0B_0 + A_0 \leftrightharpoons (AB)^- + A_0 + w_k + w_p$$

- *Splitting* of a gas molecule into positive and negative ions upon impact of an electron without attachment:

$$e + A_0B_0 \leftrightharpoons A^- + B^+ + e$$

- *Charge transfer* following a heavy particle collision:

$$A_0 + B_0 \rightarrow A^+ + B^-$$

Two attachment processes can occur in air. For electron energies ranging between 0.2 and 0.5 eV, molecular ions could be formed according to the reaction

$$O_2 + O_2 + e = O_2^- + O_2$$

For electron energies equal to about 2.9 eV, atomic ions are formed according to

$$O_2 + e = O^- + O$$

The above attachment processes involving electrons may be expressed by a relation similar to Eq. (1.5) describing electron avalanche in a gas. The formula

$$dI = -\eta I dx \tag{1.6}$$

governs the elementary electron current loss on a distance dx. For a gap of length d with a current I_0 starting at the cathode, the integral version of Eq. (1.6) becomes

$$I = I_0 e^{-\eta d} \tag{1.7}$$

1.4 IONIZATION AND ATTACHMENT COEFFICIENTS

Some results in Harrison and Geballe (1953) showed that the ionization α and attachment η coefficients in oxygen and in air are comparable in the range $25 \leq E/p \leq 60\,\mathrm{V\,cm^{-1}\,Torr^{-1}}$. By considering only the electron collision and electron attachment processes, the resulting number of free electrons on a distance dx is given by

$$dn_x = n_x(\alpha - \eta)\, dx$$

Integrating from $x = 0$ to x, with n_0 electrons starting from the cathode, gives

$$n_x = n_0 e^{(\alpha - \eta)x}$$

namely, the number of electrons at any point x in the gap. The quantity $(\alpha - \eta)$ in the exponent is denoted by $\bar{\alpha}$ and is acknowledged as the effective ionization coefficient. As a consequence, the total steady-state current is

the combinative result of a flow of electrons and negative ions. A given increase of negative ions on the distance dx can be written

$$dn_- = n_x \eta \, dx = n_0 \eta e^{\bar{\alpha} x} \, dx$$

Performing the integration in the limits 0 and x gives

$$n_- = \frac{n_0 \eta}{\bar{\alpha}} [e^{\bar{\alpha} x} - 1]$$

so that

$$I = I_0 \left[\frac{\alpha}{\bar{\alpha}} e^{\bar{\alpha} d} - \frac{\eta}{\bar{\alpha}} \right] \tag{1.8}$$

is ultimately obtained for the total current after summing the two components n_x and n_-. It is simple to verify that Eq. (1.8) reduces to $I = I_0 e^{\alpha d}$ in the absence of attachment ($\eta = 0$).

Indeed, the current measurement between parallel plane electrodes shows that the rate of increase of the current I is higher than the one given by Eqs. (1.7) or (1.8) as the voltage is significantly increased. To explain this discrepancy, Townsend postulated that an overlooked subsidiary mechanism plays a significant role in affecting the current. He first considered a release of electrons in gas by a collision of positive ions and, later, a release of electrons from the cathode by positive ion bombardment. Other processes responsible for the raised departure include secondary electron emission at the cathode by photon impact and photoionization of the gas itself. Townsend considered a second coefficient γ, referred to as "the secondary ionization coefficient," denoting the number of electrons released from the cathode because of a subsidiary emission mechanism.

1.5 ELECTRICAL BREAKDOWN OF GASES

The previously described avalanche process is important in order for a breakdown mechanism to develop. Two typical breakdown mechanisms, each of them operating under specifically favorable conditions, are discerned and labeled Townsend's mechanism and the streamer mechanism. The former takes place when the product of pressure and electrode spacing (in a uniform gap) does not exceed about 5 bar mm. If this limit is exceeded, the space charge of the avalanche could be large enough to significantly change the background field, a circumstance responsible for an avalanche-to-streamer transition. The latter mechanism is extensively treated in Section 1.6.

1.5.1 Breakdown in Steady Uniform Field: Townsend's Breakdown Mechanism

Let n_c be the total number of electrons emitted from the cathode surface and let n_0' be the number of electrons emitted by secondary ionization processes, so that $n_c = n_0 + n_0'$. The average number of collisions produced in the gap by each electron leaving the cathode is given by $(e^{\alpha d} - 1)$. Hence, the number of ionizing collisions in the gap is $n_c(e^{\alpha d} - 1)$. If γ denotes the efficiency of the secondary electrons' emission process, then the number of secondary electrons is

$$n_0' = \gamma n_c\left(e^{\alpha d} - 1\right) = n_c - n_0$$

from which

$$n_c = \frac{n_0}{1 - \gamma(e^{\alpha d} - 1)}$$

The number of electrons attaining the anode is

$$n_a = \frac{n_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$

and the steady-state current becomes

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \tag{1.9}$$

At lower field strengths $e^{\alpha d} \to 1$, thus implying $I = I_0 e^{\alpha d}$ (exponential law in the V_2–V_3 region). As V increases, both $e^{\alpha d}$ and $\gamma e^{\alpha d}$ increase in such a way that $e^{\alpha d} \gg 1$ and $\gamma e^{\alpha d}$ close to 1 are expected occurrences. Therefore, the current I approaches infinity because

$$\gamma(e^{\alpha d} - 1) = 1 \tag{1.10}$$

under the described circumstances. Such a condition is known as Townsend's criterion for breakdown. An alternative expression for Eq. (1.10) is

$$\alpha d = \ln\left(1 + \frac{1}{\gamma}\right) = K'$$

Because the value of γ is very small ($<10^{-2}$–10^{-3}), the above logarithm ranges from 8 to 10 in a Townsend's discharge. The exponential quantity $e^{K'}$

expresses the number of electrons forming the avalanche head that gives rise to the avalanche-to-streamer transition. In deriving Eq. (1.9), only the impact of positive ions on the cathode has been considered as a secondary ionization process. Further secondary processes may be considered, namely, gas ionization by positive ions (according to Townsend's original assumption), photoemission from the electrode, collision of metastable ions on the cathode, and gas ionization by photons. Accordingly, Eq. (1.9) becomes

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma_p (e^{\alpha_p d} - 1)} \tag{1.11}$$

where γ_p and α_p assume specialized expressions.

1.5.2 Paschen's Law

Consider the simple electrode assembly represented by a pair of parallel plates a distance d apart, where a gas at pressure p is the filling medium. By increasing the voltage V applied between the electrodes, an electrical breakdown occurs as soon as the value $V = V_b$ is reached. Paschen's law expresses the experimental evidence that the critical value V_b, termed the breakdown voltage, is a function of the product pd. The given curves show a minimum at $(pd)_{\min} = 10^{-2}$ bar mm, or thereabout (the minimum differs from one gas to another), and the corresponding electric field is E_m. Under the described conditions, an electron crossing the gap will produce a certain number of ionizing collisions. If $pd > (pd)_{\min}$, the number of collisions made by an electron increases and hence the energy lost in collisions is higher than one at $(pd)_{\min}$. Therefore, the probability of ionization decreases as long as E_m remains unchanged, or, differently speaking, the electric field must be increased for this loss to be compensated. Conversely, if $pd < (pd)_{\min}$, then the number of collisions and, hence, the number of ionizing collisions decreases with respect to the value at $(pd)_{\min}$. In this case, the increased ionization probability after each collision can be achieved only by increasing the energy gained by electrons within a mean free path. The consequence is that an electric field higher than the previous value of E_m is required.

The validity of Paschen's law has been confirmed experimentally, provided that the limit temperature 1100°C is not surpassed [see Alston (1968)]. It is ensured that above 2000 K, Paschen's law fails because the thermal ionization no longer can be neglected. Moreover, in order to take into account the effect of the temperature, Paschen's law must be expressed as a function of the product $(\rho_m d)$ where ρ_m is the gas density [see Abdel-Salam (1976)]. High pressure gives rise to a departure from Paschen's law because of the

predominant role assumed by the field emission. Some empirical relations have been suggested by Ritz (1932), Holzer (1932), Boyd, Bruce, and Tedford (1966), and Alston (1968) to express the breakdown voltage V_b [kV] of the uniform field in air gaps of width d [m] at atmospheric pressure. These substantially can be formulated as follows:

$$V_b = A_1 d + A_2 d^{1/2}$$

and an excellent agreement with experiment is given in Boyd et al. (1966) for $A_1 = 2449$ and $A_2 = 66.1$ (average and maximum errors equal to 0.675% and 1.83%, respectively), even though A_1 and A_2 are deprived of physical meaning. Alternative formulas are

$$V_b = 6.04\sqrt{pd} + 23.91(pd)$$

given by Bruce (1953), with p expressed in kPa, which is applicable for pd values within the limits of the validity of Paschen's law, and

$$V_b = \frac{Bpd}{\ln(100pd) + B_1}$$

provided by Townsend (1910), where $B_1 = \ln\{D/(\ln(1 + \gamma^{-1}))\}$. In this case, physical meaning can be ascribed to B and D because they are derived from Townsend's formula [see Eq. (1.4)] involving the first ionization coefficient. Therefore, D is acknowledged to be the saturation ionization in the gas at high values of E/p, while $B/2$ stands for the value of E/p at the inflection point of the α/p versus E/p curve (see Section 1.2.2) with which the paper by Heylen (1973) is concerned. It is ensured there that imposing the values of 44,804 and 14.49 to the constants B and B_1, respectively, gives a better fitting with the experimental values under normal pressure conditions (the average error is 0.485% with a maximum error of 0.85%).

1.6 STREAMER MECHANISM

Townsend's mechanism attempts to explain the formation of spark breakdown in uniform field gaps as a series of successive avalanches, but the spark breakdown's time lags obtained theoretically are not consistent with the very shorter values observed by experiment. Moreover, Townsend's mechanism applied to long gaps is not able to account for the branched configuration and irregular growth of the channel. A streamer theory applied to spark breakdown was proposed by Loeb and Meek (1941) for positive streamers and by

Raether (1956) for negative streamers. Both versions assume that the spark discharge comes from a single avalanche (whose space charge develops a plasma streamer), the electric field is locally enhanced by the space charge (notably, on the avalanche head), and the photoionization of gas molecules surrounding the avalanche is the crucial phenomenon for developing a self-propagating streamer. Loeb's version of the streamer theory accounts for the cathode-directed streamer formation by assuming that a first avalanche crosses completely the interelectrode gap (in an uniform field) and leaves behind it a cone-shaped volume of positive ions. Photoelectrons are produced in the gas surrounding the avalanche and initiate auxiliary avalanches that are oriented along the direction of the total field composed of the space-charge field and the exogenous uniform field. The process initiates near the anode where the local space-charge field is higher. The negative charge of the head of such auxiliary avalanches is attracted by the positive cone-shaped volume, and several positive branches (tails left by the auxiliary avalanches), termed streamers, intensify the surrounding field toward the cathode. The process, which repeats and develops from the anode toward the cathode, results in the formation of a conducting filament of highly ionized gas bridging the gap, throughout. Raether (1964) accounts for the negative anode-directed streamer formation by assuming that streamers develop when the initial avalanche produces a sufficient number of electrons, namely, such that the given space-charge field is comparable to the applied field. The enhanced total field is the primary cause giving rise to a number of photoionization promoted, secondary anode-directed avalanches ahead of the initial one, thus forming a negative streamer.

1.7 BREAKDOWN IN NONUNIFORM DC FIELD

A Townsend-type equation governing current growth in a nonuniform field due to primary and secondary ionizing processes is available in Pedersen (1989). Let N_c be the total number of primary ionizing collisions in the gas per primary electron emitted from a small surface of the cathode. If I_0 is the electron current due to the external source emitted from that cathode area, then

$$I = I_0(1 + N_c)$$

is the discharge current only due to the primary ionizing process. Here, N_c is the total number of primary ionizing collisions in the gas per primary electron emitted from the cathode. This discharge current will develop along a line of force from the cathode to the anode. The secondary ionizing processes, subject

to a higher onset level, can be described by the number M_e of secondary electrons released at the cathode per emitted primary electron. The consequence is that the formula for the discharge current produced by succeeding generations of avalanches reads

$$I = I_0(1 + N_c)(1 + M_e + M_e^2 + \cdots) \tag{1.12}$$

which approximately becomes

$$I = I_0 \frac{(1 + N_c)}{(1 - M_e)} \tag{1.13}$$

for $M_e < 1$. Under such conditions, the current assumes a finite value, whereas for $M_e \geq 1$ Eq. (1.12) diverges, thus predicting breakdown.

To determine the parameter N_c, pay attention to the generic distance x from the cathode and to that, expressed with the notation d, between the cathode and anode, both measured along a line of force of the electric field. The number of ionizing collisions between x and $x + dx$ due to a primary electron is then given by

$$dN_c = N_e(x)\alpha\, dx$$

where $N_e(x)$ is the number of electrons at distance x per primary electron (or the total number of electrons, residing in the head of the electron avalanche, which turns out to be a surrogate of the avalanche size) obeying the law

$$N_c(x) = \exp\left[\int_0^x (\alpha - \eta)\, dx\right]$$

Therefore,

$$N_c = \int_0^d \exp\left[\int_0^x (\alpha - \eta)\, dx\right] \alpha\, dx$$

The parameter M_e is related to N_c by the equality $M_e = \gamma N_c$, with γ also termed the Townsend secondary ionization coefficient. As a result, Eq. (1.13) becomes

$$I = I_0 \frac{\left(1 + \displaystyle\int_0^d \exp\left[\int_0^x (\alpha - \eta)\, dx\right] \alpha\, dx\right)}{\left(1 - \gamma \displaystyle\int_0^d \exp\left[\int_0^x (\alpha - \eta)\, dx\right] \alpha\, dx\right)}$$

and, then,

$$\gamma \int_0^d \exp\left[\int_0^x (\alpha - \eta)\, dx\right] \alpha\, dx = 1 \tag{1.14}$$

which results in the criterion for Townsend's mechanism of spark breakdown in an electronegative gas under nonuniform fields. A succession of electron avalanches, initiating to the cathode, is the prerequisite for Townsend's breakdown mechanism to develop. However, Townsend's criterion is hard to manage for engineering problems because the secondary ionization coefficient γ is very sensitive to the actual conditions of electrode surfaces and gas purity. Furthermore, measurements of γ have been obtained up to now only at technically unimportant pressure values of lower than 3.4 kPa. Townsend's criterion is also unable to explain breakdown under steep voltage surges.

1.8 OTHER STREAMER CRITERIA

The streamer mechanism assumes that the growth of a single electron avalanche becomes unstable before reaching the anode, even though fast-moving streamers from the avalanche head are permitted by photoionization. These streamers form a highly conducting channel across the gap, thus causing a definitive voltage collapse. Both Meek and Cragg (1953) and Reather (1964) independently developed a new equation for the breakdown of a nonuniform field gap, and Reather additionally suggested that the critical number of charge carriers for the avalanche-to-streamer transition is in the 10^8 range, irrespective of the gas pressure. By modifying Meek, Cragg, and Reather's equation, Pedersen proposed a semiempirical streamer criterion according to which

$$\int_0^x (\alpha - \eta)\, dx = \ln(N_c) = \text{const} \tag{1.15}$$

Here, x is that fraction of the gap length d representing the distance between the cathode and the point where $\alpha = \eta$, and N_c is the critical size of the avalanche. When $\alpha > \eta$, the electron avalanche grows, whereas the contrary occurs for $\alpha < \eta$. Both α and η are functions of E/p, so that in a uniform **E**-field there is a limiting field strength, one related to the condition $\alpha = \eta$ below which breakdown cannot occur because all the electrons are attached. This effect has been verified experimentally by Geballe and Reeves (1953), Crowe and Devins (1956), and Bhalla and Craggs (1962). The values of the constant k,

which depend on the product *pd* and on the nature of the electronegative gas, have been computed by Malik (1981) as a function of the applied uniform electric field. For air at $pd = 1$ bar cm, the constant in Eq. (1.15) is equal to 18.

1.9 CORONA DISCHARGE IN AIR

The term *corona* evokes partial discharges in air which, owing to physical and technological reasons limiting the applied voltage, can burn on the over-stressed zones of hot electrodes. This kind of discharge occupies a short layer (the ionization region), attached to the energized conductor, in comparison to the outer region of the gap crossed by drifting charges. In general, there are a number of active zones that are individually very confined and collectively disseminated over the electrode surfaces where the local curvature increases so much that the enhanced electric field can trespass there an established onset value. Owing to several wanted or unwanted effects concerned with corona discharges, the overall performances of this complex phenomenon have extensively been detected in the laboratory and described by theoretical models. The investigation is aimed at

- understanding the dependence of corona activity from several physical parameters,
- paying additional attention to undesired companion effects such as radio noise, power loss, and audible noise, and
- designing processes and devices for practical applications,

to name a few objects. The geometrical configurations adopted are very different. As a result, many of the modes of the corona appearance have been reproduced during experimental tests as a function of the applied voltage's polarity and magnitude, field divergence, protrusion's form and surface distribution, ambient conditions, and so on. The next subsection summarizes the characteristics of the various coronas given.

1.9.1 DC Corona Modes

Because of the low mobility of ions, space charges of both polarities accumulate in the gap near the stressed electrode. As a result, positive ions are formed by an ionization process, and negative ions are formed by an attachment process favored by the electronegative properties of air. The resulting space charge causes distortion of the local field and, ultimately, discharge. Corona modes differ according to the equilibrium between two opposite situations that are identified as creations of ionic space charge and electrostatic removal.

1.9.2 Negative Corona Modes

When the highly stressed electrode is the cathode, electron avalanches develop from the cathode toward the anode in a decreasing field. The ionization proceeds up to a distance from the cathode where $\bar{\alpha} = 0$. All the points characterized by such an equality form a boundary surface, say, S_0, where the avalanches stop. The tail of positive ions takes place between the cathode and S_0. The electrons at reduced mobility continue to migrate toward the anode and attach the oxygen molecules to form negative ions that, because of their slow drift velocity, accumulate in the gap beyond S_0. The so-formed two regions of space charge disturb the background electrostatic field, and a new field distribution enlivens the gap throughout. Substantially, the ionic space charge increases the field near the cathode and reduces the field near the anode. The surface S_0 is displaced toward the cathode, and the successive electron avalanches develop on a shorter distance where higher field strengths are present. Increasing the applied voltage leads to three modes of corona discharge, that is,

- Trichel streamers
- Pulseless glow
- Negative streamers

Trichel Streamers While studying the negative corona discharge in air for a point-to-plane configuration, Trichel (1938) and Loeb (1965) observed that the corona current is composed by discrete pulses whose magnitude and frequency are functions of the applied voltage (provided that this is only slightly larger than the onset value), point size, and ambient conditions. A Trichel discharge propagates for a few tens of nanoseconds and is randomly distributed on the surface of the stressed protrusion. The distribution simultaneously involves several spots changing their position during the observation time. The related current oscillogram shows sharp peaks of very short duration (tens of nanoseconds with a rise time of about 1.3 ns) separated by longer interpulse intervals (tens of microseconds). The amplitude of these pulses, being of the order of 10^{-8} A at a thin point electrode up to a few tens of milliamperes for a larger electrode, decreases as the applied voltage [see Trih and Jordan (1968)], pressure, and humidity [Bian et al. (2009)] increase. On the contrary, the pulse frequency increases as the voltage increases. The pulse frequency is a function of the time spent to remove the ionic space charge through the drift under the action of the applied field. Trichel's pulse frequency can be increased up to a critical value depending on the electrode geometry, pulse amplitude, and surface conditions. For a sphere of 8-mm diameter, the critical frequency is 2 kHz. Trichel's pulse converts into a new corona mode when any critical frequency is reached.

The pulsating nature of the Trichel streamer can be explained by taking into account the interaction between the ion space charge and applied field. Once a Trichel streamer is initiated and the discharge is self-sustained by the photon-induced secondary electron emission, two oppositely charged ion clouds are formed and localize in the gap in such a way as to influence the electric field and force the boundary surface S_0 to settle down in closer proximity to the cathode. The positive ion cloud is partially neutralized at the cathode by the negative ions produced by successive avalanches. The residual negative ionic charge reduces the field intensity at the cathode below the onset field and then the discharge is suppressed. This phase is followed by a period, the so-called dead time, during which the remaining negative charge is dispersed by the field and a new streamer will develop when the ionic charge has been sufficiently removed by the drift. The streamer frequency depends on the ion-removal velocity and increases with the growing applied voltage up to a critical value of the frequency: At some high fields, the pulse repetition rate can decrease and a transition to a new corona mode can occur.

Pulseless Glow By increasing the voltage even further until a critical frequency is obtained, the transition from Trichel's pulses to pulseless glow occurs. The discharge becomes stably positioned on the protrusion surface and, in a visible sense, it shows the basic features of the glow discharge; that is, a cathode dark space is followed, respectively, by a bright negative glow, a Faraday dark space, and a luminous conical positive column. During this corona mode, the electrons are emitted at low kinetic energy from the cathode (as a result of ionic bombardment) and acquire energy from the field while crossing the cathode dark zone. The consequent intensive ionization, occurring in the negative glow region, is detrimental for the electron kinetic energy. Going beyond the periphery of the negative glow region, the electrons are once again accelerated across the Faraday dark zone. The successive positive column is the result of ionization of gas atoms. The conical shape of this positive column is attributed to the diffusion of free electrons in the low-field region. The detected discharge stability in this corona mode is attributable to higher applied voltages because the field becomes more efficient in removing the negative ionic space charge and, consequently, in warding off suppression of the ionization activity. The corona current is stable in time and increases with the voltage until this mode of discharge turns into negative streamers. The reversible character of the mode transitions depends, of course, on the generally linear mechanisms involved in the discharge formation and extinction.

Negative Streamers The last mode of corona discharge at the cathode is represented by negative streamers. These occur when the voltage is increased still further. This corona mode shares several aspects with the previous

pulseless glow, along with the fact that the conical positive column is forced to form a streamer stem extending farther into the gap with no branching. The length of the streamers increases with the voltage until one of them crosses the gap, causing breakdown, or approaches a streamer eventually initiated from the anode. This corona mode also depends on electron emissions from the cathode as a result of ionic bombardment, while the formation of a streamer channel characterized by intense ionization is indicative of even more effective space-charge removal under the action of the applied field. The streamer current consists of a DC component, with superimposed pulses, which allows the discharge to never disappear altogether. The corona current increases continuously with the voltage until the discharge mode switches in proximity to the breakdown region.

1.9.3 Positive Corona Modes

When the polarity of the highly stressed electrode is positive, each electron avalanche develops from the boundary surface S_0 (where $\bar{\alpha} = 0$) toward the anode in a continuously increasing field. These favorable conditions for avalanche formation result in a critical field intensity that is slightly lower for positive than for negative coronas. A positive ion space charge (streamer) is left along the avalanche path in consequence to the lower mobility of the ions. Meanwhile this positive streamer is moving away from the point of the electrode, and photoelectrons start from the streamer and cause ionization with the consequent formation of variously directed avalanches in proximity to the electrode surface. As a result, a discharge spreads out over the surface points. The free electrons formed lose their energy by ionization of the neutral molecules near the anode, and then they can be neutralized at the anode or recombine with positive ions or create negative ions by attachment. The consequent presence of space charge of both polarities causes field reduction in the region close to the surface and enhancement in the farther region. This happens where secondary electron avalanches may be attracted to promote outwardly directed propagation of the discharge, along a streamer channel, into the gap. Four positive corona discharge modes can be observed, as the electric field at the anode is increased, prior to a definitive breakdown. These modes are summarized as follows in the order of appearance:

- Burst corona
- Onset streamers
- Positive-glow discharge
- Breakdown streamers

Burst Corona This corona mode displays a thin, luminous sheath close to the anode as a visible result of ionization spreading and avalanche formation in proximity to the anode surface. The positive ions created and left near the anode tend to reduce the field with consequent discharge suppression. The resulting discharging current consists of very small positive pulses.

Onset Streamers The positive ion charge left by the first avalanche enhances the field and produces a number of photons emitted in all directions. Some air molecules will be photoionized, and each photoelectron produced within the ionization zone will be accelerated under the action of the resultant electric field. New avalanches (called "second generation") will develop, and the discharge will assume an elongated aspect with several filamentary channels stemming from it. The absorption of free electrons at the anode gives rise to a residual positive charge that reduces the local field and ultimately causes streamer-discharge suppression. A dead time is required for the applied field to remove the ionic charge and restore the conditions for new streamer development. Thus the discharge current is a pulse of short duration, high amplitude, and relatively low repetition rate. The onset-streamer current ranges from a few tenths of milliamperes in highly divergent fields to a few hundreds of milliamperes when larger electrodes are involved. In the case of an 8-mm-diameter sphere protruding from the curved surface of a cylindrical conductor, the measured currents revolved around 250 mA. With reference to a conical boss with cone angle 30°, the current was about 3 mA. The mean rise time of the pulses was of the order of 30 ns and their half-peak time of about 100 ns [see Trinh and Jordan (1968)].

Burst corona and onset streamers develop in an alternative way over a small range of voltages immediately beyond the corona onset. In fact, for these voltage levels, the increased field is more effective in removing the positive space charge in close proximity to the anode surface, thus promoting a side-burst corona at the anode. A few microseconds after the suppression of the streamer, the anodic region is so rapidly cleared of the positive ionic space charge that incoming negative ions encounter a sufficiently high field to shed an electron at instant of impact. This free electron sustains ionization activity over the anode surface in the form of a burst corona, which develops until it is suppressed because of its own positive space charge. As the voltage is increased further, the space-charge removal at the anode becomes more effective and the burst corona enhances accordingly. As the burst corona develops, the positive ions created in the meantime are rapidly pushed away from the anode and accumulate in front of the anode. Once stably formed, the positive ionic space charge prevents radial development of discharge into the gap and a burst corona can more readily develop. This happens at the expense of the onset streamer until its suppression is accomplished. A new mode, termed positive-glow discharge (or Hermstein's glow), is then established at the anode.

Positive-Glow Discharge This corona mode consists of an intense ionization activity in the zones immediately adjacent to the anode and appears in the form of a thin, luminous layer adhering to the electrode surface. This activity is promoted by the rapid removal of positive space charge operated by the intense field. Moreover, the field intensity fails to such a great degree in allowing radial development of the discharge and streamer formation that the density of negative space charge becomes high enough to fully suppress onset streamers. As a result, this corona mode appears as a stable and uniform glow near the anode surface. The role assumed by the negative ions in forming such a stable glow was presumptively claimed by Trichel (1938) but experimentally proved by Hermstein (1960). That is why Loeb successfully proposed to call "Hermstein's glow" a positive glow. This emits discrete pulses of light and the resulting discharge current takes a saw-toothed waveform composed by a direct current (growing with the voltage) with superimposed small but stable pulses. The frequency of these burst pulses increases with the voltage and may attain a few megahertz. The pulsing nature of the glow corona becomes the subject matter carefully treated by Beattie (1975), Sigmond (1978), and Cross and Beattie (1980). In accord with these investigations, photo-detachment of negative ions by ion–electron recombination radiation provides seed electrons for pulse promotion. The transition from burst pulses to a stable glow seems to be more gradual when corpulent electrodes are adopted, in which case, however, the property of Hermstein's glow of suppressing streamers is less effective with respect to slender and pointed conductors.

Breakdown Streamers As the voltage increases, the stable positive glow loses its uniformity and one or two zones of higher luminosity are then formed. These spots of enhanced ionizing activity can be seen moving slowly over the anode and giving rise to breakdown streamers. The discharge parameters are of the same order of the onset streamers, but their elongation into the gap is larger and asymmetrical. The length, amplitude, and repetition rate of the pulses grow with the voltage. When the applied field becomes sufficiently high to remove the positive space charge from the anode region, the radial development of the discharge becomes feasible, which may result in a breakdown streamer.

1.10 AC CORONA

When an electrode is raised to a high sinusoidal potential, different corona modes of both polarities may be observed during a complete cycle depending on the applied voltage, gap length, and onset gradient. Contrary to the case of a short gap, in which the ionic space charge created during a half-cycle can impact a collector during the same half-cycle, the more usual case of a long gap is that in which it is larger than the maximum distance that the ionic space

charge travels during one half-cycle. Under the circumstances described, the ionic space charge, created during one half-cycle, is drawn back toward the highly stressed electrode during the following half-cycle, thus before impacting the collector. As a consequence, the discharge development happens to be influenced in the sense that onset streamers are suppressed in favor of the positive glow discharge. Even negative streamers cannot be observed under AC voltage, because their onset field is greater than the breakdown voltage during the positive half-cycle. All things considered, only the following corona modes can now be categorized, namely, negative Trichel streamers, negative glow discharge, positive glow discharge, and positive breakdown streamers. When the applied voltage slightly exceeds the corona onset level, then negative Trichel streamers, positive onset streamers, and burst corona can be observed in the two half-cycles.

1.11 KAPTZOV'S HYPOTHESIS

When a conductor is in corona, then the electric field on the surface is somehow influenced by the surrounding ion space charge. Assessing the actual field strength on the active surface is of prominent importance in theoretical analyses subject to boundary conditions. Kaptzov's hypothesis (KH) consists in assuming that the space charge emitted into the interelectrode gap is in amounts that hold the surface field at the onset level. A theoretical calculation of the surface electric field for positive and negative polarities is extensively available elsewhere [see Khalifa and Abdel-Salam (1973)], whereas some experimental tests prove that the surface field is lower than the corona onset level [see Waters, Rickard, and Stark (1972)]. Provided that this is the case, KH would also invalidate to some extent the theoretical prediction of current losses, in the sense that the true corona-originated losses would be greater than those given by calculations.

For cylindrical conductors, the corona onset field is generally calculated by Peek's formula

$$E_0 = E_{0p} m \delta \left(1 + \frac{K}{\sqrt{\delta r}} \right) \tag{1.16}$$

where E_0 [kV/cm] is the corona onset gradient; r [cm] is the conductor radius; $\delta = \frac{3.92}{273+t} p$ is the air relative density (pressure p in cmHg and temperature t in °C); m is the conductor surface's irregularity factor (ranging from 0.8 to 1); $E_{0p} = 29.8$ kV/cm and $K = 0.301$ in AC and in DC (negative polarity) cases for two parallel conductors above ground; and $E_{0p} = 33.7$ kV/cm and $K = 0.24$ in the DC case (positive polarity) for two parallel conductors above ground.