Corona discharge

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A **corona discharge** is an electrical discharge brought on by the ionization of a fluid such as air surrounding a conductor that is electrically charged. Spontaneous corona discharges occur naturally in high-voltage systems unless care is taken to limit the electric field strength. A corona will occur when the strength (potential gradient) of the electric field around a conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects. It is often seen as a bluish (or other color) glow in the air adjacent to pointed metal conductors carrying high voltages, and emits light by the same property as a gas discharge lamp.

Long exposure photograph of corona discharge on an insulator string of a 500 kV overhead power line. Corona discharges represent a significant power loss for electric utilities.

In many high voltage applications corona is an unwanted side effect. Corona discharge from high voltage electric power transmission lines constitutes an economically significant waste of power for utilities. In high voltage equipment like televisions, radio transmitters, X-ray machines and particle accelerators the current leakage caused by coronas can constitute an unwanted load on the circuit. In air, coronas generate gases such as ozone (O_3) and nitrogen oxide (NO), and in turn nitric oxide (NO_2), and thus nitric acid if water vapor is present. These gases are corrosive and can degrade and embrittle nearby materials, and are also toxic to people. Corona discharges can often be suppressed by improved insulation, corona rings, and making high voltage electrodes in smooth rounded shapes. However, controlled corona discharges are used in a variety of processes such as air filtration, photocopiers and ozone generators.

The corona discharge around a high-voltage coil

Contents

Introduction


Corona discharge on a Wartenberg wheel

Corona discharge is a process by which a current flows from an electrode with a high potential into a neutral fluid, usually air, by ionizing that fluid so as to create a region of plasma around the electrode. The ions generated eventually pass charge to nearby areas of lower potential, or recombine to form neutral gas molecules.

When the potential gradient (electric field) is large enough at a point in the fluid, the fluid at that point ionizes and it becomes conductive. If a charged object has a sharp point, the electric field strength around that point will be much higher than elsewhere. Air near the electrode can become ionized (partially conductive), while regions more distant do not. When the air near the point becomes conductive, it has the effect of increasing the apparent size of the conductor. Since the new conductive region is less sharp, the ionization may not extend past this local region. Outside this region of ionization and conductivity, the charged particles slowly find their way to an oppositely charged object and are neutralized.

If the geometry and gradient are such that the ionized region continues to grow until it reaches another conductor at a lower potential, a low resistance conductive path between the two will be formed, resulting in an electric arc.

Corona discharge usually forms at highly curved regions on electrodes, such as sharp corners, projecting points, edges of metal surfaces, or small diameter wires. The high curvature causes a high potential gradient at these locations, so that the air breaks down and forms plasma there first. In order to suppress corona formation, terminals on high voltage equipment are frequently designed with smooth large diameter rounded shapes like balls or toruses, and corona rings are often added to insulators of high voltage transmission lines.

Coronas may be *positive* or *negative*. This is determined by the polarity of the voltage on the highly curved electrode. If the curved electrode is positive with respect to the flat electrode, it has a *positive corona*, if it is negative, it has a *negative corona*. (See below for more details.) The physics of positive and negative coronas are strikingly different. This asymmetry is a result of the great difference in mass between electrons and positively charged ions, with only the electron having the ability to undergo a significant degree of ionising inelastic collision at common temperatures and pressures.

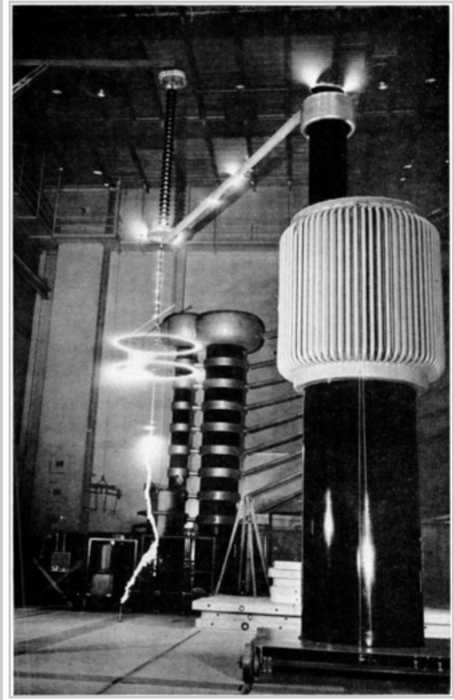
An important reason for considering coronas is the production of ozone around conductors undergoing corona processes in air. A negative corona generates much more ozone than the corresponding positive corona.

Applications of corona discharge

Corona discharge has a number of commercial and industrial applications.

- Drag reduction over a flat surface
- To create an electrochemical process that uses tiny spikes of carbon and copper to turn carbon dioxide, a greenhouse gas, into ethanol. (Oak Ridge National Laboratory)
- Removal of unwanted electric charges from the surface of aircraft in flight and thus avoiding the detrimental effect of uncontrolled electrical discharge pulses on the performance of avionic systems
- Manufacture of ozone

- Sanitization of pool water
- Scrubbing particles from air in air-conditioning systems (see electrostatic precipitator)
- Removal of unwanted volatile organics, such as chemical pesticides, solvents, or chemical weapons agents, from the atmosphere
- Improvement of wetability or 'surface tension energy' of polymer films to improve compatibility with adhesives or printing inks
- Photocopying
- Air ionisers
- Production of photons for Kirlian photography to expose photographic film
- EHD thrusters, Lifters, and other ionic wind devices
- Nitrogen laser
- Surface treatment for tissue culture (polystyrene)
- Ionization of a gaseous sample for subsequent analysis in a mass spectrometer or an ion mobility spectrometer
- Solid-state cooling components for computer chips (see solid-state fan)
- Stabiliser of Van de Graaff generators



Large corona discharges *(white)* around conductors energized by a 1.05 million volt transformer in a U.S. NIST laboratory in 1941

Coronas can be used to generate charged surfaces, which is an effect used in electrostatic copying (photocopying). They can also be used to remove particulate matter from air streams by first charging the air, and then passing the charged stream through a comb of alternating polarity, to deposit the charged particles onto oppositely charged plates.

The free radicals and ions generated in corona reactions can be used to scrub the air of certain noxious products, through chemical reactions, and can be used to produce ozone.

Issues caused by corona discharges

Coronas can generate audible and radio-frequency noise, particularly near electric power transmission lines. They are a source of power loss, and their action on atmospheric particulates, along with associated ozone and NOx production, can be harmful to human health where power lines run through built-up areas. Therefore, power transmission equipment is designed to minimise the formation of corona discharge.

Corona discharge is generally undesirable in:

- Electric power transmission, where it causes:
  - Power loss
  - Audible noise
  - Electromagnetic interference
  - Purple glow
  - Ozone production
  - Insulation damage
  - Possible distress in animals that are sensitive to ultraviolet light[1]
- Electrical components such as transformers, capacitors, electric motors and generators.

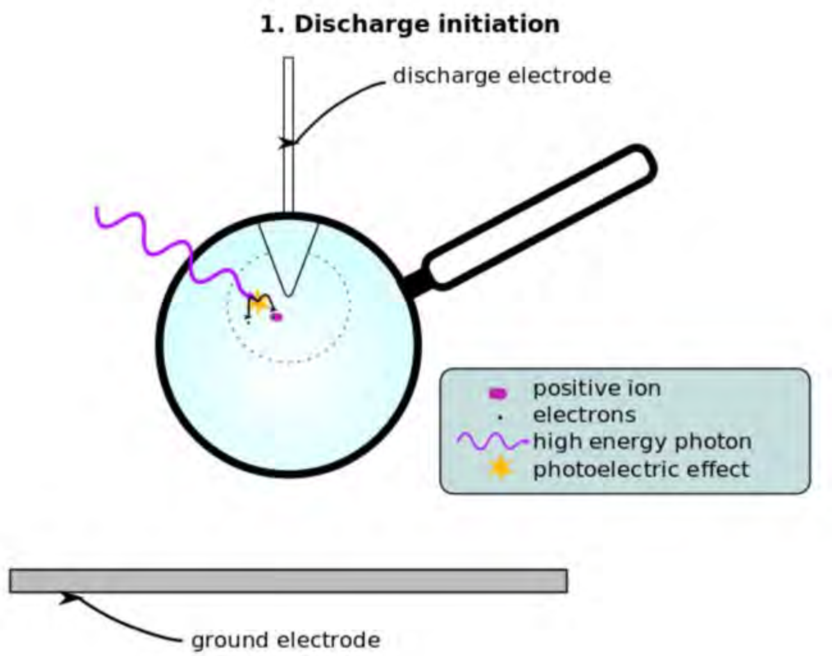
    - Corona can progressively damage the insulation inside these devices, leading to equipment failure.
    - Elastomer items such as O-rings can suffer ozone cracking
    - Plastic film capacitors operating at mains voltage can suffer progressive loss of capacitance as corona discharges cause local vaporization of the metallization[2]
- Situations where high voltages are in use, but ozone production is to be minimised
- Static electricity discharge

In many cases coronas can be suppressed by corona rings, toroidal devices that serve to spread the electric field over larger area and decrease the field gradient below the corona threshold.

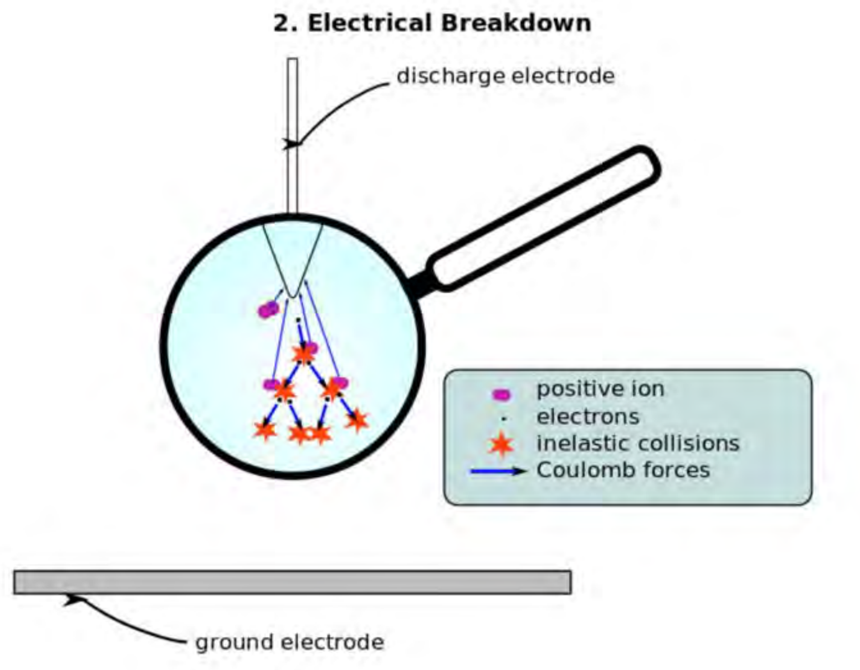
Mechanism of corona discharge

Corona discharge results when the electric field is strong enough to create a chain reaction: electrons in the air collide with atoms hard enough to ionize them, creating more electrons which ionize more atoms. See what actually happens on the gas near the electrode of highly-negative voltage with respect to ground in micro-scale in figures below. The process is:

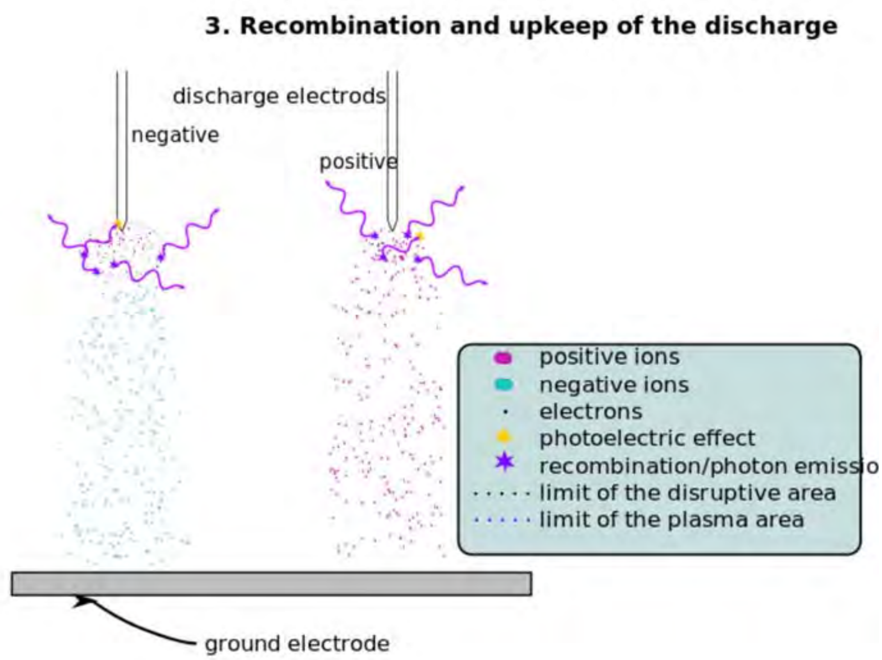
1. A neutral atom or molecule, in a region of strong electric field (such as the high potential gradient near the curved electrode) is ionized by a natural environmental event (for example, being struck by an ultraviolet photon or cosmic ray particle), to create a positive ion and a free electron.



2. The electric field accelerates these oppositely charged particles in opposite directions, separating them, preventing their recombination, and imparting kinetic energy to each of them.
3. The electron has a much higher charge/mass ratio and so is accelerated to a higher velocity than the positive ion. It gains enough energy from the field that when it strikes another atom it ionizes it, knocking out another electron, and creating another positive ion. These electrons are accelerated and collide with other atoms, creating further electron/positive-ion pairs, and these electrons collide with more atoms, in a chain reaction process called an *electron avalanche*. Both positive and negative coronas rely on electron avalanches. In a positive corona all the electrons are attracted inward toward the nearby positive electrode and the ions are repelled outwards. In a negative corona the ions are attracted inward and the electrons are repelled outwards.



4. The glow of the corona is caused by electrons recombining with positive ions to form neutral atoms. When the electron falls back to its original energy level, it releases a photon of light. The photons serve to ionize other atoms, maintaining the creation of electron avalanches.



5. At a certain distance from the electrode, the electric field becomes low enough that it no longer imparts enough energy to the electrons to ionize atoms when they collide. This is the outer edge of the corona. Outside this the ions move through the air without creating new ions. The outward moving ions are attracted to the opposite electrode and eventually reach it and combine with electrons from the electrode to become neutral atoms again, completing the circuit.

Thermodynamically, a corona is a very *nonequilibrium* process, creating a non-thermal plasma. The avalanche mechanism does not release enough energy to heat the gas in the corona region generally and ionize it, as occurs in an electric arc or spark. Only a small number of gas molecules take part in the electron avalanches and are ionized, having energies close to the ionization energy of 1 - 3 ev, the rest of the surrounding gas is close to ambient temperature.

The onset voltage of corona or corona inception voltage (CIV) can be found with *Peek's law* (1929), formulated from empirical observations. Later papers derived more accurate formulas.

Positive coronas

Properties

A positive corona is manifested as a uniform plasma across the length of a conductor. It can often be seen glowing blue/white, though many of the emissions are in the ultraviolet. The uniformity of the plasma is caused by the homogeneous source of secondary avalanche electrons described in the mechanism section, below. With the same geometry and voltages, it appears a little smaller than the corresponding negative corona, owing to the lack of a non-ionising plasma region between the inner and outer regions.

A positive corona has much lower density of free electrons compared to a negative corona; perhaps a thousandth of the electron density, and a hundredth of the total number of electrons. However, the electrons in a positive corona are concentrated close to the surface of the curved conductor, in a region of high potential gradient (and therefore the electrons have a high energy), whereas in a negative corona many of the electrons are in the outer, lower-field areas. Therefore, if electrons are to be used in an application which requires a high activation energy, positive coronas may support a greater reaction constants than corresponding negative coronas; though the total number of electrons may be lower, the number of very high energy electrons may be higher.

Coronas are efficient producers of ozone in air. A positive corona generates much less ozone than the corresponding negative corona, as the reactions which produce ozone are relatively low-energy. Therefore, the greater number of electrons of a negative corona leads to an increased production.

Beyond the plasma, in the *unipolar region*, the flow is of low-energy positive ions toward the flat electrode.

Mechanism

As with a negative corona, a positive corona is initiated by an exogenous ionisation event in a region of high potential gradient. The electrons resulting from the ionisation are attracted **toward** the curved electrode, and the positive ions repelled from it. By undergoing inelastic collisions closer and closer to the curved electrode, further molecules are ionized in an electron avalanche.

In a positive corona, secondary electrons, for further avalanches, are generated predominantly in the fluid itself, in the region outside the plasma or avalanche region. They are created by ionization caused by the photons emitted from that plasma in the various de-excitation processes occurring within the plasma after electron collisions, the thermal energy liberated in those collisions creating photons which are radiated into the gas. The electrons resulting from the ionisation of a neutral gas molecule are then electrically attracted back toward the curved electrode, attracted *into* the plasma, and so begins the process of creating further avalanches inside the plasma.

As can be seen, the positive corona is divided into two regions, concentric around the sharp electrode. The inner region contains ionising electrons, and positive ions, acting as a plasma, the electrons avalanche in this region, creating many further ion/electron pairs. The outer region consists almost entirely of the slowly migrating massive positive ions, moving toward the uncurved electrode along with, close to the interface of this region, secondary electrons, liberated by photons leaving the plasma, being re-accelerated into the plasma. The inner region is known as the **plasma** region, the outer as the **unipolar** region.

Negative coronas

Properties

A negative corona is manifested in a non-uniform corona, varying according to the surface features and irregularities of the curved conductor. It often appears as tufts of corona at sharp edges, the number of tufts altering with the strength of the field. The form of negative coronas is a result of its source of secondary avalanche electrons (see below). It appears a little larger than the corresponding positive corona, as electrons are allowed to drift out of the ionising region, and so the plasma continues some distance beyond it. The total number of electrons, and electron density is much greater than in the corresponding positive corona. However, they are of a predominantly lower energy, owing to being in a region of lower potential-gradient. Therefore, whilst for many reactions the increased electron density will increase the reaction rate, the lower energy of the electrons will mean that reactions which require a higher electron energy may take place at a lower rate.

Mechanism

Negative coronas are more complex than positive coronas in construction. As with positive coronas, the establishing of a corona begins with an exogenous ionization event generating a primary electron, followed by an electron avalanche.

Electrons ionized from the neutral gas are not useful in sustaining the negative corona process by generating secondary electrons for further avalanches, as the general movement of electrons in a negative corona is outward from the curved electrode. For negative corona, instead, the dominant process generating secondary electrons is the photoelectric effect, from the surface of the electrode itself. The work function of the electrons (the energy required to liberate the electrons from the surface) is considerably lower than the ionization energy of air at standard temperatures and pressures, making it a more liberal source of secondary electrons under these conditions. Again, the source of energy for the electron-liberation is a high-energy photon from an atom within the plasma body relaxing after excitation from an earlier collision. The use of ionized neutral gas as a source of ionization is further diminished in a negative corona by the high-concentration of positive ions clustering around the curved electrode.

Under other conditions, the collision of the positive species with the curved electrode can also cause electron liberation.

The difference, then, between positive and negative coronas, in the matter of the generation of secondary electron avalanches, is that in a positive corona they are generated by the gas surrounding the plasma region, the new secondary electrons travelling inward, whereas in a negative corona they are generated by the curved electrode itself, the new secondary electrons travelling outward.

A further feature of the structure of negative coronas is that as the electrons drift outwards, they encounter neutral molecules and, with electronegative molecules (such as oxygen and water vapor), combine to produce negative ions. These negative ions are then attracted to the positive uncurved electrode, completing the 'circuit'.

A negative corona can be divided into three radial areas, around the sharp electrode. In the inner area, high-energy electrons inelastically collide with neutral atoms and cause avalanches, whilst outer electrons (usually of a lower energy) combine with neutral atoms to produce negative ions. In the intermediate region, electrons combine to form negative ions, but typically have insufficient energy to cause avalanche ionization, but remain part of a plasma owing to the different polarities of the species present, and the ability to partake in characteristic plasma reactions. In the outer region, only a flow of negative ions and, to a lesser and radially-decreasing extent, free electrons toward the positive electrode takes place. The inner two regions are known as the corona *plasma*. The inner region is an *ionizing plasma*, the middle a *non-ionizing plasma*. The outer region is known as the *unipolar region*.

When an electrical transmission line is energized, the air surrounding the conductors is subjected to di-electric stress. At low voltage, nothing really occurs as the stress is too low to ionize the air outside. But when the voltage gradient around a conductor is higher than some threshold value, the air surrounding it experiences stress high enough to be dissociated into ions, making the atmosphere conducting. This results in electric discharge around the conductors due to the flow of these ions, giving rise to a faint luminescent glow, along with the hissing sound accompanied by the liberation of ozone, which is readily identified due to its characteristic odor. If the voltage across the lines is still increased the glow becomes more and more intense along with hissing noise, inducing very high power loss into the system.

Examples

Corona discharge may be seen around automotive spark plug wires that have become worn.

Corona discharge may arise from other conductors carrying alternating current at very high voltages, such as long-distance transmission lines and high-power short-wave transmitting antennae.

The phenomenon known as St. Elmo's Fire was, and is, a common occurrence of corona discharge. The "Fire" was what sailors called the sparks and discharge that typically occurred on the uppermost sections of sail-powered ships. Caused by a buildup of static electricity, that once the potential energy grew great enough, would arc between masts and spars among the rigging. Sailors were commonly extremely superstitious, and many believed that it was caused by ghosts. Also sailors learned that the discharge often signaled that a thunderstorm was likely imminent.

Ionized gases produced in a corona discharge are accelerated by the electric field, producing a movement of gas or "electrical wind". The air movement associated with a discharge current of a few hundred microamperes can blow out a small candle flame within about 1 cm of a discharge point. A pinwheel, with radial metal spokes and pointed tips bent to point along the circumference of a circle, can be made to rotate if energized by a corona discharge; the rotation is due to differential electric attraction between the metal spokes and the space charge shield region that around the tips.[3]

High-voltage limit

Electric transmission lines are built to limit corona as it causes electrical losses. Transmission lines that traverse large distances are built at very high voltages to limit the current flow and its associated I^2R loss. Additional conductors are added which provides a larger Geometric Mean Radius which limits corona. Presently there are ultra-high voltage electrical lines built for 1,200 kV. It is not much higher that the corona losses become greater than the savings in I^2R losses for the Geometric Mean Radius is approaching a flat plate. At that point, there is no reason to build any higher of a voltage line as it will have more electrical losses than a lower voltage transmission line.

See also

- Atmospheric pressure chemical ionization
- Dielectric barrier discharge
- Kirlian photography
- List of plasma (physics) articles
- St. Elmo's fire
- Crookes tube

References

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2. www.capacitorindustry.com: Vishay offers C-stability in X2 capacitors, 14 June 2012 (http://www.capacitorindustry.com/vishay-offers-c-stability-in-x2-capacitors)
3. Leonard Benedict Loeb *Electrical Coronas* University of California Press, 1965 pages 406-409

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External links

- Blaze Labs Research (http://blazelabs.com/l-intro.asp) — Lots of information on corona properties & Peek's Law
- Villanova University (http://www.ee.vill.edu/ion/p61.html) — Modelling Corona for different electrode configurations
- Information about the differences between corona, spark, and brush discharges (https://web.archive.org/web/20131212161356/http://www.ce-mag.com/archive/1999/novdec/mrstatic.html)
- Additional information about corona, its effects, characteristics and preventative measures (http://www.highvoltageinfo.com/articles.php#Corona)
- Dielectric Phenomena In High Voltage Engineering (https://archive.org/details/dielectricphenom028893mbp)

Categories: Electrical breakdown | Plasma physics
