Session 12:
Corona Inspection of Substations and Lines

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Abstract

This paper will focus on the aspects of Corona in MV & HV substations and lines. An overview will be provided with implications for power networks and methods of identification, predictive and preventative procedures.

The following aspects will be covered; Corona phenomenon - Theoretical aspects, physics, chemistry, implications, concerns and outcome; The concept of UV inspection; Corona cameras – Design and principles; UV spectral range Photoelectric and optics; IR cameras compliment UV inspection; Corona and the electrical grid – Where, when and what; Corona on outdoor HV substations & lines – Predictive and preventive procedures and finally UV inspection methodology – Basic and advanced aspects.

Introduction

Corona discharge is an electrical discharge bought on by the ionization of a medium (air) surrounding a conductor that is electrically energized. The discharge will occur when the potential gradient of the electric field around the conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects. Partial breakdown of the air manifests as a corona discharge on high voltage conductors at points with the highest electrical stress. The dielectric strength of the material surrounding the conductor determines the maximum strength of the electric field the surrounding material can tolerate before becoming conductive. Conductors that consist of sharp points, or edges with small radii, are more prone to causing dielectric breakdown.

Corona is sometimes seen as a bluish glow around high voltage wires and heard as a sizzling sound along high voltage power lines. Corona also generates radio frequency noise that can be heard as "static" or buzzing on radio receivers. Spontaneous corona discharges are undesirable, they waste power in high-voltage systems, high chemical activity in a corona discharge creates objectionable or hazardous compounds (such as ozone and acids with associated component corrosion), and radio interference RFI.

Corona

Corona is the process by which a current flows from an electrode with a high potential into a neutral fluid, usually air, by ionizing the air 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 air around that point will be at a much higher gradient 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.

Casually, electrical discharges are often called sparks. It is, however, more practical to reserve this name for a special kind of discharge, namely that taking place between well-rounded conductors at different potentials.

For our purposes here, the difference between the various types of discharges lies primarily in their different *incendivity* —that is, the ability of a discharge to cause ignition or combustion. How incendive, then, are the various types of discharge? The rate and density of the energy dissipated in corona discharges will always be too low to initiate an ignition—in other words, they are not incendive under any circumstances. It's a completely different story with sparks. Again, sparks are discharges between rounded conductors (one of them, often, a grounded object) at different potentials. If a spark occurs, almost all of this energy will be rapidly dissipated in the narrow discharge volume. If the discharge occurs in an explosive atmosphere, ignition may result.

Corona discharge usually forms at sharp transitions on electrodes, such as sharp corners, projecting points, edges of metal surfaces, or small diameter wires. The sharp transition 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 tori. Corona rings are often added to insulators of high voltage transmission lines.

Corona 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 we say we have a positive corona, if negative we say we have a negative corona. 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 assessing corona is the production of ozone around conductors undergoing corona processes in air. A negative corona generates much more ozone than the corresponding positive corona.

Problems Caused by Corona Discharges

Corona generally generates audible and radio-frequency noise, particularly near electric power transmission lines. In built-up areas this can cause annoyance. Corona also represents a power loss, and their action on atmospheric particles along with associated ozone and NOx production is disadvantageous. Therefore, power transmission equipment is designed to minimize the formation of corona discharge.

Corona discharge is generally undesirable in:

Electric power transmission lines and equipment, where it causes:

- Power loss (can be significant when compared with resistive loss)
- Audible noise
- Electromagnetic interference
- Radio and TV Interference, RFI & TVI
- Interference with navigation and communications
- Purple glow
- Gaseous Effluents and Ozone production
- Insulation corrosion, erosion and physical damage
- Induced Currents
- Fuel Ignition
- Interference with cardiac pacemakers
- Computer interference

Electrical components such as transformers, capacitors, electric motors and generators exhibit PD activity internally and externally. In some cases the activity generates corona which can be seen. PD progressively damages the insulation inside these devices, leading to premature equipment failure.

Situations where high voltages are in use, ozone production is to be minimized

Corona is a silent but deadly enemy for composite insulation. Corona leads to insulation failure.

Corona can be suppressed by corona rings, toroid 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 are accelerated and collide with atoms hard enough to ionize them, liberating more electrons which ionize more atoms. The process is:

- 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.
- The electric field accelerates these oppositely charged particles in opposite directions, separating them, and preventing their recombination, and imparting to each of them kinetic energy.
- The electron has a much higher charge/mass ratio and so is accelerated to a higher velocity than the 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.

- **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.
- 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 non-equilibrium 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.

Electrical Properties

There are three types of corona.

- A glow discharge occurs at a gradient of approximately 20 kV rms/cm. Glow discharge is a light glow off sharp points that does not generate objectionable RIV/TVI or cause any audible noise.
- At about 25 kV rms/cm, negative polarity “brush” discharges occur. So named because the appearance is similar to the round ends of a bottle brush. The audible noise associated with brush corona is generally a continuous background type of hissing or frying noise.
- At a gradient of around 30 kVrms/cm positive polarity plume corona is generated; so named because of its general resemblance to a plume. When viewed in the dark it has a concentrated stem that branches and merges into a violet-colored, tree-like halo. The audible noise associated with plume corona is a rather intense snapping and hissing sound. Plume corona generates significant RIV/TVI.

- These observations are based on fair weather conditions. Under wet conditions virtually all energized electrodes will be in corona of one form or another.

Corona Rings

Corona discharges only occur when the electric field (potential gradient) at the surface of conductors exceeds a critical value, the disruptive potential gradient. It is roughly 30 kV / cm, but varies with atmospheric pressure, so corona is more of a problem at high altitudes. The electric field at a conductor is greatest where the curvature is sharpest, and therefore corona discharge occurs first at sharp points, corners and edges. The terminals on very high voltage equipment are frequently designed with large diameter rounded shapes such as balls and toruses called corona caps, to suppress corona formation. However some parts of high voltage circuits require hardware with exposed sharp edges or corners, such as the attachment points where wires or bus bars are connected to insulators. Corona rings are installed at these points to prevent corona formation.

The corona ring is electrically connected to the high voltage conductor, encircling the points where corona would form. Since the ring is at the same potential as the conductor, the presence of the ring reduces the potential gradient at the surface of the conductor greatly, below the disruptive potential gradient, so corona does not form on the metal points.

Grading Rings

A very similar related device, called a grading ring is also used on high voltage equipment. Grading rings are similar to corona rings, but they encircle the ends of insulators rather than conductors. Although they may also serve to suppress corona, their main purpose is to reduce the potential gradient along the insulator, preventing premature electrical breakdown.

The potential gradient (electric field) across an insulator is not uniform, but is highest at the end next to the high voltage electrode. If subjected to a high enough voltage, the insulator will break down and become conductive at that end first. Once a section of insulator at the end has broken down, the full voltage is applied across the remaining length, so the breakdown will quickly progress from the high voltage end to the other, and a flashover arc will start. Therefore insulators can stand significantly higher voltages if the potential gradient at the high voltage end is reduced.

The grading ring surrounds the end of the insulator next to the high voltage conductor. It reduces the gradient at the end, resulting in a more even voltage gradient along the insulator, allowing a shorter, cheaper insulator to be used for a given voltage. Grading rings also reduce aging and deterioration of the insulator that can occur at the HV end due to the high electric field there.

Transmission Lines

Corona produced on a transmission line can be reduced by the design of the transmission line and the selection of hardware and conductors used for the construction of the line. For instance the use of conductor hangers that have rounded rather than sharp edges and no protruding bolts with sharp edges will reduce corona. The conductors themselves can be made with larger diameters and handled so that they have smooth surfaces without nicks or burrs or scrapes in the conductor strands.

- Corona is enhanced by irregularities on the conductor surface
- Irregularities include: dust, insects, burrs and scratches and water drops present on new conductors
- Corona will generally be greater on new conductors and will decrease to a steady-state value over a period of approximately one year in-service
- Corona is significantly increased in foul weather.

Composite Insulators

When it comes to composite insulators, corona activity can originate from the hardware, voids within the material or from defects in the interfaces.

Polymeric materials are more susceptible to degradation from UV produced by corona than from solar radiation, especially if the corona is close to the material. Corona ruptures stable oxygen molecules (O2) to create two radicals, which when combine with these molecules to form ozone (O1). The ozone then attacks unsaturated (i.e. double and triple bond) sites in elastomeric materials resulting in cracking, as commonly observed on rubber tires, gaskets, and seals. Only tiny amounts of ozone (in the ppm) range are sufficient to initiate cracking, however the time required depends on material formulation. Even though most modern elastomers are stabilized, some may eventually succumb to ozone attack should its concentration become high enough.

One of the major practical effects to reduce corona activity on composite insulators is to reduce the hydrophobicity of the insulator surface.

Corona also produces acids, both organic (oxalic) and inorganic (nitric) in the presence of moisture (eg from ambient humidity, dew, fog or water on the surface). Depending on their concentration (pH), this can also locally degrade polymers.

Corona can even drill holes in material, suggesting that degradation is not solely due to chemical attack by ozone. For example, researchers have calculated the temperature at the tip of the discharge and shown it to be high enough to cause “evaporation” of even inorganic materials such as mica. Of course, this requires repeated bombardment in always the same location. analogous to water torture. There is also the suggestion of mechanical attack, much like sandblasting, due to the impact of repeated discharges on a material.

Most of the light produced by corona has a wavelength shorter than 400nm and therefore falls in the UV range. By contrast, most solar radiation is in the visible range (400-700nm), the shorter wavelengths being filtered by the earth’s ozone layer. In fact, some peaks in the UV region of the of the corona spectrum match or exceed those in the solar spectrum.

In fact, it's amazing that any single physical phenomenon can be the trigger of so many modes of degradation-all at once.

For all practical purposes one cannot see or hear corona (at least not without specialized equipment. Since degradation is initiated at the molecular level, inorganic dielectrics with strong chemical bonds —.such as porcelain or glass — have a higher resistance to it than do polymers. But this fact should definitely not lead to the conclusion that corona will always limit the service life of composite insulators on HV transmission lines. That's because corona can be mitigated or even completely eliminated by good insulator design and manufacturing. But it's also important to realize that if there is sustained corona on the housing, the life of such insulators will be limited.

Methods to Reduce Corona Discharge Effect

Corona can be avoided

- **By minimizing the voltage stress and electric field gradient.:** This is accomplished by using utilizing good high voltage design practices, i.e., maximizing the distance between conductors that have large voltage differentials, using conductors with large radii, and avoiding parts that have sharp points or sharp edges.
- **Surface Treatments:** Corona inception voltage can sometimes be increased by using a surface treatment, such as a semiconductor layer, high voltage putty or corona dope.
- **Homogenous Insulators:** Use a good, homogeneous insulator. Void free solids, such as properly prepared silicone and epoxy potting materials work well.
- **If you are limited to using air as your insulator,** then you are left with geometry as the critical parameter. Finally, ensure that steps are taken to reduce or eliminate unwanted voltage transients, which can cause corona to start.
- **Using Bundled Conductors:** on our 345 kV lines, we have installed multiple conductors per phase. This is a common way of increasing the effective diameter of the conductor, which in turn results in less resistance, which in turn reduces losses.
- **Elimination of sharp points:** electric charges tend to form on sharp points; therefore when practicable we strive to eliminate sharp points on transmission line components.
- **Using Corona rings:** On certain new 345 kV structures, we are now installing corona rings. These rings have smooth round surfaces which are designed to distribute charge across a wider area, thereby reducing the electric field and the resulting corona discharges.
- **Weather:** Corona phenomena much worse in foul weather, high altitude
- **New Conductor:** New conductors can lead to poor corona performance for a while.
- **By increasing the spacing between the conductors:** Corona Discharge Effect can be reduced by increasing the clearance spacing between the phases of the transmission lines. However increase in the

phase's results in heavier metal supports. Cost and Space requirement increases.

- **By increasing the diameter of the conductor:** Diameter of the conductor can be increased to reduce the corona discharge effect. By using hollow conductors corona discharge effect can be improved.

Corona Detection

- Light Ultraviolet radiation: Corona can be visible in the form of light, typically a purple glow, as corona generally consists of micro arcs. Darkening the environment can help to visualize the corona. **Daylight Corona cameras with solar blinds tuned to the UVc band width are the most effective tools for identifying and grading corona activity and can be used at extensive distances.**
- Sound (hissing, or cracking as caused by explosive gas expansions): You can often hear corona hissing or cracking Sound. Ultrasound devices can be used to identify corona on short distances.
- In addition, you can sometimes smell the presence of ozone that was produced by the corona.
- Salts, sometimes seen as white powder deposits on Conductor.
- Mechanical erosion of surfaces by ion bombardment
- Heat (although generally very little, and primarily in the insulator)
- Carbon deposits, thereby creating a path for severe arcing

Conclusion

Corona is exhibited at areas of high potential stress on high voltage equipment. Corona activity is deleterious in that it causes electrical losses; generates noise, generates RFI, TVI, and communication interference and also produces corrosive effluents which degrade the structure of HV components and cause them to fail. Corona can be mitigated by the use of effective design policies. Corona can be effectively identified and quantified from long distances by the use of highly effective daylight corona cameras with solar blinds tuned to the UVc light bandwidth. The use of corona cameras enables utilities to identify areas of high activity and to take corrective action on their networks ahead of failures.

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