Physics of Corona
AC vs DC

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Introduction

- Electrical Design, Operation, & Maintenance of High Voltage AC & DC Transmission Lines requires consideration of:
  
  - Air Insulation
  - Corona
  - Insulators

- All three aspects require knowledge of electrical discharges in air, which may comprise:
  
  - Partial Breakdown (Corona)
  - Complete Breakdown (Gap Discharges)
Corona & Gap Discharges

- **Corona** is an electrical discharge (i.e. partial breakdown of air insulation) occurring in the high electric field region, generally in the vicinity of conducting surfaces, but sometimes also near insulating surfaces, due to ionization processes in the air.

- Complete electrical breakdown of air insulation between two electrodes separated by a very small gap is known as a micro-gap discharge or simply known as **Gap Discharge**.
Basic Ionization Processes

- Classical Bohr’s Model of Atom
- Ionization and Excitation by Electron Impact
- Collision of an electron with an atom can cause excitation or ionization depending on the energy impact.
  - Excitation = electron within the atom moves to higher orbit
  - Ionization = electron separates from atom and moves far away from atom

\[
\begin{align*}
A + e & \rightarrow A^* + e \quad \text{(excitation)} \\
A + e & \rightarrow A^+ + e + e \quad \text{(ionization)}
\end{align*}
\]

- Photo excitation (absorption of light) & Photo ionization - \( h\nu = \text{energy released or absorbed} \)
  - \( h = \text{Planck’s constant}, \nu = \text{frequency of radiation} \)

\[
\begin{align*}
A + \nu & \leftrightarrow A^* \quad \text{(Photo excitation)} \\
A + \nu_1 & \rightarrow A^+ + e + \nu_2 \quad \text{(Photo ionization)}
\end{align*}
\]
Basic Ionization Processes

- Electron Attachment & Detachment
  \[ A + e \rightarrow A^- + hv \] (attachment)
  
  \[ hv = \text{energy released in this process} \]
  
  \[ A^- + hv \rightarrow A + e \] (detachment)

- Recombination
  
  - If negative charged particles are electrons
    \[ A^+ + e \rightarrow A + hv \]

  - If negative charged particles are negative ions
    \[ A^+ + B^- \rightarrow A + B \]
Discharge in Uniform Fields

Field intensified ionization & electron avalanche
Gas Discharge in a Uniform Field Electrode Arrangement

- Discharge development and breakdown
Breakdown and Corona

- Excitation of molecules and photon emission occur simultaneously with ionization

- Secondary ionization processes, due to impact of ions or photons, play a crucial role in **breakdown**

- In non-uniform fields, such as in a Conductor – Plane gap, only partial breakdown or **Corona** occurs.
Negative DC Corona Modes

Space Charges following the completion of the first generation of avalanches
Negative DC Corona Modes

Field Distribution near the Conductor
Modes of Corona in Air – Negative DC Corona

• *Negative DC Corona Modes.*
Se crea una carga espacial que cambia la distribución de campo.

- Trichel Pulse
- Negative Glow
- Negative streamer

Depende se los constituyentes ($N_2$, $O_2$), generación de fotones, carga espacial.
Modes of Corona in Air: Visual Appearance of Negative DC Corona Modes

- Trichel pulse
- Glow
- Streamer
Positive DC Corona Modes – Avalanche Development near Conductor
Modes of Corona in the Air – Positive DC Corona

- **Positive DC Corona Modes:**
  - Onset Streamer (el más importante)
  - Positive Glow
  - Breakdown Streamer

Fig. 5 Development of an electron avalanche toward the anode
Modes of Corona in Air: Visual appearance of Positive DC Modes

Onset streamer

Glow
Modes of Corona in Air – AC Modes
Gap Discharges in Air

Gap discharges may occur:

- Between metallic hardware parts of transmission and distribution lines
- Between metallic and insulating surfaces
- On the surface of polluted insulators
Light Emission from Discharges

- Excitation: $A + e \rightarrow A^* + e$
- Photo Emission: $A^* \rightarrow A + hv$
  
  with $hv = E_2 - E_1$

Where $E_2$ - Energy of the excited state & $E_1$ – Energy of the ground state to which the molecule returns

- Light spectrum emitted in air is mainly that of molecular nitrogen
- Excitation potentials of $N_2 = 6.3$ eV, and of $O_2 = 7.9$ eV
Diagram of the Electronic and Vibrational Energy Levels of the Nitrogen Molecule

Distinctos tipos de fotón según el salto de energía
Light Emission from Discharges

- The frequency band of light emitted is in the UV range, with the stronger emissions having wavelengths in the range of 300 nm to 500 nm and the weaker emissions in the range of 80 nm to 200 nm.

- The excitation coefficient (i.e. number of molecules excited by an electron drifting 1 cm in the field direction) depends on the composition of the air and is a function of E/p.

- Presence of any trace gases such as argon, carbon dioxide, etc., can change the light spectrum emitted by discharges in air.

- Spectroscopic data in air suggest that sparks (breakdown) produce more intense light than streamers (corona).
Photo Absorption

- Photons developed during avalanche development in air are absorbed:
  
  (a) Partly by other gas molecules
  
  (b) Partly by negative oxygen molecules in the gas leading to photo-detachment
  
  \[ O_2^- + hv \rightarrow O_2 + e \]

- Other mechanisms leading to loss of photons are:
  
  - Photoionization, stepionization, dissociation, and dissociative ionization

- Overall photoabsorption may be characterized by I
  
  \[ I = I_0 e^{-\mu X} \]

  where \( \mu \) is the absorption coefficient.

  Typical values of \( \mu \) at atmospheric pressure are:
  
  - For \( N_2 \), \( \mu = 0.3 \text{ cm}^{-1} \),
  - \( O_2 \), \( \mu = 30 \text{ cm}^{-1} \),
  - Air, \( \mu = 5 \text{ cm}^{-1} \)

  The presence of moisture in air reduces \( \mu \) by about 25%.
Radiation from a Corona Discharge

Corona discharge emission in air (210–500 nm).
Radiation from Sun
Corona Onset Gradient (en kV pico / cm)

\[ E_c = m E_0 \delta \left( 1 + \frac{K}{\sqrt{\delta r_c}} \right) \]

- \( E_0 \) and \( K \) are empirical constants (for positive dc, \( E_0=33.7 \) & \( K=0.24 \), for negative dc & ac, \( E_0 =30.0 \) kV/cm & \( K = 0.30 \))
- \( \delta = (273+t_0).p/(273+t)p_0 \) is the relative air density; \( t \) is the temperature and \( p \) the pressure of ambient air and \( t_0 \) and \( p_0 \) are reference values; (\( t_0 = 25^\circ \text{C} \) and \( p_0 = 760 \text{ mm} \))
- \( r_c \) is the conductor radius in cm
- \( m \) conductor surface irregularity factor, depende de la
Corona Effects on AC and DC Transmission Lines

- For both AC and DC Lines:
  - Corona (power) Loss (CL)
  - Electromagnetic Interference (EMI) – includes RI (Radio Interference), TVI (Television Interference), etc.
  - Audible Noise (AN)
  - Ozone, NO\textsubscript{x}, etc.

- For DC Lines
  - Space charge effects
AC Space Charges and Corona Loss

I\textsubscript{corona} es capacitiva, por desplazamiento de la carga espacial.
Main Types of DC Transmission

Unipolar Lines

Bipolar Lines
Physical Description of Unipolar Corona

- Unipolar ions created near the conductor drift towards the ground, filling the entire space
Physical Description of Bipolar Corona

- Ions of both polarities fill the space, creating two unipolar regions and a bipolar region
Generation of RI (Radio Interference)

- Corona current pulse trains are injected into conductors.
- The high-frequency current components propagate along the conductors and produce RI near the transmission line.
Corona and Gap Discharge Current Pulse Characteristics

- Both positive and negative corona, as well as gap discharge, current pulses have a fast-rising front (1 to 50 ns) and a slowly decaying tail (50 to 200 ns) as shown.
## Corona Current Pulse Characteristics

<table>
<thead>
<tr>
<th>Type of Pulse</th>
<th>Amplitude (mA)</th>
<th>Rise-time (ns)</th>
<th>Duration (ns)</th>
<th>Repetition Rate (pulses/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Corona</td>
<td>10 – 50</td>
<td>50</td>
<td>250</td>
<td>$10^3 - 5.10^3$</td>
</tr>
<tr>
<td>Negative Corona</td>
<td>1 – 10</td>
<td>10</td>
<td>100</td>
<td>$10^4 - 10^5$</td>
</tr>
<tr>
<td>Gap Discharge</td>
<td>500 - 2000</td>
<td>1</td>
<td>5</td>
<td>$10^2 - 5.10^3$</td>
</tr>
</tbody>
</table>
Corona Current Pulse Characteristics

- Frequency Spectra of Corona and Gap Discharge Pulses
RI (Radio Interference) Characteristics of AC Lines

- RI from transmission lines is generally defined in terms of three characteristics:

1. Frequency Spectrum

![Graph showing RI characteristics vs frequency](image)
2. Lateral Profile (proporcional a 1/D)
3. Statistical Distribution

![Graph showing RI (Radio Interference) characteristics of AC Lines](image.png)
RI (Radio Interference) Characteristics of DC Lines

Lateral Profile

El positivo contribuye mucho más a la radiointerferencia.
Producida por las descargas tipo streamer.
RI (Radio Interference) Characteristics of DC Lines

Statistical Distribution

![Graph showing statistical distribution of RI (Radio Interference) characteristics of DC lines. The x-axis represents RI (dB (μV/m) QP) ranging from 20 to 65, and the y-axis represents the percentage time above the abscissa ranging from 0.5 to 99.9%.]
Audible Noise Generation and Propagation

Generated Corona Acoustic Pulse

• AN Propagation
AN (Audible Noise) Characteristics of AC Lines

- Audible noise from AC lines is described, similar to RI, in terms of frequency spectrum (figure below), lateral profile and statistical distribution.
Corona-generated Hum noise

- Oscillatory movement of the ionic space charge creates hum noise at twice power frequency; Figure shows lateral profile of hum noise
AN (Audible Noise) Characteristics of DC Lines

- Lateral profile & Statistical distribution are similar to those for RI;
- Frequency spectrum is given below
DC Electric Field and Space Charge Profiles
Corona Effects Design Criteria

- Corona Loss

- Economic Choice of Conductor Bundle
Corona Effects Design Criteria (at 1 MHz)

- **Radio Interference**

**USA**
RI from power systems is governed by the FCC Rules

**Canada**
Design Limits

<table>
<thead>
<tr>
<th>Nominal Phase-to-Phase Voltage (kV)</th>
<th>Interference Field Strength (dB above 1 µV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 70</td>
<td>43</td>
</tr>
<tr>
<td>70 – 200</td>
<td>49</td>
</tr>
<tr>
<td>200 – 300</td>
<td>53</td>
</tr>
<tr>
<td>300 – 400</td>
<td>56</td>
</tr>
<tr>
<td>400 – 600</td>
<td>60</td>
</tr>
<tr>
<td>Above 600</td>
<td>63</td>
</tr>
</tbody>
</table>
Corona Effects Design Criteria

- **Audible Noise**

  **USA**

  - The Environmental Protection Agency (EPA) published guidelines for AN in general.
  - However, each state is responsible to legislate noise regulations and these regulations may vary widely from state to state.
  - The EPA document recommends that the day-night average sound level, Ldn, be limited to 55 dB(A) outdoors and 45 dB(A) indoors.
DC Fields and Ions Design Criteria

- Design criteria for electric fields and ion currents under DC lines are established on the basis of human perception studies.
- Based on such studies, the following design limits have been proposed:
  \[ E = 25 \text{ kV/m} \text{ (en ca 10 kV/m)} \]
  \[ j = 100 \text{ nA/m}^2 \text{ (corriente iónica)} \]
### Similarities and Differences between HVDC and HVAC from Live Work Perspective

<table>
<thead>
<tr>
<th>Item</th>
<th>Difference</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overvoltages</td>
<td>Much lower on HVDC than on HVAC:</td>
<td>Required MAD can be smaller for HVDC than for HVAC – however, must</td>
</tr>
<tr>
<td></td>
<td>HVDC about 1.8 pu</td>
<td>consider HVDC corona</td>
</tr>
<tr>
<td></td>
<td>HVAC up to 3 pu (or higher in some cases)</td>
<td></td>
</tr>
<tr>
<td>Space charge</td>
<td>HVAC: confined to vicinity of conductors</td>
<td>Does this affect MAD?</td>
</tr>
<tr>
<td></td>
<td>HVDC: drifts away from conductors and fills the space</td>
<td>Performance of tools?</td>
</tr>
<tr>
<td>Electric field</td>
<td>HVDC electric field depends on space charge. HVAC field is not affected</td>
<td>Does this affect MAD?</td>
</tr>
<tr>
<td></td>
<td>much by space charge. HVDC field is not affected much by space charge.</td>
<td>Performance of tools?</td>
</tr>
<tr>
<td></td>
<td>HVDC field is reduced near conductors due to space charge, is enhanced</td>
<td></td>
</tr>
<tr>
<td></td>
<td>near ground and tower</td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Field of HVDC lines is static (does not vary with time).</td>
<td>No significant effects.</td>
</tr>
<tr>
<td>Induction - voltage</td>
<td>Field of HVDC lines is static (does not vary with time), i.e., no induced</td>
<td>Does this affect MAD?</td>
</tr>
<tr>
<td></td>
<td>voltages. However, HVDC electric field depends on space charge.</td>
<td>Performance of tools? For example, metallic parts (endfittings, studs)?</td>
</tr>
<tr>
<td>Induction – current</td>
<td>Field of HVDC lines is static (does not vary with time), i.e., no induced</td>
<td></td>
</tr>
<tr>
<td></td>
<td>current.</td>
<td></td>
</tr>
<tr>
<td>Step, touch and transferred</td>
<td>Fault currents are typically smaller on HVDC lines.</td>
<td>No issues have been reported to date during DC LW.</td>
</tr>
<tr>
<td>potentials (system faults)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opening switches</td>
<td>No natural current zero crossing on HVDC lines. Current must be forces to</td>
<td>Considerably larger gap needed to break the arc.</td>
</tr>
<tr>
<td></td>
<td>zero.</td>
<td></td>
</tr>
</tbody>
</table>
Together…Shaping the Future of Electricity