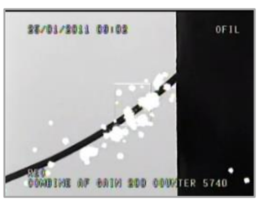
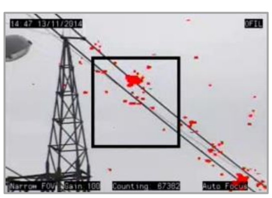
Corona on Conductors

Due to their function, conductors are considered to be the most important components of overhead lines. Construction cost of a new overhead line, material and installation, can mount 40% of the total capital costs of the line. The choices of overhead lines depends upon power delivery requirements, line design requirements and environmental considerations. Delivering power is limited by the current carrying capacity, which in turn is affected by electrical resistive and corona losses. Line design considers the distances to be spanned and the corresponding type of conductors, sag and clearance. Power losses, resistive and corona, account for the bulk revenue losses of the transmission system. Corona plays a major role in the life cycle of electrical elements in general and of conductors in particular, both as an indicator of electrical and mechanical faults and as an active reagent. Therefore, when designing overhead lines it is necessary to take into consideration the electrical field effect (EMF) which is the prerequisite for corona to develop, and when maintaining lines it is mandatory to use corona cameras that can see those discharges.

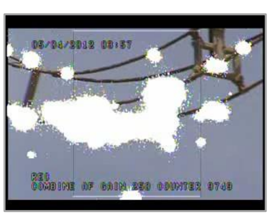
Corona



Corona discharge is an electrical partial discharge phenomenon that takes place in air on the surface of an energized conductors resulting from intense localized ionization of air. Corona occurs when the electric field around a conductor is high enough to form a conductive region, but not high enough to cause a complete electrical breakdown to nearby objects. Corona discharge is usually formed in irregular surfaces, highly curved regions, small diameter wires, sharp corners, projecting points, or in edges of metal surfaces etc. Corona can generate audible noise and radio-frequency interference and is undesirable to human health. The amount of heat dissipated by corona is negligible.

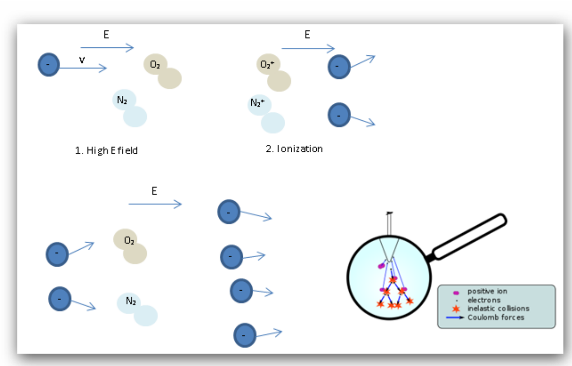


The formation of corona is always accompanied with losses. Energy Loss, incurred by corona, affects the transmission efficiency of the line. Material loss caused by Ozone, a violent corrosive agent a byproduct of corona, compromises the mechanical and electrical properties of conductors. The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal voltage drop occurs in the line which may cause inductive interference with neighboring communication lines.



With the growth in power demand and consequently the rise in voltage levels, corona gets greater attention both from conductors' manufacturers and electrical utilities. Basically, the critical economic factors involved ask for much attention and careful selection of conductors' configuration to meet the present and predicted future load requirements.

E-Field – Air Ionization - Corona



Under normal conditions the air around conductors contains ionized particles (free electrons & positively charged ions) and neutral molecules maintaining some kind of equilibrium. But, when higher voltages are applied a potential gradient builds up in the air around the conductor that induces intense ionization. The intensity of the electrostatic field around a conductor is non-uniform: it has its maximum strength at the surface of the conductor. As the voltage level in the conductor is raised and a critical field strength approaches about 30kV per cm initial discharges occur but only at, or very near, the conductor surface. If the voltage is further increased flashover is imminent. In the growing electrical field free electrons move rapidly to and fro the conductor by the alternating electric field gaining enough kinetic energy to extract more electrons and ions from neutral molecules they collide with. The energy used for extracting electrons is then dissipated as UV photons when the electrons and ions are attracted to each other and recombine to create back a neutral molecule. This process of ionization/recombination is cumulative resulting in either corona or sparks created between the conductors.

Factors Affecting Corona on Conductors

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line.

1. **Atmosphere:** Since corona is formed by ionization of air molecules the physical state of the atmosphere affects corona inception: pressure, temperature, humidity etc., that affect the density of electrons.

   In order for corona to appear the potential gradient value on the conductor must be equal to the breakdown strength of air. The breakdown strength of air at 76cm of mercury and 25^0 is about 30 kV/cm (max) or 21.2 kV/cm (r.m.s). This value is directly proportional to air density, and when the air density changes the critical breakdown voltage of air changes accordingly.

$$V_c = g_0\, \delta r \ln \frac{d}{r}$$

   Under standard condition the value of air density factor δ =1 or else $\delta = \frac{3.92b}{273+t}$

   b = barometric pressure

   t = temperature

   g_0 = breakdown strength of air kV/cm

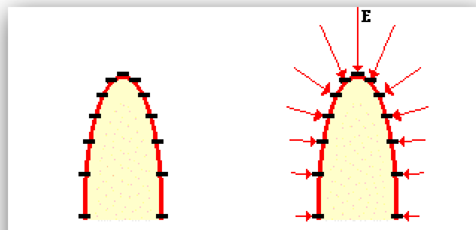
r = radii of a conductor

d= space between 2 conductors, cm

V_c= critical disruptive voltage

δ = air density factor

Indeed, at higher altitudes where the air density is lower corona inception voltage is lower and hence the concern when designing UHV lines on very tall poles. DayCor® cameras demonstrate vividly the occurrences of intensive corona on transmission lines that run in elevated areas.



Charge tends to accumulate in greater numbers at locations of greatest curvature. The electric field strength at these locations of greatest curvature is larger in magnitude.

2. **Conductor size and shape:** The size and weight of electrical equipment has drastically reduced over the years, requiring smaller high voltage interconnections in such professional equipment and devices. The inevitable consequence of conductor diameter reduction is the formation of corona. The reduced life of insulating materials under corona imposes limitations on miniaturization and on the choice of materials. Conventional HV cables of large sizes, when bent sharply, are even more prone to corona stress (at bend points) and to early failure. Corona depends on the electrical field size and uniformity. If the field is non-uniform, an increase in voltage will first cause a discharge in the air at points with highest electric field intensity: bending and sharp and protruding points.

Unevenness of the conductor's surface decreases the value of breakdown voltage. Thus stranded conductors with irregular surfaces give rise to more corona than solid conductors. Yet, all conductors used for overhead lines are preferable stranded in order to increase flexibility. If m_o represents a factor of surface condition, V_c – the critical breakdown voltage of air is expressed by:

$$V_c = m_0 g_0 \, \delta r \ln \frac{d}{r}$$

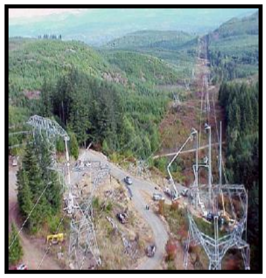
m_0 = 1 for polished conductors

m_0 = 0.98-0.92 for dirty conductors

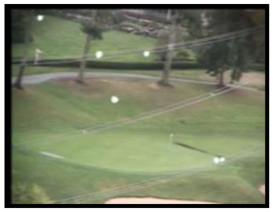
m_0 = 0.87- 0.8 for stranded conductors

Case study: *The SnoKing Tap Project/BPA WA, USA*

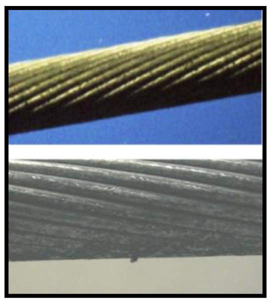
Background: In 2001 BPA initiated the SnoKing project in northwest Washington was aimed to improve the reliability of an existing 13-miles



long transmission system that was built in the 70s. Originally this line was designed and built for 500-kV but practically it operated at 230-kV. The mission was accomplished in September 2003 and the line started operating at 500kV. Shortly after the SnoKing line regained its



operation BPA started receiving complaints about unbearable noise. In response BPA initiated an investigation encompassing both the transmission line and the feeding substation. Investigation included noise measurements



along the transmission line in various weather condition, close-range tower and equipment inspections, helicopter corona inspections, EMF testing.

Research showed a high level of corona activity on the conductors. Close range photos showed a film of algae on the conductor. The algae managed to survive during 30 years at the lower voltage covering the conductors evenly. But as the voltage was raised to 500kV the high temperature of the line dried the algae leaving spikes at the bottom of the conductors. These spikes were identified as sources of corona noise, especially during mildly damp conditions.

The line was then cleaned using special mechanical brushes that were designed and built by BPA.

Dirt on conductors does not in itself change drastically the breakdown critical voltage (m_0 = 0.98-0.92 for dirty conductors), however if dirt is deposited unevenly on the surface of the conductor it will affect the regularity of the e-field

and leads to corona emission. In contaminated areas rain drops that accumulate on the lower side of conductors dry out due the conductor's heat leaving residues of dirt/salt, as seen in the pictures taken by DayCor camera.

While speaking of conductors' shapes and types it is necessary to mention the appearance of broken strands. A broken strand, for that matter violates the electrical field uniformity and becomes an irregular shape emitting strong corona. Broken strands can result from mishandling during storage and installation but often they result from Aeolian vibrations.

Aeolian vibrations are common occurrences in transmission lines and are triggered by smooth winds of 5-15 mph that blow across conductors' surface. The resulting standing vibrations are typically with frequencies of 10 to 50 Hz and amplitudes less than the diameter of the conductors. The severity and duration of Aeolian vibrations relate to conductors' tension, terrain and prevailing wind direction (high tension with open terrain and winds perpendicular to the line being the worst).

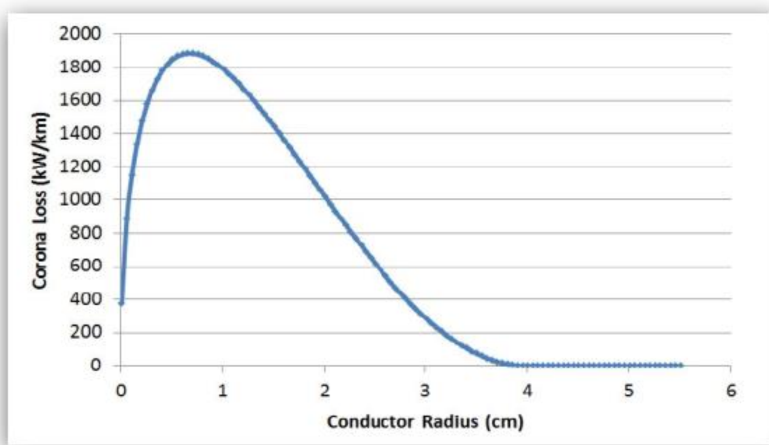
The Aeolian vibration activity in a span creates dynamic bending stresses on the conductor, at the structure support hardware, at each end of the span, and at the dampers, spacers or spacer dampers within the span. When the vibration activity and the associated bending stresses are severe enough, the aluminum strands of a conductor will crack and then break (fatigue failure) at some point in time. Aeolian vibrations are not uniform throughout a year, hence in winter time and cold weather the tension of wires increases resulting in stronger vibrations, while during summer the tension decreases. The number of bending cycles required to produce a crack is directly related to how much the actual bending stresses exceed the endurance limit of the aluminum material in the stranded wires. The weakening associated with bending stresses above the endurance limit is cumulative and typically after a number of years, cracking and breaking of conductor strands begin to appear.

3. **Spacing between conductors** – A large distance between conductors reduces electrostatic stress and reduces corona. If the spacing between conductors is made very large as compared to their diameters, there may not be any corona effect.

4. **Line voltage** - The line voltage greatly affects corona. At low voltages the air surrounding the conductors undergoes no change and hence no corona is formed. However, if the line voltage reaches a value that creates electrostatic stress on the conductor surface the air around the conductor conducts and corona is formed.

5. **Conductor radius** - The impact of conductors' radius on corona onset and power loss was investigated at Fuat Kulunk High Voltage laboratory of Istanbul Technical University. The study investigated corona onset voltages and corona losses for several different conductor sizes in an indoor corona cage under DC and AC voltages. The results obtained from the experiments are presented. According the researchers their results match those of other studies, as listed in the published paper .

   When plotting Peek's (see below) equation for power loss for conductors' radius the following graph is obtained, showing clearly the effect of a small diameter on losses.



Plotting corona loss in kilowatts lost per kilometer of wire as a function of radius

Fuat Kulunk' results:

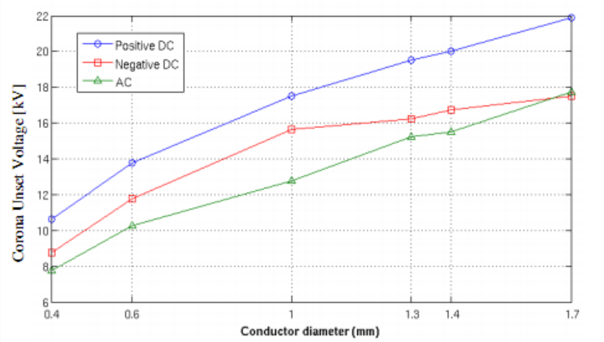


Fig. 4 Effect of conductor diameter on corona onset voltage

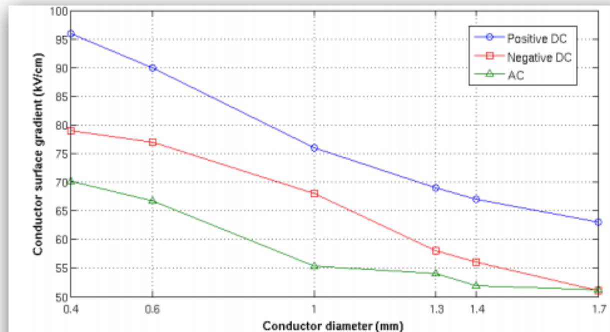


Fig. 5 Effect of conductor diameter on corona onset gradient

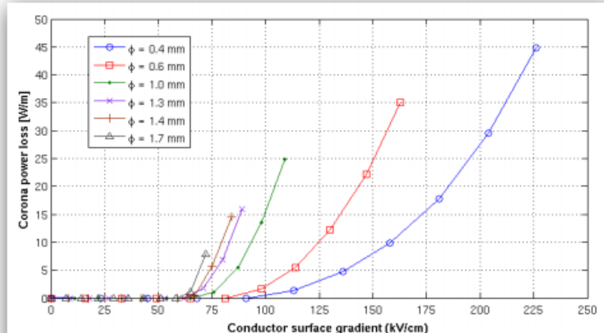


Fig. 6 Effect of conductor gradient on corona losses: positive DC

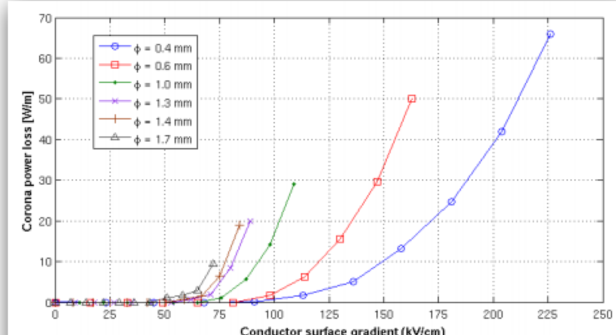


Fig. 7 Effect of conductor gradient on corona losses: negative DC

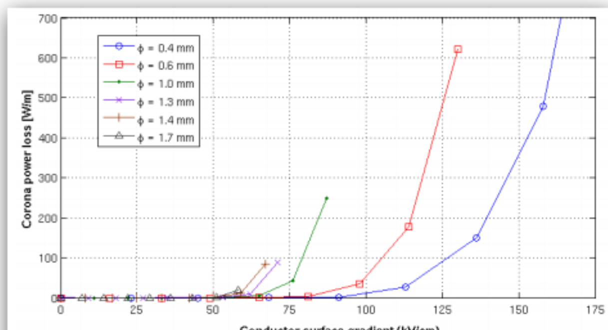


Fig. 8 Effect of conductor gradient on corona losses: AC

Conclusions:

1. Corona onset voltage increases with an increasing conductor diameter
2. Corona onset gradient decreases with an increasing conductor diameter
3. Corona onset voltages for positive DC excitation are the highest while they are the lowest for AC excitations

4. Corona losses increase with an increasing conductor surface gradients for all types of voltages. AC corona losses are significantly higher when compared with DC losses and losses for negative DC are higher than those for positive DC

Power Loss Due to Corona

Formation of corona is always accompanied by energy loss. Corona loss only occurs when the line to line voltage exceeds the corona threshold. Unlike resistive loss where the amount of power lost is a fixed percentage of input, the percentage of power lost due to corona discharges is a function of the signal's voltage and is highly dependent on ambient weather and temperature conditions.

To calculate power losses incurred by corona on AC systems several empirical formulas have been suggested, Peek's formula is one of them:

$$p \; = 241 \times 10^5 \left(\frac{f + 25}{\delta}\right) \sqrt{\frac{r(v - v_c)^2}{d}} \; kW/km$$

f = supplied frequency (Hz)
δ = the air density correction factor
v = operating voltage kV
v_c = critical breakdown voltage (r.m.s) per phase kV
r = radius of the conductors m'
d = spacing (or equivalency spacing) between conductors m'

More about corona losses will be discussed in our next issues. Additional papers on corona losses can be found in Ofil's website www.ofilsystems.com

Finally, in a study about conductor optimization for overhead lines by Dipeen Dama, Dzevad Muftic and Riaz Vajeth lists 16 procedures that were tested aiming to optimize the selection of conductors and tower configuration. The steps evaluate the different possible configurations from a line life cycle costing point of view. The listed steps are as follows:

1: Obtain the Planning Requirements such as the line length, voltage and expected reliability levels of the new overhead power line.

2: Determine the field effect (EMF) and corona limits (radio interference and audible noise) for the conductor and tower configurations that can meet the above planning requirements.

3: Ascertain any design limitations from an environmental perspective

4: Select a combination of options, each with a suitable conductor bundle and tower type, based on the line loading and corona and field effect limits, and thereafter estimate the capital investment cost (CIC) for each option.

5: Calculate the electrical line parameters

6: Based on the loading forecast perform line life cycle costing analysis

7: Select the most suitable conductors and tower option

8: Perform unbalance studies to determine the need for phase transposition or phase optimization for parallel lines

9: Calculate cost of system losses for each option for the entire life cycle of the line.

10: Determine the thermal limits (short lines)

11: Calculate the impact on fault levels for the various options.

12: Aim at extending the power transfer margin and evaluate the SIL - Surge impedance loading

13: Evaluate operating and maintenance costs

14: Consider the need for high reliability

15: Consider the need for flexibility in terms of ease to uprate in the future and the cost and outage times for such uprating.

16: Incorporate all the factors into an index to determine the optimum option, based on the cost/benefit or weighting of each factor.

The design phase of electrical system ends with its construction. The life time of the overhead lines is affected by the design but more so by maintenance. Ofil's mission, as a manufacturer of testing equipment, is to assist unities maintain their ongoing profitable operation and ensures reliable supply of electricity to consumers. Ofil's corona cameras are used worldwide for early detection of faults and losses incurred by corona. Ofil keeps on developing and improving its products and the ability to pinpoint corona.

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