Lecture # 6

Corona

The term corona originally belongs to the field of astronomy and is the rarefied gaseous envelope of the sun and other stars. In electrical engineering corona is ionization of medium due to concentrated localized electric field in the vicinity of high voltage conductor and is a characteristic of non-uniform electric field. Thus corona can be defined as a localized partial breakdown of the medium surrounding the highly stressed points when the electric stress exceeds a critical value called disruptive critical gradient (which is 21.1kV/cm RMS for air at STP) and the voltage at which this occurs is called disruptive critical voltage or corona inception voltage. Corona is seen as a localized faint glow in medium such as air around the high voltage surface. Corona manifests (marks its appearance) itself in the form of:

1. Audible noise
2. Visual appearance
3. Irritating smell of ozone as a by-product of corona

Corona is a pre-breakdown phenomenon and has the capability for degrading insulators, and causing systems to fail. Thus corona can be regarded as an early warning signal for some catastrophic electrical discharge event. Corona can also occur naturally at tall pointed objects (such as minarets, treetops, cellular phone towers and ship masts) during thunderstorms due to charge concentration on the tip of these objects.

Characteristics of Corona

Corona is partial localized breakdown of air when the field exceeds a critical value. The audible noise produced by corona may be due to the violent activity of ionization, more likely due to the movement of positive ions as they are suddenly formed in an intense electric field region. The visual glow produced is probably due to the recombination of positive nitrogen ions with free electrons in the vicinity of high stress regions. Corona is also accompanied by the production of ozone, due to splitting of diatomic oxygen molecules, which then recombine to form ozone (O_3). Ozone can be detected due to its pungent and irritating smell to which sensitive tissues of nasal track may react, resulting in sneezing.

Corona discharge usually forms at sharp regions on electrodes, such as corners, projecting points, edges of metal surfaces, or small diameter wires. The sharp curvature causes a high potential gradient at these locations, so that the air breaks down and forms plasma. In practice if a charged object such as current carrying conductor of a transmission line has a sharp point, such as a broken strand, the air around that point will be at a much higher gradient than elsewhere around the conductor. In order to suppress corona formation, terminals on high-voltage equipment are frequently designed with smooth large diameter having more rounded shapes. Corona is also accompanied with localized high temperatures that may result in hotspots at these sites. Corona discharge in power system and high-voltage equipments generally causes the following undesirable effects:

1. Power loss
2. Audible noise
3. Electromagnetic interference (radio interference)
4. Local heating or hot-spots
5. Ozone production
6. Insulation degradation

Corona in Overhead Transmission Lines

Overhead transmission lines are exposed to open environment, it is much prone to corona effects under normal and abnormal voltage stresses in fair and foul weather (rain snow, windy) conditions. The mathematical relationship between corona inception voltage and various factors governing corona can be derived by considering a system of two conductors with equal surface charge distribution in magnitude, each having the same radius *r* and are separated by a center to center distance *D* as shown in Fig (1). Consider that each conductor has surface charge of magnitude *q* and is uniformly distributed all along its length.

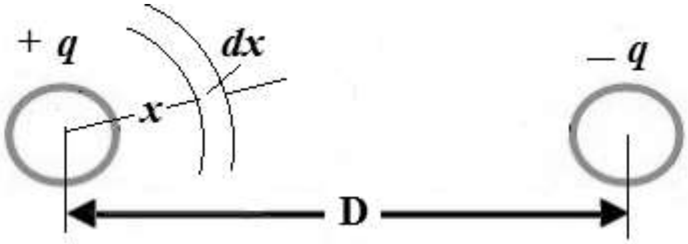

Figure 1: Two-wire Line

The electrostatic flux density at a radial distance *x* from the center of conductor with surface charge +*q*, considering per unit length is:

$$D(x) = \frac{q}{2\pi x}$$

The electric field at this distance *x* is then:

$$E(x) = \frac{q}{2\pi\varepsilon_0 x}$$

The potential difference is then: $V = \int E dx$

$$V = \int_r^D \frac{q}{2\pi\varepsilon_0 x} dx = \frac{q}{2\pi\varepsilon_0} \ln\left(\frac{D}{r}\right)$$

$$V = \frac{q}{2\pi\varepsilon_0}\ln\left(\frac{D}{r}\right) \qquad 1$$

If we divide and multiply the right-hand side of the above expression and then make use of the expression of electric field we have:

$$V = E(x)x\ln\left(\frac{D}{r}\right)$$

The electric field will have a maximum value at the surface of conductor, and is the region from where corona initiates. Thus the disruptive critical gradient is E_0 where $x = r$, so that:

$$E_0 = \frac{V_0}{r\ln(D/r)}$$

Or

$$V_0 = E_0 r\ln\left(\frac{D}{r}\right) \qquad 2$$

Where V_0 is measured in kV and is the corona inception voltage or disruptive critical voltage for the start of audible corona. Since corona is initiated when the electric field in the medium surrounding the conductor exceeds 21.1kV/cm (RMS), which cause the surrounding air to ionize at STP, then Eq (2) can be expressed as:

$$V_0 = 21.1r\ln\left(\frac{D}{r}\right) \qquad 3$$

A correction factor is necessary to extend the above expression to be applicable for corona voltage calculations at conditions other than STP. A correction factor to account for environment factors is introduced; called air density correction factor δ is included in Eq (3) to extend its use for other ambient conditions that is:

$$V_0 = 21.1r\delta\ln\left(\frac{D}{r}\right) \qquad 4$$

Where:

$$\delta = \frac{3.92p}{t+273} \qquad 5$$

Where p is the atmospheric pressure in cm-Hg and t is the temperature in degree Celsius. In addition, the expression can be further modified to account for conductor surface characteristics by incorporating a factor m, referred to as conductor surface irregularity factor, whose maximum value for smooth cylindrical conductor surface is unity and between 0.9 and 0.98 for weathered solid cylindrical conductors. Eq (4) is thus further modified as:

$$V_0 = 21.1 r\delta m \ln\left(\frac{D}{r}\right) \qquad 6$$

The value of irregularity factor *m* is also dependent on the number of strands of the conductor. For weathered, conductors with 37 strands or more it is better to use m = 0.9 to 0.95 in most numerical problems. Eq (6) is used for calculating the disruptive critical voltage for audible corona. If the voltage is further increased to a value V_v, a transition from audible corona to visual corona will result and Eq (6) is modified as:

$$V_v = 21.1 r\delta m\left(1 + \frac{0.3}{\sqrt{r\delta}}\right)\ln\left(\frac{D}{r}\right) \qquad 7$$

To make it simple, the distance *D* in Eqs (6) and (7) will be the Geometric Mean Distance (GMD). In case for bundle conductor arrangement, the GMR is used instead of *r* in Eqs (6) and (7). Presence of contaminants and pollutants, such as smoke, dust, industrial fumes and brine in coastal areas increase the chances of corona. Fig (2) shows images of corona in high voltage transmission lines.

Figure 2: Images of Corona in High Voltage Transmission Lines

Corona inception voltage is mostly governed by the size of conductor and the distance between conductors. Smaller radius conductors are more vulnerable to corona than conductors with larger radius for the same separation. Usually the corona inception voltage is lower for symmetrical arrangement of conductors compared to horizontal arrangement and is less when bundle conductors are used. Corona inception voltage is different at sea level and at an altitude. This is due to the reduction in atmospheric pressure as the height above the sea level or altitude increases. Table (1) gives the atmospheric pressure with altitude, which is useful in determination of corona inception voltages at different altitudes and at sea level.

Table 1: Barometric Pressures at Different Altitudes

Altitude (feet)	Barometric pressure (cm-Hg)	Altitude (feet)	Barometric pressure (cm-Hg)
Sea level	76.00	6000	60.91
1000	73.30	7000	58.67
2000	70.66	8000	56.44
3000	68.10	10,000	52.27
4000	65.54	15,000	42.88
5000	63.22	20,000	34.93

Example 1: The conductors of a 220kV, 50 Hz, 3-phase, single circuit overhead transmission line are arranged in equilateral triangle fashion with spacing between phase conductors of 3m. If the overall diameter of each conductor is 2.15cm with surface irregularity factor of 0.93 in either case for audible and visual corona, determine the disruptive critical voltage in RMS for audible and visual corona. Assume ambient temperature of 10°C at a normal atmospheric pressure. Determine the corona inception voltage for audible and visual corona for the transmission line.

Solution:

Given that: D = 3m or 300cm, and $r = d / 2 = 1.075$cm

$m = 0.93$

$t = 10°\text{C}$

p = 76 cm of Hg (normal atmospheric pressure)

The air density correction factor is:

$$\delta = \frac{3.92p}{t+273} = \frac{3.92(76)}{10+273} = 1.05$$

For disruptive critical voltage, which sets audible corona, we use:

$$V_0 = 21.1 r\delta m \ln\left(\frac{D}{r}\right)$$

$$V_0 = 21.1\times1.075\times1.05\times0.93\times\ln\left(\frac{300}{1.075}\right) = \mathbf{124.73\ kV\ /\ phase}$$

For disruptive critical voltage for visual corona, we use:

$$V_v = 21.1 r\delta m\left(1+\frac{0.3}{\sqrt{r\delta}}\right)\ln\left(\frac{D}{r}\right)$$

$$V_v = 21.1\times1.075\times1.05\times0.93\times\left(1+\frac{0.3}{\sqrt{1.075\times1.05}}\right)\ln\left(\frac{300}{1.075}\right) = \mathbf{159.66\ kV\ /\ phase}$$

The voltages as calculated above are single-phase quantities; the corresponding 3-phase values are **216.06 kV** for audible corona and **276.53 kV** for visual corona. In this case audible corona will take place.

Example 2: Repeat Example (1) for the case when the conductors are arranged horizontally with adjacent spacing between middle and outer conductors being 3m.

Solution:

The distance between two outer conductors will be 6m and the distance between middle and outer conductors will be 3m. Everything else remains the same as in Example (7.1), except the spacing *D*, in the present case is the GMD between conductors, which is:

$$D = \sqrt[3]{(3\times3\times6)} = 3.73\,\text{m} = 373\text{cm}$$

Using the expressions for audible and visual corona, the voltages determined are as follows:

$$V_0 = 21.1\times1.075\times1.05\times0.93\times\ln\left(\frac{373}{1.075}\right) = \mathbf{129.56\ kV\ /\ phase}$$

And $$V_v = 21.1\times1.075\times1.05\times0.93\times\left(1+\frac{0.3}{\sqrt{1.075\times1.05}}\right)\ln\left(\frac{373}{1.075}\right) = \mathbf{165.83\ kV\ /\ phase}$$

The corresponding 3-phase voltages are 224.39 kV and 287.21 kV for audible and visual corona respectively. It can be seen that when the conductors are arranged horizontally, the corona inception voltage for both audible and visual corona increases, no corona will take place in this case.

Example 3: Compare the magnitude of disruptive critical voltage and visual critical corona voltages for the transmission line in Example 1, if the transmission line is situated at approximate altitude of 7000 feet.

Solution:

The only difference in this case would be the different air density correction factor δ, which is dependent on the atmospheric temperature. The value of atmospheric pressure from Table (7.1) for an altitude of 7000 feet is 58.65 cm-Hg. The air density correction factor given by Eq (7.5) is calculated as:

$$\delta = \frac{3.92p}{t+273} = \frac{3.92\times58.65}{10+273} = 0.812$$

Using this value of δ in the expression for audible corona given in Eq (7.6), we have:

$$V_0 = 21.1\times1.075\times0.812\times0.93\times\ln\left(\frac{300}{1.075}\right) = \mathbf{96.46\ kV}$$

For visual corona, we use Eq (7.7) that is:

$$V_v = 21.1\times1.075\times0.812\times0.93\times\left(1+\frac{0.3}{\sqrt{1.075\times1.05}}\right)\ln\left(\frac{300}{1.075}\right) = \mathbf{123.46\ kV}$$

Comparing the values of the corona inception voltages, it can be seen that there is a reduction in the voltages for both audible and visual corona when the same specification line is situated at high altitude, or when the atmospheric pressure is less. Thus in these examples, for 220kV line, both audible and visual corona will take place when the same line is situated at an altitude of 7000 feet, since the phase voltage for 220kV line is 127.02kV.

Power Loss due to Corona

As mentioned earlier, corona is accompanied by power loss, especially in the transmission line system. Though a small percentage of the total losses generally are accountable for corona, however, their significance is increased under foul weather conditions and in the case of long lines. Two expressions are generally used to determine the power loss due to corona in transmission line system, these are; Peek's formula and Peterson's formula. The Peek formula is:

$$P_C = \frac{241}{\delta}(f+25)\left(\frac{r}{D}\right)^{1/2}(V-V_0)^2 \times 10^{-5} \text{ kW/km/phase} \qquad 8$$

The Peterson's formula (preferably used) for power loss due to corona is:

$$P_C = \frac{1.1106\times 10^{-4}}{\left[\ln(D/r)\right]^2} fV^2F \text{ kW/km/phase} \qquad 9$$

Where f is the frequency, V is the operating voltage in kV, F is the corona factor, whose values are given in Table (2) for different ratios of the voltages V/V_0.

Table 2: Corona Factor (F) for Different Ratios of V/V_0

V/V_0	F	V/V_0	F	V/V_0	F	V/V_0	F
1.00	0.037	1.26	0.120	1.52	1.10	1.78	4.72
1.02	0.039	1.28	0.136	1.54	1.33	1.80	4.95
1.04	0.042	1.30	0.154	1.56	1.59	1.82	5.17
1.06	0.045	1.32	0.176	1.58	1.88	1.84	5.39
1.08	0.048	1.34	0.200	1.60	2.20	1.86	5.60
1.10	0.052	1.36	0.228	1.62	2.52	1.88	5.81
1.12	0.057	1.38	0.260	1.64	2.83	1.90	6.01
1.14	0.063	1.40	0.30	1.66	3.13	1.92	6.21
1.16	0.069	1.42	0.38	1.68	3.42	1.94	6.41
1.18	0.075	1.44	0.48	1.70	3.70	1.96	6.61
1.20	0.082	1.46	0.60	1.72	3.97	1.98	6.81
1.22	0.092	1.48	0.74	1.74	4.23	2.00	7.00
1.24	0.105	1.50	0.90	1.76	4.48	---	---

The validity of Eqs (8) and (9) is only when the corona inception voltages calculated vide Eq (6) is less than the operating phase voltage of the line. It must be remembered that for calculation of wet weather corona, a multiplying factor of 0.8 is used for the determination of corona inception voltages. The transmission line design engineers prefer to use the Peterson's formula.

Example 4: The conductors of a 200km, 400 kV, 50 Hz, 3-phase, single-circuit overhead transmission line are arranged in equilateral triangle fashion with spacing between phase conductors of 5.5 m. If the overall diameter of each conductor is 3cm with surface irregularity factor of 0.97 in either case for audible and visual corona, determine the total power loss due to corona. Assume ambient temperature of 10°C at a normal atmospheric pressure.

Solution:

Given that: D = 5.5m or 550cm, and r = 1.5cm
$m = 0.97$
$t = 10°C$
p = 76 cm of Hg (normal atmospheric pressure)

For disruptive critical voltage, which sets audible corona, we use:

$$V_0 = 21.1 r \delta m \ln\left(\frac{D}{r}\right)$$

$$\delta = \frac{3.92p}{t+273} = \frac{3.92(76)}{10+273} = 1.05$$

Substituting all the required quantities in the above expression for audible corona, we have:

$$V_0 = 21.1 \times 1.5 \times 1.05 \times 0.97 \times \ln\left(\frac{550}{1.5}\right) = 190.33 \text{ kV/phase}$$

From the given data; the transmission line is operated at 400 kV or 230.94 kV per phase. From Table (2), the ratio V/V_0 is therefore 1.2, which gives the corresponding value of corona factor $F = 0.082$. Using:

$$P_C = \frac{1.1106 \times 10^{-4}}{[\ln(D/r)]^2} fV^2F \text{ kW/km/phase}$$

Or

$$P_C = \frac{1.1106 \times 10^{-4}}{[\ln(550/1.5)]^2} \times 50 \times (230.94)^2 \times 0.082 = 0.69 \text{ kW/km/phase}$$

Since the line length is 200 km, the power loss due to corona per phase is:

$$P_C = 0.69 \times 200 = 138 \text{ kW/phase}$$

The total 3-phase power loss due to corona will be:

$$P_C = 3 \times 138 = \mathbf{414\ kW}$$