2. Each line of a 3-phase system is suspended by a string of 3 similar insulators. If the voltage across the line unit is 17·5 kV, calculate the line to neutral voltage and string efficiency. Assume that shunt capacitance between each insulator and earthed metal work of tower to be 1/10th of the capacitance of the insulator. **[52 kV, 86·67%]**
3. The three bus-bar conductors in an outdoor sub-station are supplied by units of post insulators. Each unit consists of a stack of 3-pin insulators fixed one on the top of the other. The voltage across the lowest insulator is 8·45 kV and that across the next is 7·25 kV. Find the bus-bar voltage of the station. **[38·8 kV]**
4. A string of suspension insulators consists of three units. The capacitance between each link pin and earth is one-sixth of the self-capacitance of each unit. If the maximum voltage per unit is not to exceed 35 kV, determine the maximum voltage that the string can withstand. Also calculate the string efficiency. **[84·7 kV; 80·67%]**
5. A string of 4 insulators has self-capacitance equal to 4 times the pin-to-earth capacitance. Calculate (*i*) the voltage distribution across various units as a percentage of total voltage across the string and (*ii*) string efficiency. **[(*i*) 14·5%, 18·1%, 26·2% and 40·9% (*i*) 61·2 %]**
6. A string of four suspension insulators is connected across a 285 kV line. The self-capacitance of each unit is equal to 5 times pin to earth capacitance. Calculate :
   (*i*) the potential difference across each unit, (*ii*) the string efficiency.
   [(*i*) 27·65 kV, 33·04 kV, 43·85 kV, 60 kV (*i*) 68·5%]
7. Each of three insulators forming a string has self-capacitance of "*C*" farad. The shunt capacitance of each cap of insulator is 0·25 C to earth and 0·15 C to line. Calculate the voltage distribution across each insulator as a pecentage of line voltage to earth and the string efficiency. **[31·7%, 29·4%, 38·9%; 85·7%]**
8. Each of the three insulators forming a string has a self capacitance of *C* farad. The shunt capacitance of each insulator is 0·2 C to earth and 0·1 C to line. A guard-ring increases the capacitance of line of the metal work of the lowest insulator to 0·3 C. Calculate the string efficiency of the arrangement :
   (*i*) with the guard ring, (*ii*) without guard ring. **[(*i*) 95% (*ii*) 86·13%]**
9. A three-phase overhead transmission line is being supported by three-disc suspension insulators; the potentials across the first and second insulator from the top are 8 kV and 11 kV respectively. Calcualte (*i*) the line voltage (*ii*) the ratio of capacitance between pin and earth to self capacitance of each unit (*iii*) the string efficiency. **[(*i*) 64·28 V (*ii*) 0·375 (*iii*) 68·28%]**
10. A 3-phase overhead transmission line is supported on 4-disc suspension insulators. The voltage across the second and third discs are 13·2 kV and 18 kV respectively. Calculate the line voltage and mention the nearest standard voltage. **[118·75 kV; 120 kV]**

8.10 Corona

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called *critical disruptive voltage,* the conductors are surrounded by a faint violet glow called corona.

The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. The higher the voltage is raised, the larger and higher the luminous envelope becomes, and greater are the sound, the power loss and the radio noise. If the applied voltage is increased to breakdown value, a flash-over will occur between the conductors due to the breakdown of air insulation.

The phenomenon of violet glow, hissing noise and production of ozone gas in an overhead transmission line is known as **corona.**

If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductors, otherwise the rough points will appear brighter. With d.c. voltage, there is difference in the appearance of the two wires. The positive wire has uniform glow about it, while the negative conductor has spotty glow.

Theory of corona formation. Some ionisation is always present in air due to cosmic rays, ultra-violet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionised particles (*i.e.*, free electrons and +ve ions) and neutral molecules. When p.d. is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons.

When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which is turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cummulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

8.11 Factors Affecting Corona

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. The following are the factors upon which corona depends :

(*i*) *Atmosphere.* As corona is formed due to ionsiation of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

(*ii*) *Conductor size.* The corona effect depends upon the shape and conditions of the conductors. The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona that a solid conductor.

(*iii*) *Spacing between conductors.* If the spacing between the conductors is made very large as compared to their diameters, there may not be any corona effect. It is because larger distance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.

(*iv*) *Line voltage.* The line voltage greatly affects corona. If it is low, there is no change in the condition of air surrounding the conductors and hence no corona is formed. However, if the line voltage has such a value that electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

8.12 Important Terms

The phenomenon of corona plays an important role in the design of an overhead transmission line. Therefore, it is profitable to consider the following terms much used in the analysis of corona effects:

(*i*) **Critical disruptive voltage.** *It is the minimum phase-neutral voltage at which corona occurs.*

Consider two conductors of radii r cm and spaced d cm apart. If V is the phase-neutral potential, then potential gradient at the conductor surface is given by:

$$g = \frac{V}{r \log_e \frac{d}{r}} \text{ volts / cm}$$

In order that corona is formed, the value of g must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25ºC is 30 kV/cm (*max*) or

21·2 kV/cm (*r.m.s.*) and is denoted by g_o. If V_c is the phase-neutral potential required under these conditions, then,

$$g_o = \frac{V_c}{r \log_e \frac{d}{r}}$$

where g_o = breakdown strength of air at 76 cm of mercury and 25ºC
= 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*)

∴ Critical disruptive voltage, $V_c = g_o \, r \log_e \frac{d}{r}$

The above expression for disruptive voltage is under standard conditions *i.e.*, at 76 cm of Hg and 25ºC. However, if these conditions vary, the air density also changes, thus altering the value of g_o. The value of g_o is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of *b* cm of mercury and temperature of *t*ºC becomes $\delta \, g_o$ where

$$\delta = \text{air density factor} = \frac{3 \cdot 92b}{273 + t}$$

Under standard conditions, the value of δ = 1.

∴ Critical disruptive voltage , $V_c = g_o \, \delta \, r \log_e \frac{d}{r}$

Correction must also be made for the surface condition of the conductor. This is accounted for by multiplying the above expression by irregularity factor m_o.

∴ Critical disruptive voltage, $V_c = m_o \, g_o \, \delta \, r \log_e \frac{d}{r}$ kV/phase

where m_o = 1 for polished conductors
= 0·98 to 0·92 for dirty conductors
= 0·87 to 0·8 for stranded conductors

(*ii*) Visual critical voltage. *It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.*

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage V_c but at a higher voltage V_v, called *visual critical voltage.* The phase-neutral effective value of visual critical voltage is given by the following empirical formula :

$$V_v = m_v \, g_o \, \delta \, r \left(1 + \frac{0 \cdot 3}{\sqrt{\delta \, r}}\right) \log_e \frac{d}{r} \text{ kV/phase}$$

where m_v is another irregularity factor having a value of 1·0 for polished conductors and 0·72 to 0·82 for rough conductors.

(*iii*) Power loss due to corona. Formation of corona is always accompanied by energy loss which is dissipated in the form of light, heat, sound and chemical action. When disruptive voltage is exceeded, the power loss due to corona is given by :

$$P = 242 \cdot 2 \left(\frac{f + 25}{\delta}\right) \sqrt{\frac{r}{d}} \, (V - V_c)^2 \times 10^{-5} \text{ kW / km / phase}$$

where f = supply frequency in Hz
V = phase-neutral voltage (*r.m.s.*)
V_c = disruptive voltage (*r.m.s.*) per phase

8.13 Advantages and Disadvantages of Corona

Corona has many advantages and disadvantages. In the correct design of a high voltage overhead line, a balance should be struck between the advantages and disadvantages.

Advantages

(*i*) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.

(*ii*) Corona reduces the effects of transients produced by surges.

Disadvantages

(*i*) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.

(*ii*) Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.

(*iii*) The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal voltage drop occurs in the line. This may cause inductive interference with neighbouring communication lines.

8.14 Methods of Reducing Corona Effect

It has been seen that intense corona effects are observed at a working voltage of 33 kV or above. Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33 kV and higher voltages otherwise highly ionised air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment. The corona effects can be reduced by the following methods :

(*i*) *By increasing conductor size.* By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced. This is one of the reasons that *ACSR* conductors which have a larger cross-sectional area are used in transmission lines.

(*ii*) *By increasing conductor spacing.* By increasing the spacing between conductors, the voltage at which corona occurs is raised and hence corona effects can be eliminated. However, spacing cannot be increased too much otherwise the cost of supporting structure (*e.g.*, bigger cross arms and supports) may increase to a considerable extent.

Example 8.13. *A 3-phase line has conductors 2 cm in diameter spaced equilaterally 1 m apart. If the dielectric strength of air is 30 kV (max) per cm, find the disruptive critical voltage for the line. Take air density factor δ = 0·952 and irregularity factor m_o = 0·9.*

Solution.

Conductor radius, $r = 2/2 = 1$ cm

Conductor spacing, $d = 1$ m $= 100$ cm

Dielectric strength of air, g_o = 30 kV/cm (*max.*) = 21·2 kV (*r.m.s.*) per cm

Disruptive critical voltage, $V_c = m_o\, g_o\, \delta\, r \log_e (d/r)$ kV*/phase (*r.m.s.* value)

$= 0{\cdot}9 \times 21{\cdot}2 \times 0{\cdot}952 \times 1 \times \log_e 100/1 = 83{\cdot}64$ kV/phase

∴ Line voltage (*r.m.s.*) $= \sqrt{3} \times 83{\cdot}64 =$ **144·8 kV**

Example 8.14. *A 132 kV line with 1·956 cm dia. conductors is built so that corona takes place if the line voltage exceeds 210 kV (r.m.s.). If the value of potential gradient at which ionisation occurs can be taken as 30 kV per cm, find the spacing between the conductors.*

* As g_o is taken in kV/cm, therefore, V_c will be in kV.

Solution.

Assume the line is 3-phase.

Conductor radius, $r = 1{\cdot}956/2 = 0{\cdot}978$ cm

Dielectric strength of air, $g_o = 30/\sqrt{2} = 21{\cdot}2$ kV (*r.m.s.*) per cm

Disruptive voltage/phase, $V_c = 210/\sqrt{3} = 121{\cdot}25$ kV

Assume smooth conductors (*i.e.*, irregularity factor $m_o = 1$) and standard pressure and temperature for which air density factor $\delta = 1$. Let d cm be the spacing between the conductors.

∴ Disruptive voltage (*r.m.s.*) per phase is

$$V_c = m_o\, g_o\, \delta\, r \log_e (d/r) \text{ kV}$$

$$= 1 \times 21{\cdot}2 \times 1 \times 0{\cdot}978 \times \log_e (d/r)$$

or $$121{\cdot}25 = 20{\cdot}733 \log_e (d/r)$$

or $$\log_e \frac{d}{r} = \frac{121{\cdot}25}{20{\cdot}733} = 5{\cdot}848$$

or $$2{\cdot}3 \log_{10} d/r = 5{\cdot}848$$

or $$\log_{10} d/r = 5{\cdot}848/2{\cdot}3 = 2{\cdot}5426$$

or $$d/r = \text{Antilog } 2{\cdot}5426$$

or $$d/r = 348{\cdot}8$$

∴ Conductor spacing, $d = 348{\cdot}8 \times r = 348{\cdot}8 \times 0{\cdot}978 =$ **341 cm**

Example 8.15. *A 3-phase, 220 kV, 50 Hz transmission line consists of 1·5 cm radius conductor spaced 2 metres apart in equilateral triangular formation. If the temperature is 40ºC and atmospheric pressure is 76 cm, calculate the corona loss per km of the line. Take $m_o = 0{\cdot}85$.*

Solution.

As seen from Art. 8.12, the corona loss is given by :

$$P = \frac{242{\cdot}2}{\delta}(f + 25)\sqrt{\frac{r}{d}}\,(V - V_c)^2 \times 10^{-5} \text{ kW/km/phase}$$

Now, $$\delta = \frac{3{\cdot}92\, b}{273 + t} = \frac{3{\cdot}92 \times 76}{273 + 40} = 0{\cdot}952$$

Assuming $$g_o = 21{\cdot}2 \text{ kV/cm } (r.m.s.)$$

∴ Critical disruptive voltage per phase is

$$V_c = m_o\, g_o\, \delta\, r \log_e d/r \text{ kV}$$

$$= 0{\cdot}85 \times 21{\cdot}2 \times 0{\cdot}952 \times 1{\cdot}5 \times \log_e 200/1{\cdot}5 = 125{\cdot}9 \text{ kV}$$

Supply voltage per phase, $V = 220/\sqrt{3} = 127$ kV

Substituting the above values, we have corona loss as:

$$P = \frac{242{\cdot}2}{0{\cdot}952}(50 + 25) \times \sqrt{\frac{1{\cdot}5}{200}} \times (127 - 125{\cdot}9)^2 \times 10^{-5} \text{ kW/phase/km}$$

$$= \frac{242{\cdot}2}{0{\cdot}952} \times 75 \times 0{\cdot}0866 \times 1{\cdot}21 \times 10^{-5} \text{ kW/km/phase}$$

$$= 0{\cdot}01999 \text{ kW/km/phase}$$

∴ Total corona loss per km for three phases

$= 3 \times 0{\cdot}01999$ kW = **0·05998 kW**

Example 8.16. *A certain 3-phase equilateral transmission line has a total corona loss of 53 kW at 106 kV and a loss of 98 kW at 110·9 kV. What is the disruptive critical voltage? What is the corona loss at 113 kV?*

Solution.

The power loss due to corona for 3 phases is given by :

$$P = 3 \times \frac{242 \cdot 2 (f + 25)}{\delta} \sqrt{\frac{r}{d}} (V - V_c)^2 \times 10^{-5} \text{ kW/km}$$

As f, δ, r and d are the same for the two cases,

$$\therefore \quad P \propto (V - V_c)^2$$

For first case, P = 53 kW and $V = 106/\sqrt{3}$ = 61·2 kV

For second case, P = 98 kW and $V = 110 \cdot 9/\sqrt{3}$ = 64 kV

$$\therefore \quad 53 \propto (61 \cdot 2 - V_c)^2 \quad \text{...(i)}$$

$$\text{and} \quad 98 \propto (64 - V_c)^2 \quad \text{...(ii)}$$

Dividing [(*ii*)/(*i*)], we get,

$$\frac{98}{53} = \frac{(64 - V_c)^2}{(61 \cdot 2 - V_c)^2}$$

or V_c = **54 kV**

Let W kilowatt be the power loss at 113 kV.

$$\therefore \quad W \propto \left(\frac{113}{\sqrt{3}} - V_c\right)^2$$

$$\propto (65 \cdot 2 - 54)^2 \quad \text{...(iii)}$$

Dividing [(*iii*)/(*i*)], we get,

$$\frac{W}{53} = \frac{(65 \cdot 2 - 54)^2}{(61 \cdot 2 - 54)^2}$$

$$\therefore \quad W = (11 \cdot 2/7 \cdot 2)^2 \times 53 = \textbf{128 kW}$$

TUTORIAL PROBLEMS

1. Estimate the corona loss for a three-phase, 110 kV, 50 Hz, 150 km long transmission line consisting of three conductors each of 10 mm diameter and spaced 2·5 m apart in an equilateral triangle formation. The temperature of air is 30ºC and the atmospheric pressure is 750 mm of mercury. Take irregularity factor as 0·85. Ionisation of air may be assumed to take place at a maximum voltage gradient of 30 kV/cm. **[316·8 kW]**
2. Taking the dielectric strength of air to be 30 kV/cm, calculate the disruptive critical voltage for a 3-phase line with conductors of 1 cm radius and spaced symmetrically 4 m apart. **[220 kV line voltage]**
3. A 3-phase, 220 kV, 50 Hz transmission line consists of 1·2 cm radius conductors spaced 2 m at the corners of an equilateral triangle. Calculate the corona loss per km of the line. The condition of the wire is smoothly weathered and the weather is fair with temperature of 20ºC and barometric pressure of 72·2 cm of Hg. **[2·148 kW]**

8.15 Sag in Overhead Lines

While erecting an overhead line, it is very important that conductors are under safe tension. If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases the conductor may break due to excessive tension. In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip or sag.

The difference in level between points of supports and the lowest point on the conductor is called **sag.**