Corona Losses Dependence from the Conductor Diameter

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Abstract: - This paper presents possibility to decrease the corona power losses in overhead transmission lines. Corona power losses can be reduced by increasing the diameter of the conductor and used bundled conductors per phase. The objectives were to determine the corona power losses depend on conductors diameters. The simulation is completed using the corona model for one 400 kV and 220 kV overhead transmission line is developed in Matlab/Simulink. The objectives are to determine the corona effect in high voltage transmission lines, and to identify factors of decreasing the corona losses, such as increasing the diameter of conductors, and thus have to increase the critical disruptive voltage. The paper describes the analytical approach, computational tools and simulations models.

Key-Words: - Electric discharge, Electric field, Corona model, Critical disruptive voltage, Power losses, Transmission line.

1 Introduction

During the unusual situation in the overhead transmission line when the intensity of the electric field exceeds the dielectric strength of air, then around the conductor is electric drilling, which causes increasing losses and increasing the apparent conductivity. This phenomenon is called the corona. Therefore, corona, defined as a self-sustained electric discharge in which the field intensified ionization is localized only over a portion of the distance between the electrodes. When the voltage higher than the critical voltage is applied between to parallel polished wires, the glow is quite even. After operation for a short time, reddish beads or tufts form along the wire, while around the surface of the wire there is a bluish white glow.

The a.c. corona viewed through a stroboscope has the same apperance as direct current corona. As corona phenomenon is initiated a hissing noise is heard and ozone gas is formed which can be detected by its chracteristic colour.

2 Corona in transmission line
2.1 Critical disruptive voltage

If one-phase transmission line shown in Fig.1. Let \( r \) be the radius of each conductor and \( d \) the distance between the conductors such that \( d \gg r \). In this single-phase transmission line, let \( q \) be the charge per unit length on one of the conductors and hence \( -q \) on the other. If the operating voltage is \( U \), the potential of conductor A with respect to neutral plane N will be \( U/2 \) and that of conductor B will be \(-U/2\).

![Fig. 1 1-ph transmission line](image-url)
The electric field intensity at P due to the both line charge will be

\[ E_x = \frac{q}{2\pi \varepsilon_0} \left( \frac{1}{x} + \frac{1}{d-x} \right) \]  

(1)

The potential different between the conductors

\[ U = - \int_{d-r}^{r} E_x \, dx = \frac{q}{\pi \varepsilon_0} \ln \frac{d-r}{r} \]  

(2)

Since \( r \) is very small as compared to \( d \), \( d-r=d \). Substituting for \( q \) from the above equation,

\[ q = \frac{\pi \varepsilon_0 U}{\ln \frac{d}{r}} \]  

(3)

\[ E_x = \frac{U' d}{x(d-x)\ln \frac{d}{x}} \]  

(4)

Where \( U' \) is the line to neutral voltage of the systems.

Critical disruptive voltage is defined as the voltage at which complete disruption of dielectric occurs. This voltage corresponds to the gradient at the surface equal to the breakdown strength of air. This dielectric strength is denoted by \( g_0 \) and is equal to \( 30 \text{kV/cm} \) peak at NPT i.e., \( 25^\circ \text{C} \) and 760 mm of Hg.

At any other temperature and pressure

\[ g_0' = g_0 \delta \]  

(5)

Where is the air density correction factor and is given by

\[ \delta = \frac{3.92b}{273+t} \]  

(6)

Therefore the critical disruptive voltage is given by

\[ U_0 = r g_0 \delta \ln \frac{d}{r} \text{ [kV]} \]  

(7)

For high voltage transmission line the ACSR conductors are used. The cross-section of such conductors a series of arcs of circles each of much smaller diameter then the conductor as a whole. The potential gradient for such conductor will be greater than for the equivalent smooth conductor. The irregularities on the surface are increased further because of the deposition of dust and dirt on its surface and the breakdown voltage is further reduced. Average value for the ration of breakdown voltage for such conductor and a smooth conductor lines between 0.85, and is denoted by \( m_0 \).

The final expression for the critical disruptive voltage after taking into account the surface of the conductor is given by:

\[ U_0 = r g_0 \delta m_0 \ln \frac{d}{r} \text{ [kV]} \]  

(8)

2.2 Corona loss

In high voltage transmission line when the applied voltage exceeds a critical disruptive value, the thin layer of air around the transmission line ionizes. This ions result in space charges which move round the conductor. To remain the charges in the motion required the energy derived from the supply system. To maintain the flow of energy over the conductor it is necessary to supply this additional loss from the supply system. This additional power is referred to as corona loss.

Peek study the effect of various parameters on the corona loss and he deduced an empirical relation:

\[ P = 241 \times 10^{-5} \left( \frac{f + 25}{\delta} \right) \sqrt{\frac{r}{d}} \left( U_p - U_0 \right) \text{ kW/km} \]  

(9)

Where \( f \) is the frequency supply (Hz), \( \delta \) the air density correction factor, \( U_p \) the operating voltage in kV, \( U_0 \) the critical disruptive voltage (kV), \( r \) radius of the conductors (m) and \( d \) spacing (or equivalency spacing) between conductors (m).

In overhead transmission line the following factors affect corona los: (i) electrical factors, (ii) atmospheric factors and (iii) factors connected with the conductors.

Electrical factors, referring to the equation (9) it is seen that the corona loss is a function of frequency. Thus higher the frequencies of supply and the losses are higher due to corona. This means that d.c. corona loss is less as compared with a.c. corona loss. This is because during the corona phenomenon of a.c. is always present third harmonics and hence frequency is not only 50 Hz but it is contains also third harmonic component.
Atmospheric Factors, consist in air density and weather condition. Air density affects the generation of corona sources as demonstrated by Peek empirical equation (9). From this equation the losses are a function of air density correction factor $\delta$. The lower value of $\delta$ causes the higher the loss, because appears directly in the denominator of the equation and indirectly in the value of critical disruptive voltage.

$$U_0 = 21.1 m_0 \delta r \ln \frac{d}{r} \text{ [kV]} \quad (10)$$

For the lower value of $\delta$ losses will be higher, because the lower value of $U_0$, will have the lower value of $U_0$ and hence higher the value of $(U - U_0)^2$, where $U$ is the operating voltage in kV.

During the bad weather conditions such as rain, snow and hailstorm will diminish the critical disruptive voltage and hence increase the corona loss. These is due to the fact that rain droplets on the transmission line conductors can be viewed as sharp edges which enhances the electric field and therefore reduces the corona disruptive voltage and hence increase the corona loss. Corona generation increases whenever moisture accumulates on the conductor. Conductor current, if it heats the conductor, discourages the formation of water drops during fog and during high humidity, but has little effect during heavy rain and snow. Corona loss observations in the operating lines during the hoarfrost have shown that the highest corona losses occur when hoarfrost accumulates on a cold conductor, during the night time hours, when load currents are not sufficient to warm the conductors enough to melt the hoarfrost [3].

Wind speed has been found to have a very small effect on corona generation unless the wind is blowing particles onto conductors.

Factor connected with conductors consist in conductor surface conditions, conductor diameter and number of conductors.

The conductors are exposed to atmospheric conditions; the surface would have dirt etc. deposited on it which will lower the disruptive voltage and increase corona loss. Audible noise is primarily a foul-weather phenomenon therefore conductor-surface conditions are important only inasmuch as they affect water drop formation.

From the equation (9) for corona loss shows that the conductor size appears at two places and the other parts of equation are assumed constant, so:

$$P = k \sqrt{\frac{r}{d}} (U_p - U_0)^2 \text{ kW / km} \quad (11)$$

From this expression shows that the first losses are proportional to the square root of the diameter of the conductor, if the diameter of conductor are larger, then the loss will be larger. Secondly, since $U_0$ is approximately directly proportional to the diameter of the conductor, hence larger the size of the conductor now the critical disruptive voltage has to be large and hence smaller will be difference between the operate and critical disruptive voltage.

Number of conductors is an input into the calculation of the electric field at the surface of conductors. For operating voltage 400 kV and above, it, is found that one conductor per phase gives large corona loss and hence large radio interference (RI) level which interferes with the communication lines which are normally run parallel with the power lines. Most research has shown that the RI does not increase with the number of conductors for a fixed conductor diameter [3].

The higher the corona losses in the power transmission lines with one conductor is solved with by using two or more than two conductors per phase or as they are known as bundling of conductors. By bundling the conductors the self geometric mean distance (GMD) of the conductors is increased thereby; the critical disruptive voltage is increased and hence corona loss is reduced.

To reducing corona loss can be used following methods: (i) large diameter of conductors (ii) hallows conductors, (iii) bundled conductors.

With the aim to reduce the corona power losses, have been made experiments and research how affects have the larger diameter and bundled conductors.

If conductor radius is larger, surface field intensity is less and hence corona losses are lower. For the same current carrying capacity, an ACSR conductor has larger radius, therefor the transmission lines with ACSR conductors have lower corona loss. Also, for bundled conductors lines effective radius is larger and hence corona loss is less.

Corona losses do not generally play an important role in the overall design of transmission lines. With most computer programs that evaluate only the cost of resistive losses in overhead transmission lines. But, there are conditions where corona losses may influence the economic choice of conductors, and compact lines may be one of those conditions. The cost of transmission line conductors, usually expressed in terms of an annualized cost, is made up
of the annualized cost of capital investment and the annual cost of energy losses incurred during the operation of the line. The capital cost is almost directly proportional to the conductor cross-section, or to \( d^2 \), where \( d \) is the conductor diameter. In the absence of corona on conductors, the energy losses consist mainly of the resistive or \( I^2R \) losses, where \( I \) is the load current flowing through the line, and \( R \) is resistance of the conductor. Insulator leakage losses are generally negligible compared to the resistive losses.

The economic choice of conductors, for a given transmission voltage and load current, involves minimizing the total annualized cost of conductors over the expected life of the line. Since the capital cost increases while the cost of resistive energy losses decreases with \( d \), there is an optimum value of \( d \) for which the total cost attains a minimum. In Figure 2, curve 1 shows the variation of the total cost as a function of conductor diameter \( d \). Minimum total cost is obtained for an optimum conductor diameter \( d_1 \). For conductor sizes either lower or higher than \( d_1 \), the total cost will be higher. The increase in total cost may become important for lower load currents and/or higher energy costs.

![Fig. 2 Economic choice of conductors](image)

In the presence of corona on conductors, the mean annual corona losses should be added to the resistive losses to determine the annualized energy losses. As in the case of resistive losses, corona losses decrease as \( d \) increases. This is illustrated by curve 2 of Figure 2, which differs from curve 1 at lower values of \( d \) and merges asymptotically with curve 1 for the increased value of \( d \). The minimum total cost of curve 2 occurs at a slightly larger diameter \( d_2 \).

With the increasing cost of energy, studies carried out in several countries have shown that it is important to take into account the cost of corona losses in the economic choice of conductors, particularly for lightly loaded or compact transmission lines in the range of 230–400 kV, lines in traversing regions of high altitude or of extreme pollution, and also for normally loaded lines at voltages above 750 kV (3).

The mean annual corona losses of high-voltage transmission lines are usually an order of magnitude lower than the resistive losses. However, the maximum corona losses can be of the same order of magnitude as the resistive losses.

### 3 Case studies

Matlab/Simulink has been used to develop the corona model for analyzing the corona losses in 400 kV overhead transmission line. Figure 3 shows the block schematic of the presented model in Matlab/Simulink for the corona losses in 400kV transmission lines.

![Figure 3. Simulation corona model for 400kV transmission line](image)

With simulation the corona model and applying the Peek expression are calculate the corona loss. The effects of critical disruptive voltage in the corona loss are shown in Figure 4.

![Figure 4. Corona losses in 400kV transmission line](image)
In the case, where the critical disruptive voltage is less, the difference between the operating voltage $U_p$ and critical disruptive voltage $U_0$ is the largest, hence the corona losses are larger. During the foul weather, especially when there is fog, the dielectric strength is less hence the critical disruptive voltages are less. In opposite, during the fair weather, the dielectric strength is larger hence the critical disruptive voltages are larger.

Similar calculations were made for 230 kV transmission line, in this case corona loss are lower than the corona losses in the 400 kV transmission lines.

The effects of critical disruptive voltage in the corona loss, in the 220 kV transmission lines, are shown in Figure 5.

![Figure 5. Corona losses in 230kV transmission line](image)

While, lower corona losses in the 230kV transmission lines than the corona losses in the 400kV transmission lines, are presented in Figure 6.

Critical disruptive voltage is defined as the voltage at which the gradient at the surface equal to the breakdown strength of air equal to 30 kV/cm. So, if the operates voltage less than critical disruptive voltage, then corona will not appear. However, if the operates voltage is larger than the critical disruptive voltage, then will corona appears. Corona discharge is the greater if the difference between operating voltage and the critical disruptive voltage is larger. From the expression (8) of critical disruptive voltage is seen that to increasing the critical disruptive voltage can be done by increasing the diameter of the conductor.

Also, to show the reduction of corona losses with increasing diameter of conductor are used MATLAB/ SIMULINK to develop the corona model for analyzing the corona losses in 400 kV overhead transmission line depend of the diameter of conductors. Figure 6 shows the block schematic of the presented model in Matlab/Simulink for the corona losses in 400kV transmission lines depend of the conductor diameter.

![Figure 6. Simulation corona model for transmission line depend of conductor diameter](image)

The effects of increase the conductor diameter to decrease the corona loss, in the 400 kV transmission lines, are shown in Figure 7.

![Figure 7. Corona losses in 400kV transmission line depend of the conductor diameter](image)

Similarly the effects of increase the conductor diameter to decrease the corona loss, in the 230 kV transmission lines, are shown in Figure 8.

![Figure 9. Corona losses in 230kV transmission line depend of the conductor diameter](image)
4 Conclusion

In this paper has been presented the effects of conductor diameter in critical disruptive voltage and in the corona losses. Matlab/Simulink model has been used to analyzing the corona power losses depends of the critical disruptive voltage or for the diameter of conductors.

The results obtained from the simulation have shown that corona losses are larger, where the critical disruptive voltage is less; hence the difference between the operating voltage \( U_p \) and critical disruptive voltage \( U_0 \) is the largest. During the foul weather, the critical disruptive voltages are less, and hence the corona power losses are larger.

On the other hand, a very efficient measure to reduce corona losses is to increase the diameter of the conductor. By using the Peek empirical formula the corona power loss is calculated. The results show that corona losses are decrease if the conductors’ diameters are increased.

References: