INVESTIGATING THE CHARACTERISTICS OF CORONA EFFECT ON AC TRANSMISSION LINE WITH VARIATION OF LINE PARAMETERS

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ABSTRACT

This paper presents the study of characteristics of corona effect on AC high voltage transmission line with variation of parameters associated with the transmission line. This objective was achieved with the aid of MATLAB m-file function program. The line specifications are 220 kV line-to-line, 50 Hz, 1.2 cm conductor radius, 200 cm distance between conductors, and 0.85 conductor surface condition factor. The responses of the simulation on the effect of corona on transmission line show that as line width from the point of electric field intensity is decreased towards the conductor radius, the potential gradient increases and power loss decreases, and at point when line width is decreased to conductor radius, potential gradient attained its maximum value. Also when the line width is increased towards the value of conductors distance, the potential gradient tends to infinity and power loss tends to zero. When conductor surface condition factor is increased, the critical disruptive voltage increases while the power loss decreases. On the other hand, increase in frequency increases power loss and the variation of line voltage from minimum to maximum value increases the potential gradient and subsequent decrease in corona power loss. However, as the decrement in corona power loss gets to the point of 180 kV line-to-line critical disruptive voltage, the power loss started increasing thereafter. The results obtained from this work in relation to other literatures show that in designing transmission line, these effects need to be considered for the lines to properly manage corona effect during discharges and underground cable can also be employed in some design since it can prevent power loss as it is not affected by change in weather condition.

Keywords: Corona; Corona Power Loss; Critical Disruptive Voltage; Visual Critical Voltage; MATLAB; Potential Gradient.

1. INTRODUCTION

The phenomenon and event of corona is due to the ionization of air around conductors which is due to the applied alternating potential difference. This phenomenon is accompanied by a hissing sound, production of ozone, power loss and radio interference. Corona discharge is a phenomenon of an electrical partial discharge that takes place in air on the surface of an energized conductors resulting from intense localized ionization of air. 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. This corona glow around the conductor is uniform throughout the length if the conductors are polished and smooth, and if not, the glow appears only at the rough points and if the gap between conductors is not as large as their diameters, corona may short the conductors which causes flash-over before any luminous glow is noticed. As corona is caused by the ionization of the surrounding air within the conductors, it is directly affected by system line voltage, the physical state of the atmosphere, the shape and size of the conductor, and the spacing between them, which is made large as compared to the diameters (Mehta and Mehta, 2008; Sivanagaraju and Satyanarayana, 2012; Turan, 2014; Gupta, 2015; Ofil, 2015). Corona effects which are associated with the operation of high voltage transmission lines are limited to radio interference, audible noise, decrease in insulation system reliability which leads to insulation degradation and apparently system failure due to breakdown in dielectric strength, gaseous effluents (Ozone and Nitrogen oxide) and shock potential while on the other hand, its benefits range from the production of sound which can be utilized to build accuracy audio speaking, and there is zero mass that need to be moved to create the sound which helps in reducing the system transient (Ogar et al., 2017; Abdulate, 2019).

Corona in transmission lines is normally affected by a number of factors which are centered on the atmospheric and line physical conditions. The atmospheric conditions which are conductivity of air, density of air, ion density in
number/m³, size and charge per ion, and the effect of rain and dust while the line physical conditions are conductor surface, conductor size, spacing between conductors, conductor radius, effect of line voltage, ratio D/r and contour, effect of system voltage, bundling of conductors, and effect of load current (Gupta, 2008). It can be applied in manufacturing of ozone, sanitization of pool water, ionization of a gaseous sample for subsequent analysis in a mass spectrometer, removal of unwanted volatile organics such as chemical pesticides and solvents (Sharma et al., 2012).

Corona is formed due to atmospheric radiation and the presence of ultraviolet rays in the air which naturally contains some ionic particles. The discharges observed at the conductor surfaces are due to the formation of electron avalanches which occur when the intensity of the electric field at the conductor surface exceeds a certain critical value. When a potential difference is applied between conductors, voltage gradient is set up in the air between the conductors and the free electrons attain greater momentum. The higher the potential, the higher the voltage gradient and subsequent increase in free electrons. At the point when potential gradient of the air reaches its maximum value of 30 kV/cm, this results in the ionization of the neutral molecules with enough force to dislodge one or more electrons from it, thus making the process of ionization cumulative by producing another ion and one or more free electrons, which in turn are accelerated until they collide with other neutral molecules, thus producing other ions. This aggravation of ions causes the electrical breakdown of the air surrounding the conductor leading to formation of corona discharge which appears as bluish (or violet-colored) tuffs and streamers and glows around the conductor, being more or less concentrated at irregularities on the conductor surface. It can also appear on critical regions of insulator surfaces during high-humidity conditions (Mehta and Mehta, 2008; Sivanagaraju and Satyanarayana, 2012; Turan, 2014; Ogar et al., 2017).

Minimum potential difference required between conductors to start ionization is called disruptive critical voltage for corona formation. For a visual corona, the line voltage has to be somewhat higher than the disruptive critical voltage and this is known as visual critical voltage. The potential gradient at which a dielectric disrupts fully is known as the dielectric strength of the material. Corona formation always comes along with energy loss that is dissipated in light form, sound, heat and the action of chemical. This occurs when the disruptive critical voltage is exceeded, and the energy lost in this form is termed corona power loss (Mehta and Mehta, 2008).

Undesirable features of corona includes power loss, harmonic current causing non-sinusoidal voltage, radio interference (RI). These undesirable features affect or are considered in designing any transmission line. Power loss due to corona somewhat affects efficiency of the line but it is never sufficient enough to cause any appreciable effect on the voltage regulation of such a line since it varies from 1 – 2 kW/km for 500kV (Turan, 2014; Gupta, 2015).

Several recent studies were carried out on the effect of corona discharges on transmission line. A new model for analyzing the electromagnetic transients along transmission lines was presented by Safar and Saied (2003) based on the v–q characteristic of the line. In Herdem and Mamis (2003), state-space method is used to compute transients in power transmission lines by considering corona discharges. Freitas et al. (2008) represented corona effect by using the Gary and Skilling-Umoto models and including it in a frequency dependent transmission line model, while the currents and voltages along the line are calculated by using state-space technique. Lessa et al. (2012) presented the application of π circuits for simulation of corona effect in transmission lines. This includes RL parallel blocks used in modifying the π circuit structure for transmission line transient analyses in consideration of the frequency influence on the line, however, they did not show how the frequency variations affect the power loss associated with corona discharge. Sharma et al. (2012) reviewed corona effects on extra high voltage (EHV) AC transmission lines, factors affecting corona loss, applications of corona discharge and methods of reducing corona. Kumar (2013) discussed the effect of corona on transmission lines and the ways it can be reduced. He depicted the ways of reducing the corona effect on transmission line which include having inception voltage higher than the phase voltage. Power loss due to corona on high voltage transmission lines as presented by Yahaya et al. (2013) with the aid of MATLAB. Their results showed that the value of corona loss in rainy season is more than that of the dry season. Dawood and Narejo (2015) carried out modeling of corona effect in AC transmission systems with the aid of MATLAB/SIMULINK. Their model provides analysis of corona loss impact on transmission power with respect to the variation in temperature, conductor radius and conductor spacing. However, frequency variations also has great effect on the power loss. In Puneeth et al. (2015), transmission line corona effects on 1200 kV line was carried out by considering and evaluating the minimum height of the conductor in a span, the electric fields, magnetic fields, audible noise levels and radio Interference levels at different altitudes above the ground produced due to power flow in the line. He et al. (2016) studied the effects of defects on the AC corona characteristics on the surface of stranded conductors which affects corona onset voltage (COV). Their results show that as the defect degree deepens, COVs decrease gradually. A study of energy loss due to corona phenomenon with Gary’s model and Peak’s formula were carried out by Tonmitr and Ratanabuntha (2016) using...
MATLAB program for the power loss simulation in 115 kV and 230 kV system. They verified that the corona power loss varies with variation in conductor radius and line width, but they did not show how frequency variation affect power loss due to corona. Tonmitr et al. (2016) studied reduction of power loss from corona phenomena in high voltage transmission line 115 kV and 230 kV using MATLAB program. Their results showed that power loss is decreased by increasing the conductor radius and the spacing, but since frequency is directly related to power loss, hence it needs to be taken into consideration. Analysis of corona effect on high voltage transmission line which is one of the causes of power loss in electric power system network was presented by Ogar et al. (2017) with the aid of MATLAB. However, the effect of variation in line distance to the potential gradient was not captured. In Abdulate (2019), effect of corona on high voltage transmission lines was analyzed and simulated with the aid of MATLAB. He centered on the power loss associated with corona discharges but were not able to depict how variation in the distance between lines affect the potential gradient of the line.

From the above reviewed literatures, it is seen that the effect of variation in the value of line width from point of electric field intensity up-to conductor radius and up-to distance between conductors were lacking, the response of the potential gradient when line width equals conductor radius, effect of variation of conductor surface condition factor to the disruptive critical voltage and the effect of frequency variation to the energy loss due to corona were lacking in their analysis. As a result, a comparative analysis of the effect of frequency variation on corona power loss and the effect of variation of conductor condition surface factor on the critical disruptive voltage, and subsequently on corona power loss were carried out on this paper. Also effect of decrease and increase of line width towards conductor radius and conductors distance respectively were carried out in order to determine the reaction of the potential gradient of the line. This will also help to determine the actual line data for minimum power loss.

2. METHODOLOGY

The simulation of the model equation of the transmission line with respect to corona discharges is done with the aid of MATLAB as it has become the software platform for the simulation of most electrical engineering analysis.

In a single-phase transmission line in Figure 1 having two conductors “A” and “B” with a distance of “D” apart.
The conductors have their respective radius as \( r_a \) and \( r_b \) which are very much less than the distance of separation \( D \) \((r_a, r_b \ll D)\). Where \( A \) and \( B \) are the conductors, \( q \) is the charge per unit length on one of the conductors and hence \( -q \) on the other. The Equations 1 to 16 were used to describe the potential gradient of the line, critical disruptive voltage, and corona power loss associated with the line (Wadhwa, 2012; Gupta, 2015).

Calculating the electric field intensity at any point “P” at a distance “\( x \)” for the centre of conductor “A” due to both conductors in the line,

\[
q = \text{charge per unit length of conductor “A” and } -q \text{ = charge per unit length of “B”, we have}
\]

\[
E_x = \frac{q}{2\pi\varepsilon_0 x} + \frac{q}{2\pi\varepsilon_0 (D - x)} \quad \ldots \quad (1)
\]

\[
E_x = \frac{q}{2\pi\varepsilon_0 (1 + \frac{1}{x} + \frac{1}{D - x})} \quad \ldots \quad (2)
\]

The potential difference between the conductors is given by

\[
V = \int_{D-x}^{D} E_x \, dx = \int_{r}^{D-r} q \left[ \frac{1}{2\pi\varepsilon_0 x} + \frac{1}{2\pi\varepsilon_0 (D - x)} \right] \, dx \quad \ldots \quad (3)
\]

\[
V = \frac{qI_nD}{2\pi\varepsilon_0 r} \quad \ldots \quad (4)
\]

The gradient at point “P” in Figure 1 is given by

\[
E_x = \frac{q}{2\pi\varepsilon_0 (1 + \frac{1}{x} + \frac{1}{D - x})} \quad \ldots \quad (5)
\]

\[
E_x = \frac{q}{2\pi\varepsilon_0 x(D - x)} \quad \ldots \quad (6)
\]

Substituting for \( q \) from Equation (4) into Equation (6)

\[
E_x = \frac{\pi\varepsilon_0 V}{I_nD/r} \frac{1}{2\pi\varepsilon_0 x(D - x)} \quad \ldots \quad (7)
\]

Therefore,

\[
E_x = \frac{V}{2I_nD/r} \frac{D}{x(D - x)} \quad \ldots \quad (8)
\]

\[
E_x = \frac{V}{x(D - x)I_nD/r} \frac{V^lD}{V^lD} \quad \ldots \quad (9)
\]

Where \( V^l \) is the line-to-neutral voltage of the system. For a three-phase system, \( V^l = V_{\text{line}}/\sqrt{3} \).

Hence,

\[
g_{\text{max}} = E_r = E_{\text{max}} = \frac{V^lD}{r(D - r)I_nD/r} \equiv \frac{V^l}{rI_nD/r} \quad \ldots \quad (10)
\]

The critical disruptive voltage \( V_d \) assuming a solid conductor with a smooth surface is given as

\[
V_d = r q_0 \delta m \frac{D}{r} \text{ kV} \quad \ldots \quad (11)
\]

To determine critical disruptive voltage for a conductor with irregular surface due to stranding, Equation (11) becomes

\[
V_d = \frac{r q_0 \delta m I_n}{D/r} \text{ kV rms line - to - neutral} \quad \ldots \quad (12)
\]

\[
\delta = \text{air density factor} = \frac{3.92b}{273 + t}
\]

The line-to-neutral effective model of visual critical voltage is given by

\[
V_v = \frac{r q_0 \delta m I_n}{D/r}(1 + \frac{0.3}{\sqrt{6D}}) \text{ kV/phase} \quad \ldots \quad (13)
\]

The corona power loss under normal weather condition which occurs when the critical disruptive voltage is surpassed which is given as

\[
P_1 = 242.2 \left( \frac{f + 25}{\delta} \right) \sqrt{\frac{V}{D}} \frac{(V - V_c)^2}{2} \times 10^{-5} \text{ kW/km/phase} \quad \ldots \quad (14)
\]

For the corona power loss under abnormal weather conditions like stormy weather, the disruptive critical voltage is multiplied by 0.8 which is given as

\[
P_1 = 242.2 \left( \frac{f + 25}{\delta} \sqrt{\frac{V}{D}} \frac{(V - 0.8V_c)^2}{2} \times 10^{-5} \right) \text{ kW/km/phase} \quad \ldots \quad (15)
\]

When power loss due to corona is low and the ratio of phase voltage to critical disruptive voltage is less than 1.8, Peterson’s formula is employed in determining corona power loss and is given as

\[
P_1 = \frac{21 \times 10^{-6} fV^2}{(\log_{10} D/r)^2} \times K \text{ kW/km/phase} \quad \ldots \quad (16)
\]

Where \( m_0 \) is the irregular surface or stranding factor which varies from surface-to-surface which is 1 for polished conductors, 0.98 to 0.92 for dirty conductors, and 0.87 to 0.8 for stranded conductors, while \( m_v \) is another irregularity factor applied to visual critical voltage having a value of 1.0 for polished conductors and 0.72 to 0.82 for rough conductor.

\( f \): supply frequency in Hz
\( V^l \): line-to-neutral voltage (r.m.s.) in kV
\( V_c \): critical disruptive voltage (r.m.s.) per phase in kV
\( b \): barometric pressure in centimeters of mercury
\( t \): ambient temperature in degrees Celsius
\( K \): a factor, which varies with the ratio of phase voltage to critical disruptive voltage.

3. RESULTS AND DISCUSSION

This section introduces the results of the analysis which were done by the use of MATLAB function program to observe the various characteristics of corona discharge with the variation of its parameters. The effect of variation of line width on potential gradient towards conductor radius and conductors distance is as shown in Tables 1 and 2. Table 3 shows the effect of variation of conductor surface condition factor on critical disruptive voltage and power loss. While Tables 4 and 5 show the effect of frequency and line voltage variation to the characteristics of corona discharge.
Table 1: Effect of decrease in line width towards conductor radius

<table>
<thead>
<tr>
<th>x (cm)</th>
<th>80</th>
<th>70</th>
<th>60</th>
<th>50</th>
<th>40</th>
<th>30</th>
<th>20</th>
<th>10</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex (kV/cm)</td>
<td>0.259</td>
<td>0.273</td>
<td>0.296</td>
<td>0.331</td>
<td>0.388</td>
<td>0.487</td>
<td>0.690</td>
<td>1.307</td>
<td>10.407</td>
</tr>
</tbody>
</table>

Table 2: Effect of increase in line width towards conductor distance

<table>
<thead>
<tr>
<th>x (cm)</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>170</th>
<th>180</th>
<th>190</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex (kV/cm)</td>
<td>0.259</td>
<td>0.251</td>
<td>0.248</td>
<td>0.250</td>
<td>0.259</td>
<td>0.273</td>
<td>0.296</td>
<td>0.331</td>
<td>0.388</td>
<td>0.487</td>
<td>0.690</td>
<td>1.307</td>
</tr>
</tbody>
</table>

Table 3: Effect of variation of conductor surface condition factor

<table>
<thead>
<tr>
<th>m₀</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vd (kV)</td>
<td>12.513</td>
<td>25.025</td>
<td>37.538</td>
<td>50.051</td>
<td>62.563</td>
<td>75.076</td>
<td>87.589</td>
<td>100.101</td>
<td>112.64</td>
<td>125.127</td>
</tr>
<tr>
<td>Pl (kW)</td>
<td>192.405</td>
<td>152.651</td>
<td>117.494</td>
<td>86.931</td>
<td>60.963</td>
<td>39.591</td>
<td>22.813</td>
<td>10.613</td>
<td>3.044</td>
<td>0.052</td>
</tr>
</tbody>
</table>

Table 4: Effect of frequency variations on corona power loss

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
</tr>
</thead>
</table>

Table 5: Effect of line voltage on the potential gradient and power loss

<table>
<thead>
<tr>
<th>Vl (kV)</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>170</th>
<th>180</th>
<th>190</th>
<th>200</th>
<th>210</th>
<th>220</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex (kV/cm)</td>
<td>0.129</td>
<td>0.141</td>
<td>0.152</td>
<td>0.165</td>
<td>0.176</td>
<td>0.188</td>
<td>0.200</td>
<td>0.212</td>
<td>0.223</td>
<td>0.235</td>
<td>0.247</td>
<td>0.259</td>
</tr>
<tr>
<td>Pl (kW)</td>
<td>26.944</td>
<td>20.172</td>
<td>14.379</td>
<td>9.564</td>
<td>5.727</td>
<td>2.869</td>
<td>0.989</td>
<td>0.087</td>
<td>0.164</td>
<td>1.219</td>
<td>3.252</td>
<td>6.263</td>
</tr>
</tbody>
</table>

Figures 2 to 4 show that at different values of line spacing, under normal weather condition, the potential gradient of the line increases as the line spacing decreases. Figure 2 shows that as line spacing decreases, the value of potential gradient increases. In Figures 2 and 3, it can be seen that when line spacing started to increase, the value of line gradient decreases up to the point of 100 cm before it started increasing again. When the line spacing equals the conductor radius, the potential gradient attained maximum value, and when x equals D, the potential gradient tends infinite as can be seen in Figure 4. Figure 5 shows that under normal weather condition at various line spacing between the conductors corona power loss is inversely proportional to the spacing between conductors. If the spacing is increased to larger value, corona power loss tends to 0 kW.
Figures 6 and 7 show the responses of disruptive critical voltage and corona power loss with respect to the variation of the condition of the surface of conductors. In Figure 6, it is seen that as the conductor surface condition factor is varied from zero to one, it leads to increase in disruptive critical voltage due to the direct relation between critical disruptive voltage and the conductor surface factor. Figure 7 shows that corona power loss decreases with increased values of the conductor surface condition factor.

Figure 8 shows that the lower the value of disruptive critical voltage, the higher the corona power loss. During stormy weather conditions like rains, corona effects increases as reduced value of disruptive critical voltage increases power loss. Figure 9 shows that as the supply frequency increases, the value of corona power loss increases since power loss due to corona is directly related to the supply frequency and this is due to the presence of harmonic component which leads to increase in power loss.
In Figures 10 and 11, it is seen that the effect of variation in line voltage directly affects the corona power loss and the potential gradient of the line. Figure 10 shows that as line voltage increases, the corona power loss decreases up to the point of critical disruptive voltage which stood at 180 kV line-to-line (103.92 kV line-to-neutral). After this point, increase in line voltage leads to increase in corona power loss. Figure 11 shows that increase in line voltage leads to subsequent increase in line potential gradient since they have direct relation.

4. CONCLUSION

In this paper, a mathematical model of transmission line equations which include the potential gradient of the line, critical disruptive voltage, visual critical voltage and corona power loss of the line are simulated with the aid of MATLAB m-file in order to determine the effect of line parameters variation to the characteristics of corona phenomenon on AC transmission line. The results show that as line space is increased, the potential gradient of the line decreases up to the point of 100 cm before it started increasing. Effect of increase in conductor surface condition factor leads to increase in critical disruptive voltage and subsequent decrease in the corona power loss. It is observed...
that in stormy condition, the value of corona loss is more as compared to normal weather condition thereby underground system of transmission can prevent power loss since it is not affected by change in weather conditions. Increase in frequency of supply also increases the corona power loss due to their direct relation. As line voltage is increased, the potential gradient of the line increases with subsequent decrease in the power loss. Due to the above observations, in the design of transmission line, it is important to consider these effects for maximum utilization of the advantages that come with the effect of corona phenomenon and for the protection of the AC transmission lines especially during stormy weather.

REFERENCES


