Collation of Predetermination Formulae for Radio Interference generated from HVDC Transmission Lines

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SUMMARY

Radio noise (RN) which originates in corona discharges on a surface of conductor employed in high voltage transmission lines is an electromagnetic disturbance, so-called radio interference (RI), and there is a possibility that RN influences reception of AM radio and TV picture. Therefore, RN is an important factor related to conductor design of high voltage transmission lines.

In the case of commercial transmission lines, the electric field strength on a conductor surface is usually lower than that of the full-corona state at rated voltage, in other word, the surface of conductor is in partial-corona state. In this condition, the followings are well known;

(i) positive corona discharges (streamer corona) on a conductor having positive polarity mainly cause higher RI level than negative corona discharges on a conductor having negative polarity,
(ii) RI level of AC transmission lines is higher in rainy weather than in fair weather,
(iii) in contrast, RI associated with HVDC transmission lines has a higher level in fair weather than in rainy weather.

Therefore, from the viewpoint of conductor design related to HVDC transmission lines, it is essential to study the RN characteristics related to positive corona discharges in fair weather. However, the space charges, which exist near conductors all along until reaching the ground or a conductor having opposite polarity, result in giving difficulty to define an amount of RN generation, and it is meaningful to review how the effect is incorporated in developed predetermination formulae.

Several institutes have delivered their own predetermination formula for RI generated from HVDC transmission lines. They are divided into two separate groups which are referred to as comparative and analytical method. In this paper four formulae in the comparative method and two formulae in the analytical method are introduced. Two formulae in the comparative method take the effect of space charge into account and incorporates the pole spacing. In these formulae static maximum conductor surface gradient ($g_m$) is used in spite of existence of space charges around conductors. Two formulae in the analytical method are described in this paper and the prediction formula from CRIEPI introduces maximum conductor surface gradient ($F_m$) considering space charge.

Employing formulae developed by CRIEPI, RI level for the Pacific HVDC Intertie is calculated.

KEYWORDS

Radio Interference - Radio Noise - Prediction, Predetermination Formula - HVDC - Transmission Lines
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1. Introduction

Radio noise (RN) which originates in corona discharges on a surface of conductor employed in high voltage transmission lines is an electromagnetic disturbance, so-called radio interference (RI), and there is a possibility that RN influences reception of AM radio and TV picture. Therefore, RN is an important factor related to conductor design of high voltage transmission lines.

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Several institutes have delivered their own predetermination formula for RI generated from HVDC transmission lines. They are divided in to two separate groups which are referred to as comparative method and analytical method.

In the comparative method, a well-defined RN field intensity measurement, which includes the combined effects of RN generation and propagation, is used as a reference value. To predict the RN level for lines of different design parameters, various corrections for corona generation, measurement frequency, and lateral distance are made. The corona generation is related to the operating voltage, the subconductor diameter, the number of subconductor, the subconductor spacing and the space charge near conductors. Of course it also depends on the weather condition.

In the analytical method, a characteristic quantity of RN generation which is called the excitation function is used. The excitation function is measured in single-phase test cages and/or test lines for different conductor arrangements. Using the measurement and the known line parameters, the method proceeds to calculate the total noise currents on the line and the resulting field intensity at its vicinity.

In this paper four formulae in the comparative method and two formulae in the analytical method are introduced. Two formulae in the comparative method take the effect of space charge into account and incorporates the pole spacing. In these formulae static maximum conductor surface gradient ($g_m$) is used in spite of existence of space charges surrounding conductors. Two formulae in the analytical method are described in this paper and the prediction formula from CRIEPI introduces maximum conductor surface gradient ($F_m$) considering space charge.

Employing formulae developed by CRIEPI, RI levels for the Pacific HVDC Intertie are calculated and those are compared with the measured data.

2. COLLATION of PREDETERMINATION FORMULAE for RI LEVEL

As for RI generated from HVDC transmission lines, several institutes have delivered their own predetermination formulae. The formulae that belong to the comparative method are summarized in Table 1. The same symbols are used for all common terms, whether they belong to all formulae or not. They are listed below:

\[ E = \text{RI level refer to 1 [} \mu \text{V/m}] \]
\[ g_m = \text{static maximum conductor surface gradient, [kV/cm]} \]
\[ d = \text{(sub)conductor diameter, [cm]} \]
\[ n = \text{number of subconductors in a bundle} \]
\[ D = \text{conductor to antenna or radial distance, [m]} \]

Symbols peculiar to one formula only are given with the description of the formula.
The formulae in Table 1, which can directly calculate RI level (Quasi peak, so-called QP) at 1 MHz in fair weather using applied voltage, conductor parameters, and pole arrangement. The formula from Anneberg is only for monopolar lines, and others are for bipolar lines.

In these formulae, static maximum conductor surface gradient ($g_m$) is used in spite of existence of space charges around conductors. The formulae developed by CRIEPI take the effect of space charge into account and incorporate the pole spacing into the predetermination formulae.

<table>
<thead>
<tr>
<th>Affiliation</th>
<th>Formulae of RI level in dB µV/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPA(1) (USA)</td>
<td>For bipolar lines, $E = 51.7 + K_1 \log_{10}\left(\frac{d}{g_m/g_n}\right) + 40 \log_{10}(d/4.62) + 10\left{\log_{10}(f)\right} + 40\log(10.9/D) + q/300$</td>
</tr>
<tr>
<td>Anneberg(2) (SW)</td>
<td>For monopolar lines, $E = 25 + 1.5(g_m - g_n) + 20 \log_{10}\left(\frac{d}{2}\right) + 10 \log_{10}(n) + 40 \log_{10}\left(\frac{30}{D}\right)$</td>
</tr>
<tr>
<td>CISPR standard</td>
<td>For 50% values, $g_m = 22$, $\delta$: relative density of air</td>
</tr>
<tr>
<td>CRIEPI-I(3) (JP)</td>
<td>For single circuit bipolar lines, $E = N_0 + 1.8(g_m - 25) + 40 \log_{10}\left(\frac{d}{2.53}\right) + 20 \log_{10}\left(\frac{10h}{D^2}\right) + K_w(W)$</td>
</tr>
<tr>
<td></td>
<td>$50%$ value, Old JRTC standard, $N_0=64.5$ for $n=1$, $N_0=58.5$ for $n=2$, 62 for $n=3$ and 4, $h$: height difference between a positive conductor and an antenna, $K_w$: correction for horizontal pole to pole distance ($W$) $K_w = 24.5/\sqrt{W} - 8.5$, Conversion coefficient from Old JRTC to ANSI is $–5.7$dB</td>
</tr>
<tr>
<td>CRIEPI-II(4) (JP)</td>
<td>For double circuit bipolar lines, $E = N_0 + K_f(g_m - 20) + 20 \log_{10}\left(\frac{10h}{D^2}\right) + K_w(W) + K_n(H) + K_c(C)$</td>
</tr>
<tr>
<td>Pole arrangement</td>
<td>$N_0$</td>
</tr>
<tr>
<td>@ –</td>
<td>53</td>
</tr>
<tr>
<td>– @</td>
<td>54</td>
</tr>
<tr>
<td>50% value, Old JRTC standard, $H$: height of a positive conductor [m], $h$: height difference between a positive conductor and an antenna, $C$: vertical pole to pole distance [m], $W$: horizontal pole to pole distance [m], $K_w$: correction for $H$, $K_n$: correction for $C$, $K_c$: correction for $W$, Conversion coefficient from Old JRTC to ANSI is $–5.7$dB</td>
<td></td>
</tr>
</tbody>
</table>

Three formulae in analytical method are shown in Table 2. The prediction formula from CRIEPI introduces maximum conductor surface gradient ($F_m$) considering space charge surrounding conductors.

<table>
<thead>
<tr>
<th>Affiliation</th>
<th>Formulae of excitation function in dB µA/m1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>IREQ(5) (CA)</td>
<td>$\Gamma = \Gamma_0 + K_f\left(g_m - g_n\right) + 40 \log_{10}(d/d_0) + K_w \log_{10}(n/n_0)$</td>
</tr>
<tr>
<td>Season</td>
<td>$\Gamma_0$</td>
</tr>
<tr>
<td>Summer</td>
<td>27.1</td>
</tr>
<tr>
<td>Fall/Spring</td>
<td>23.4</td>
</tr>
<tr>
<td>Winter</td>
<td>18.7</td>
</tr>
<tr>
<td>Overall Fair Weather</td>
<td>22.9</td>
</tr>
<tr>
<td>ANSI standard, 50% value, QP $g_m$=25 kV/cm, $d_0$=4.064 cm, $n_0$=6</td>
<td></td>
</tr>
<tr>
<td>CRIEPI-III(6) (JP)</td>
<td>$\Gamma = \Gamma_0 + 2.3 F_m + 40 \log_{10}(d/3.84) + C_{g_m=20 kV/cm}$</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = -7.8$ for $n=1$, $-13.8$ for $n \geq 2$</td>
</tr>
<tr>
<td>50% value, Old JRTC standard, $F_m$: maximum conductor surface gradient considering space charges surrounding conductors, this formula can be applied to $n=1$ to 6 and $d=2.24$ to 5 cm $C_{g_m=20 kV/cm}=–4.41$, Conversion coefficient from Old JRTC to ANSI is $–5.7$dB</td>
<td></td>
</tr>
</tbody>
</table>
$F_m$ is calculated as follows.

There are three assumptions when calculating $F_m$. Those are;

1. The space charge affects only the magnitude but not the direction of the electric field (Deutsch's assumption),
2. The mobility of ions is constant (independent of the drift time from generation and atmospheric humidity),
3. The generated ion current density is determined by the conductor surface gradient in the presence of space charge regardless of the electrode arrangement around the conductor bundle.

Assumption (3) is to give a boundary condition on the surface of the conductor where corona discharges are generated. Corona current is obtained by integrating ion current density on the entire conductor surface. The fundamental equations are as follows;

\begin{align}
    j_0 &= (K_2 / K_1) \exp\{(0.28 K_a(K_1 F - 25) + 7)\} \\
    K_1 &= g_a / G = \left[1 + (n - 1) d / 2 R_a\right] / \left[1 + (n - 1) d \cos \theta / 2 R_a\right] \\
    K_2 &= K_a(0.65 + 0.195 n)(d / 2.53)^2 \\
    2R_a &= S_b / \sin(\pi / n)
\end{align}

where $j_0$ [pA/cm$^2$] is the generated ion current density, $G$ [kV/cm] the static conductor surface gradient, and $F$ [kV/cm] the conductor surface gradient in the presence of space charge. Of course, the maximum value of $G$ is $g_m$. $K_a$ and $K_b$ are experimental constants to determine corona current generation characteristics. Other parameters are as follows:

- $S_b$: subconductor spacing [cm],
- $\theta$: angle from the direction of the maximum gradient on the conductor surface.

The electric field in the presence of space charge is obtained by solving the following equations:

\begin{align}
    \text{div} \mathbf{E} &= (\rho^+ - \rho^-) / \varepsilon_0, \\
    \mathbf{j}^+ &= \mu^+ \rho^+ \mathbf{E}, \\
    \mathbf{j}^- &= \mu^- \rho^- \mathbf{E}, \\
    \mathbf{j} &= \mathbf{j}^+ + \mathbf{j}^-. \\
    \text{div} \mathbf{j}^+ &= -R_a \rho^+ \rho^- / e, \\
    \text{div} \mathbf{j}^- &= R_a \rho^+ \rho^- / e, \\
    \mathbf{E} &= -\text{grad} \phi,
\end{align}

where $\mathbf{E}$: electric field in the presence of space charge,
- $\mathbf{j}$: ion current density,
- $\rho$: space charge density,
- $\varepsilon_0$: permittivity of free space,
- $\mu$: mobility of ions,
- $R_a$: recombination coefficient of positive and negative ions,
- $e$: charge of an electron,
- $\phi$: potential in the presence of space charge.

The suffixes $+$ and $-$ indicate positive and negative ions respectively. In this calculation, 1.7 cm$^2$/Vs for $\mu^+$ and $\mu^-$ and 2.2x10$^{-6}$cm$^3$/s for $R_a$ are used.

By using the assumption (1), Eq. (5) are converted into one dimensional form along the static electric flux line and the numerical calculation is carried out to obtain the conductor surface gradient $F$ and the ion current density $\mathbf{j}$ ($= \mathbf{j}^+ + \mathbf{j}^-$) on the conductor surface. On the surface of the positive pole, $\mathbf{j}^+$ would be $j^+$ to satisfy Eq. (1). The similar calculation is done around the conductor surface, and $F_m$ and the corona current are obtained as the maximum value of $F$ and the integrated value of $\mathbf{j}$ respectively.
3. Calculation of RI level of Pacific HVDC Intertie

**Measured RI level of Pacific HVDC Intertie**

The Pacific HVDC Intertie is an HVDC transmission line of 1360 km in length in U.S.A. and BPA measured RI level at the Grizzly Mountain HVDC Research Facility that was located 81 miles south of the Celilo HVDC terminal. The pole arrangement and the location of loop antenna to measure RI level are illustrated in Figure 1.

![Pole arrangement and position of loop antenna of Pacific HVDC Intertie](image)

The measured RI level is 62.5 dB (in fair weather, 50 % level, 500 kHz) using ANSI noise meter.

**Comparison between Measured Value and Predicted RI level**

Employing the predetermination formulae developed by CRIEPI, RI levels of Pacific HVDC Intertie are calculated. To calculate RI levels at 0.5 MHz and given antenna position, frequency conversion, calculation of lateral attenuation, and conversion coefficient between noise meters conforming to different standard are required, but Ref. [1, 2, 5] do not give explicitly, so prediction of RI level using these formulae is not done.

The predicted values and the measured value are summarized in Table 3, where frequency conversion coefficient from 1MHz to 0.5 MHz is derived by the equation,

\[ C_f = -12 \log_{10}(f)^2 - 17 \log_{10}(f) \text{ MHz} \]

When converting from \( \Gamma \) to RI level, the field factor is calculated based on the modal propagation analysis, and the conversion coefficient from \( \Gamma \) to RI level is 24.7dB.

The predicted RI level using CRIEPI-III formula that employs \( F_m \) shows good agreement with the measured value, in contrast, the predicted RI level using CRIEPI-I formula is quite less than measured value.

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Predicted RI level</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.5</td>
<td>57</td>
</tr>
<tr>
<td>64</td>
<td>CRIEPI-I</td>
</tr>
<tr>
<td>64</td>
<td>CRIEPI-III</td>
</tr>
</tbody>
</table>

**4. Conclusion**

Several institutes have delivered their own predetermination formulae for RI level from HVDC transmission lines and they are summarized in this paper. There are some difficulty to carry out direct comparison between them because noise meters confirming to the different standard are used. Moreover, a way how to convert frequency and a way how to calculate lateral attenuation are not explicitly given in some formulae.
The result calculated from the formula that employs maximum conductor surface gradient \((F_m)\) considering space charge shows good agreement with the measured value.

**REFERENCES**


