Panel Paper 2010TD0683: Grounding of Overhead Transmission Lines

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How Grounding Affects Overhead Groundwire (OHGW) Protection
Dealing with Lightning Challenges

- **Direct Stroke Termination**
  - Directly to the unshielded line
  - To ground or an object near the line

- **Grounding of the Stroke Current**
  - Into Normal Soil
  - Across surface of High-Resistivity Soil

- **Equalization of Potentials**
  - Electromagnetic coupling
  - Surge arresters
Stroke Incidence – Side View

- Direct Stroke
- Induced Voltage Flashover

\( r_s \)
\( h \)
\( y = 0 \)
\( y_{min} \)
\( y_{max} \)

\( V_{INDUCED} \geq 1.5 \text{ CFO} \)
\( V_{INDUCED} < 1.5 \text{ CFO} \)
Stroke Incidence – Side View

OHGW Interception

\[ r_s \]

\[ y=0 \]

\[ h \]

\[ y_r \]

\[ r_g \]

DIRECT STROKE
\[ \Delta V \propto I_{pk} \cdot R_f \]
Effectiveness of OHGW

Calculating Low Frequency Resistance $R_f$ using the “Chiz-Whiz” Method

2010 IEEE T&D Expo
Panel Session on Lightning Performance of Overhead Lines
Geometric and Contact Resistance

- **Grounding of the Stroke Current**
  - Into Normal Soil of Resistivity $\rho$ (Ωm)
  - Split into “Geometric” and “Contact” Resistance
  - Solid Disc, Ring have:
    - **SAME** Geometric Resistance
    - **DIFFERENT** Contact Resistance (Disc $R_{contact} \approx 0$)

$$R_{Geometric} + R_{Contact} = \frac{\rho}{2\pi} \left( \frac{1}{g} \ln \left( \frac{11.8g^2}{A} \right) + \frac{1}{L} \ln \left( \frac{A}{F \cdot A_{Wire}} \right) \right)$$
Resistivity (local soil near tower)

\[ R_{Geometric} + R_{Contact} = 2\pi \left( \frac{1}{g} \ln \left( \frac{11.8g^2}{A} \right) + \frac{1}{L} \ln \left( \frac{A}{F \cdot A_{Wire}} \right) \right) \]
Geometric and Contact Resistance

Size (geometric radius)

\[ R_{\text{Geometric}} + R_{\text{Contact}} = \frac{\rho}{2\pi} \ln \left( \frac{11.8g^2}{A} \right) + \frac{1}{L} \ln \left( \frac{A}{F \cdot A_{\text{Wire}}} \right) \]
Geometric and Contact Resistance

Shape Factor, pointy = larger

\[ R_{Geometric} + R_{Contact} = \frac{\rho}{2\pi} \left( \frac{1}{g} \right) + \frac{1}{L} \ln \left( \frac{A}{F \cdot A_{Wire}} \right) \]
Geometric and Contact Resistance

\[ R_{\text{Geometric}} + R_{\text{Contact}} = \frac{\rho}{2\pi} \left( \frac{1}{g} \ln \left( \frac{11.8g^2}{A} \right) + \ln \left( \frac{A}{F \cdot A_{\text{Wire}}} \right) \right) \]
Fill Factor \((F \approx 2)\)

\[
R_{\text{Geometric}} + R_{\text{Contact}} = \frac{\rho}{2\pi} \left( \frac{1}{g} \ln \left( \frac{11.8g^2}{A} \right) \right) + \frac{1}{L}
\]
Evaluation of Simple Models for the Resistance of Solid and Wire-Frame Electrodes

William A. Chisholm, Fellow, IEEE

Abstract—A single, simplified, and general model for the resistance of solid or wire-frame electrodes offers insight into the performance improvements that can be expected when additional electrode components are added in parallel. This model separates the geometric and contact resistance terms $R_{\text{Geometric}}$ and $R_{\text{Contact}}$. For solid and wire-frame electrodes, $R_{\text{Geometric}}$ depends on the geometric radius and the overall surface area. For solid electrodes, $R_{\text{Contact}} = 0$; however, for wire-frame approximations, it depends on the ratio of overall to wire surface area. The simple model incorporates the effects of depth of burial and wire radius to give remarkably good estimates of resistance, as compared to reference calculations, and can be used to identify weaknesses in many traditional expressions when used outside their conditions of derivation.

Index Terms—Electrode, grounding, soil resistivity, wire frame.

\begin{equation}
R_{\text{Geometric}} = \frac{\rho}{2\pi s} \ln \left( \frac{2\pi es^2}{A} \right)
\end{equation}
Geometric and Contact Resistance

- Worked example shows problem with $n$ rods in a row formula

Fig. 4. Validation of the IEC/Sunde model [14] and the general resistance model (2) and (7) against the numerical reference method for rods in a row with connecting bare horizontal wire.
Changes in Resistivity: Region to Region, Tower to Tower
Rise Time Maps Ground Resistivity

Hudson Bay
Clay Belt
Canadian Shield (High Resistivity)

2003 Average Rise Time Map, All Polarity
Full U.S. - Lat 23.20N-52.00N; Lon 125.90W-65.85W
Based on Flash data

Rise Time in μ-sec
10 km grid

- 12 and up (1364)
- 10 to 12 (2859)
- 8 to 10 (9346)
- 6 to 8 (24855)
- 5 to 6 (27826)
- 4 to 5 (48367)
- 3 to 4 (23421)
- 2 to 3 (1554)
- 1 to 2 (30)
- 0+ to 1 (6)
FCC M3 Conductivity Map

2 mS/m = 500 Ωm
4 mS/m = 250 Ωm
8 mS/m = 125 Ωm
15 mS/m = 67 Ωm
Soil Suitability for Ground Penetrating Radar

[Map showing soil suitability for GPR]
Footing Resistance Statistics

• TVA carried out 10,600 measurements of tower footing resistance in early 1990s.
  ▪ 500-kV towers had insulated overhead groundwires.
  ▪ For the most part, untreated with expectation that $R_f < 40 \, \Omega$.
  ▪ Analyzed with Pearson Classification.
Pearson Classification, TVA Lines, $R_f$
Pearson Classification, TVA Lines, ln R_f

[Graph showing Pearson Classification with TVA 500-kV Lines, Pearson Types I, IV, and VI, and an area labeled 0, 3 = Normal.]

- Pearson Type V
- Pearson Type III
- Lower Bound
- ln (Ground Resistance)
Recent Work in Portugal

• Campaign to test grounding of 150-kV, 220-kV and 400-kV Footing Resistance
  - Made use of ABB 26-kHz meter
  - Summarized by Susana de Almeida de Graaff

Invited Papers

PREDICTION OF FAULTS CAUSED BY LIGHTNING FOR TRANSMISSION SYSTEM OPERATIONS

Susana A. B. De Almeida\textsuperscript{1,2}, C.S. Engelbrecht\textsuperscript{4}, Rui Pestana\textsuperscript{1}, F. P. Maciel Barbosa\textsuperscript{2,3}
Portugal: REN Lines, ITU Conductivity (mS/m)
Recent Comparison Work

- Measurements corrected for overhead groundwire connection to adjacent structures
- TVA and REN data evaluated in similar ways

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Lines</th>
<th>Towers</th>
<th>Footing Resistance $R_f(\Omega)$</th>
<th>ln (Footing Resistance $R_f,\Omega$)</th>
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<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Std. Dev</td>
<td>Skew</td>
<td>Kurtosis</td>
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<td>53</td>
<td>4840</td>
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<td>400 kV</td>
<td>23</td>
<td>3052</td>
<td>11.0</td>
<td>37.5</td>
</tr>
</tbody>
</table>
Recent Comparison Work

• REN reported median 18.2 \( \Omega \) and \( \sigma_{\ln R_f} = 1.05 \) on a system-wide basis.

• TVA and REN data have similar (log-normal) distributions of footing resistance with values of standard deviation \( \sigma \) of \( \ln(R_f) \) of 0.92 (TVA) and 0.73 (REN), compared the same way on a line-by-line basis.

• 2015 SIPDA XIII Invited Lecture has details (28 September to 2 October 2015).
Conclusions
Conclusions

• Footing resistance has an important effect on the performance of overhead groundwire protection.

• Simple formulas exist for relating the resistance of structures to the local soil resistivity.

• Several different ways exist to infer the soil resistivity in regions, but not on a tower-by-tower basis.

• Tower-by-tower variation of soil resistivity and footing resistance is very large.
Conclusions

• Regions of similar size (TN, USA and Portugal), similar numbers transmission of towers, Footing resistance data measured with earth resistance tester (TVA) or ABB 26-kHz meter (REN).

• On line-by-line basis, high skew and kurtosis, so data were not normally distributed.

• Transformation ln (Rf) got rid skew and kurtosis.

• Footing resistance is log-normally distributed with wider value of standard deviation than peak current.
Questions
Dr. William A. (Bill) Chisholm is a well-known expert in electric power reliability problems involving adverse weather including lightning, winter pollution and low wind conditions.

**IEEE Fellow in 2007.**

Led/leading IEEE Standards 1243 and 1410 for improving lightning protection of transmission and distribution lines.

Associate at Kinectrics (former Ontario Hydro Research Division) in Transmission and Distribution group.

Principal author of EPRI Transmission Line Reference (*Red Book*), 200 kV and Above, Chapter 6 (lightning protection) and main technical contributor to the upcoming *Grey Book* (lightning and grounding).

Spent 2007-2008 at the University of Quebec at Chicoutimi, co-writing a book for and teaching lightning protection.

Columnist (Transient Thoughts) for INMR Magazine.