Lightning Insulation Coordination Study

Presenter: Nguyen Dong Hai Le
DIGSILENT Pacific

Presentation Outline

- Introduction
- Network Components Model
- Stroke Current Model
- Case Studies and Results
- Conclusions
Introduction – Lightning Insulation Coordination

Insulation Coordination is required to ensure

• Equipment’s insulation shall withstand voltage stress caused by lightning strike.
• Efficient discharge of over voltages due to lighting strike.

Network Component Models

• Transmission Line Model
• Equipment’s Stray Capacitance
• Surge Arrester.
• Current Dependant Characteristic of Tower Footing Resistance
• Tower Surge Impedance.
• Time Dependant Characteristic of Insulator Strength.
• Stroke Current Model.
• Determination of Critical Stroke Current’s Parameters.
Network Component Models – Transmission Line

- Individual tower model
- Separated circuit of Earth Wire(s)
- Ph-E coupling capacitance due to string insulator

Network Component Models – Equipment’s Stray Capacitance

Typical data of equipment’s stray capacitance

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Capacitance to Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive Potential Transformer</td>
<td>8000pF</td>
</tr>
<tr>
<td>Reactive Potential Transformer</td>
<td>620pF</td>
</tr>
<tr>
<td>Current Transformer</td>
<td>320pF</td>
</tr>
<tr>
<td>Disconnector</td>
<td>120pF</td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>170pF</td>
</tr>
<tr>
<td>Bus Support Insulator</td>
<td>100pF</td>
</tr>
<tr>
<td>590kVA Transformer HV</td>
<td>2700pF</td>
</tr>
<tr>
<td>690kVA Transformer LV</td>
<td>2500pF</td>
</tr>
<tr>
<td>10kVA Transformer TV</td>
<td>2000pF</td>
</tr>
<tr>
<td>Between Transformer winding</td>
<td>50pF</td>
</tr>
</tbody>
</table>
**Network Component Models – Surge Arrester Model**

<table>
<thead>
<tr>
<th>Discharge Current (kA)</th>
<th>Max Residual Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>527.9</td>
</tr>
<tr>
<td>0.4</td>
<td>558.4</td>
</tr>
<tr>
<td>1</td>
<td>582.0</td>
</tr>
<tr>
<td>2</td>
<td>602.4</td>
</tr>
<tr>
<td>5</td>
<td>643.0</td>
</tr>
<tr>
<td>10</td>
<td>676.8</td>
</tr>
<tr>
<td>12</td>
<td>701.9</td>
</tr>
<tr>
<td>13</td>
<td>820.5</td>
</tr>
<tr>
<td>15</td>
<td>900.0</td>
</tr>
</tbody>
</table>

Typical Discharge Current vs Residual Voltage Characteristic of 220kV Surge Arrester.

**Network Component Models – String Insulator Model**

\[
\frac{V_B}{CFO} = 0.58 + 1.39t
\]

where

- \(V_B\): the breakdown, flash over, or crest voltage,
- \(t\): the time to breakdown or flash over

\(CFO\): Critical Flash Overvoltage in kV.

\(CFO\) implies the voltage level that results in a 50% probability of flash over if applied to the insulation.
Network Component Models – Tower Surge Impedance

where $\theta$ is the sine of the half angle of the cone

\[
Z_T = 60\ln \left( \frac{2h}{r} \right) - 60
\]

where $h$ and $r$ are the height and radius of the cylinder, respectively

Network Component Models – Tower Footing Resistance(1)

• Current to initiate sufficient soil ionization

\[
I_s = \frac{1}{2\pi} \frac{\rho E_0}{R_0}
\]

• Tower Footing Resistance

\[
R_f = \frac{R_0}{\sqrt{1 + I_s / I_i}}
\]

where $I_s$: Surge tower footing resistance

$R_0 = 100 \Omega$ is assumed to be high current resistance for transmission tower footing resistance and $R_i = 100 \Omega$ for earth resistance inside substation (worst case).

$E_0 = 400kV/m$: assumed soil ionization gradient

$I_i$: lightning current through the footing impedance

$\rho$: soil resistivity.
Network Component Models – Tower Footing Resistance (2)

- Current to initiate sufficient soil ionization
  \[ I_s = \frac{1}{R_{II}} \frac{\rho E_0}{2\pi R_{II}} \]

- Tower Footing Resistance
  \[ R_t = \frac{R_e}{\sqrt[3]{I_s/I_L}} \]

Stroke Current Model – Heidler Function

Mathematical Model - Heidler function

\[ I = \frac{I_s}{\eta} x(t)^n y(t) = \frac{I_s}{\eta} \left( \frac{t}{T_1} \right)^n e^{-\frac{t}{T_1}} \]

where
- \( T_1 \): proportional to \( t_{ext} \)
- \( T_2 \): proportional to \( t_{cal} \)
- \( I_0 \): Peak value.
- \( \eta \): correction factor of peak current
- \( n \): influences the time of the maximum slope
Stroke Current Model – Direct Strokes

The maximum shielding failure current \( I_m \) is calculated by:

\[
I_m = \left( \frac{\gamma \alpha \gamma}{A} \right)^{1/2}
\]

where approximation of \( \gamma \alpha \gamma \) is calculated by:

\[
\gamma \alpha \gamma = \frac{h+y}{2h(1-\gamma \sin \alpha)}
\]

\( h \): shielding height (m)
\( y \): highest conductor height (m)

\[
\sin \alpha = \frac{a}{\sqrt{a^2 + (h-y)^2}}
\]

where \( a \) is the horizontal distance between highest phase conductor and shielding wire (m)

\[
\gamma = \frac{444}{462-\delta} \text{ for } h>18 \text{m};
\]

\[\gamma = 1 \text{ for } h \leq 18 \text{m.}\]

(IEEE 1995 Substation Committee, Hileman pp.244, pp.248)

Stroke Current Model – Back Flashover Rate (BFR)

\[
BFR = \frac{1}{d_{MTBS}} \text{ flashes per 100km-years}
\]

where \( d_{MTBS} \) is the distance from gantry to the first

With any specific MTBS, there exists a critical stroke current \( I_s \) that the substation insulation may fail under if the first tower suffered from stroke current \( I > I_s \)

\[
P(I > I_s) = \frac{1}{0.6d_{MTBS}N_{MTBS}}
\]
Stroke Current Model – Critical Stroke Current

CIGRE Working Group Report [9] suggests the statistical distribution of all parameters of the flash can be approximated by the lognormal distribution whose probability density function is of the form:

\[ f(I) = \frac{1}{\sqrt{2\pi} \beta} e^{-\frac{(\ln(I/M) - \beta)^2}{2\beta^2}} \]

where \( Z = \frac{\ln(I/M)}{\beta} \)

\( I \) - probability distribution
\( M \) - median
\( \beta \) - log standard deviation obtained from Berger's data [1]

We have:

\[ 1 - P(I > I_c) = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z_c} e^{-\frac{Z^2}{2}} dZ \]

\[ 1 - P(I > I_c) = \frac{1}{\sqrt{2\pi}} \int_{Z_c}^{\infty} e^{-\frac{Z^2}{2}} dZ \]

From table of Cumulative Normal Distribution Function, finding the approximate value of \( Z_c \).

The critical stroke current is then calculated:

\[ I_c = Me^{\beta \text{Z}_c} \]

---

Stroke Current Model – Front Time Median

**Front Time Median**

\[ t_f = 0.207 I_c^{0.53} \]

(Conditional Lognormal Distributions from Berger's Data)
Determining the tail time constant is an iterative process, whereby the following formula is applied in the sequence, as suggested by Bewley (Hilemen pp397):

\[ R_x = \frac{R_z Z_x}{Z_x + 2R_i} \]

\[ I_x = \frac{R_z I_S}{R_i} \]

\[ I_S = \frac{1}{2\pi} \frac{E_o \rho}{R_0^2} \]

\[ R_i = \frac{R_{ns}}{\sqrt{1 + I_x / I_S}} \]

\[ Z_x \] is the surge impedance of earth wire conductor(s).

**Calculation Example**

<table>
<thead>
<tr>
<th>Iteration no.</th>
<th>( R_z (\Omega) )</th>
<th>( I_x (O) )</th>
<th>( I_S (A) )</th>
<th>( R_i (\Omega) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>9.70717</td>
<td>259.054</td>
<td>6.99351</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>6.85524</td>
<td>261.35</td>
<td>6.96</td>
</tr>
</tbody>
</table>

**Tail Time Median**

\[ \tau = \frac{Z_x}{R_i} T_S \]

Where \( T_S \) is to be time travel of surge for the first span length.
Case Studies

DIgSILENT PowerFactory 14.0.523
BROCKMAN SUBSTATION
INSULATION COORDINATION STUDY
Project: 2030       Graphic: Brockman  Date:     2/23/2011  Annex:

Nodes
Branches

BRK 11kV
BRK 33kV

Circuit #2
Earth Wire
Circuit

Circuit #1
Earth Resistance
Tower
Lightning Stroke
Struck Tower

T0001 T0002
SA4
SA2
SA3
SA1
Gantry

Case Studies – Stroke Current Waveform Summary

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Current Waveform</th>
<th>η</th>
<th>T1</th>
<th>T2</th>
<th>Tn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Stroke</td>
<td>20 kA 1.2/50 us.</td>
<td>0.98</td>
<td>7.51033E-07</td>
<td>6.8117E-05</td>
<td>8</td>
</tr>
<tr>
<td>Ideal First Stroke(AS 1768)</td>
<td>150 kA 4.6/40 us</td>
<td>0.88</td>
<td>3.9549E-06</td>
<td>4.2941E-05</td>
<td>13</td>
</tr>
<tr>
<td>250yrs MTBF design</td>
<td>112kA 2.5/91 us.</td>
<td>0.97</td>
<td>1.31343E-06</td>
<td>0.000122304</td>
<td>13</td>
</tr>
</tbody>
</table>
Case 1 Results - Direct Stroke

1. BR_Gantry1 220kV: m:U:A, m:U:B, m:U:C
   - Y = 773.815 kV
   - BIL = 1016 kV

2. CB1_1: m:U:A, m:U:B, m:U:C
   - Y = 678.341 kV
   - BIL = 1016 kV

   - Y = 656.973 kV
   - BIL = 1016 kV

4. IS3_1: m:U:A, m:U:B, m:U:C
   - Y = 696.743 kV
   - BIL = 1161 kV

5. SA1 ABB PEXLIM Q288-XV245SE: MO absorbed Energy in MWs
   - 0.197 MWs

6. SA2 ABB PEXLIM Q288-XV245SE(1): MO absorbed Energy in MWs
   - 0.203 MWs

7. SA3 ABB PEXLIM Q288-XV245SE: MO absorbed Energy in MWs

8. SA1 ABB PEXLIM Q288-XV245SE: MO Current A in kA
   - Y = 11.746 kA
   - 0.0444 us

9. SA2 ABB PEXLIM Q288-XV245SE(1): MO Current A in kA
   - Y = 11.395 kA
   - 0.0444 us

10. SA3 ABB PEXLIM Q288-XV245SE: MO Current A in kA

Date: 8/11/2008
Annex: 2030 /12
Case 2 Results - Ideal Stroke 150 kA 4.6/40us
Case 2 Results - Ideal Stroke 150 kA 4.6/40us

Diagrams showing voltage waveforms for different components and phases.

- **BR_Gantry1 220kV:**
  - Phase Voltage A in kV
  - Phase Voltage B in kV
  - Phase Voltage C in kV

- **CB1_1:**
  - Phase Voltage A in kV
  - Phase Voltage B in kV
  - Phase Voltage C in kV

- **T10001:**
  - Phase Voltage A/HV-Side in kV
  - Phase Voltage B/HV-Side in kV
  - Phase Voltage C/HV-Side in kV

- **IS3_1:**
  - Phase Voltage A in kV
  - Phase Voltage B in kV
  - Phase Voltage C in kV

- **T10001:**
  - Phase Voltage A/MV-Side in kV
  - Phase Voltage B/MV-Side in kV
  - Phase Voltage C/MV-Side in kV

- **BR_11kV:**
  - Phase Voltage A in kV
  - Phase Voltage B in kV
  - Phase Voltage C in kV

- **Brockman 33kV:**
  - Phase Voltage A in kV
  - Phase Voltage B in kV
  - Phase Voltage C in kV

**BIL** values:
- BR_Gantry1: 1016 kV
- CB1_1: 701.608 kV
- T10001: 73 kV
- IS3_1: 165 kV
- Brockman 33kV: 165 kV

**Y** values:
- BR_Gantry1: 1111.908 kV
- CB1_1: 831.373 kV
- T10001: 865.666 kV
- IS3_1: 15.694 kV
- Brockman 33kV: 122.014 kV

**Date:** 8/11/2008

**Annex:** 2030/12
Case 2 Results - Ideal Stroke 150 kA 4.6/40us

Case 3 Results - Earth Wire Stroke 112 kA 2.5/91us
Case 3 Results - Earth Wire Stroke 112 kA 2.5/91us

<table>
<thead>
<tr>
<th>R_earth_P1: Phase Current A/Terminal</th>
<th>Magnitude (kA)</th>
<th>Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100.0</td>
<td>79.80</td>
</tr>
<tr>
<td></td>
<td>59.60</td>
<td>39.40</td>
</tr>
<tr>
<td></td>
<td>19.20</td>
<td>-1.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R_earth_P1: Line-Ground Voltage Phasor, Magnitude/Terminal</th>
<th>Magnitude (kV)</th>
<th>Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120.00</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>80.00</td>
<td>60.00</td>
</tr>
<tr>
<td></td>
<td>40.00</td>
<td>20.00</td>
</tr>
<tr>
<td></td>
<td>0.00</td>
<td>-20.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R_earth_P1: Resistance (Input) in Ohm</th>
<th>Magnitude (Ω)</th>
<th>Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>-25.00</td>
<td>-50.00</td>
</tr>
<tr>
<td></td>
<td>-75.00</td>
<td>-100.00</td>
</tr>
<tr>
<td></td>
<td>-125.00</td>
<td>-150.00</td>
</tr>
</tbody>
</table>

Stroke Current: Current, Magnitude A in kA

---

Case 3 Results - Earth Wire Stroke 112 kA 2.5/91us

<table>
<thead>
<tr>
<th>BR_Gantry1 220kV: Phase Voltage</th>
<th>Magnitude (kV)</th>
<th>Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.783</td>
<td>9.870</td>
</tr>
<tr>
<td>B</td>
<td>2.946</td>
<td>10.00</td>
</tr>
<tr>
<td>C</td>
<td>2.964</td>
<td>10.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CB1_1: Phase Voltage</th>
<th>Magnitude (kV)</th>
<th>Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>763.070</td>
<td>2.983</td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T10001: Phase Voltage</th>
<th>Magnitude (kV)</th>
<th>Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/HV-Side</td>
<td>662.564</td>
<td>1.999</td>
</tr>
<tr>
<td>B/HV-Side</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C/HV-Side</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IS3_1: Phase Voltage</th>
<th>Magnitude (kV)</th>
<th>Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>789.244</td>
<td>2.999</td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Case 3 Results - Earth Wire Stroke 112 kA 2.5/91us

**Case 3: 112kA 2.5/91us, Phase A, Milstream Line, 300m span**

**Date:** 8/12/2008

**Annex:** 2030/13

**DigSILENT PowerFactory Users' Conference 2011**
Conclusions

This paper introduces modelling techniques to achieve more accurate results when executing lightning insulation coordination studies using DIgSILENT PowerFactory.

Thank you