Lightning Insulation Coordination Study

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DIgSILENT Pacific

Presentation Outline

- **Introduction**
- **Network Components Model**
- **Stroke Current Model**
- **Case Studies and Results**
- **Conclusions**

Introduction – Lightning Insulation Coordination

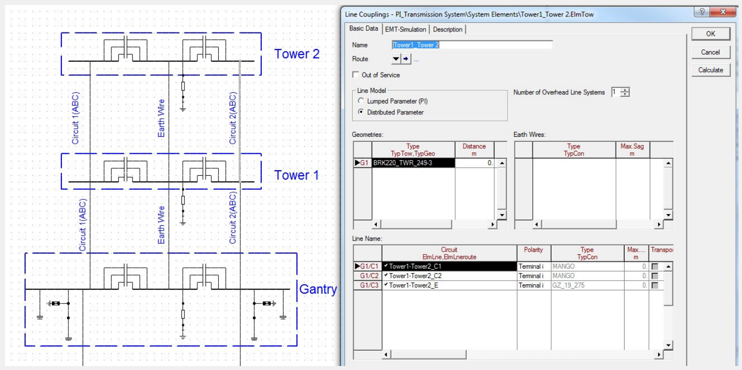
Insulation Coordination is required to ensure

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

Network Component Models

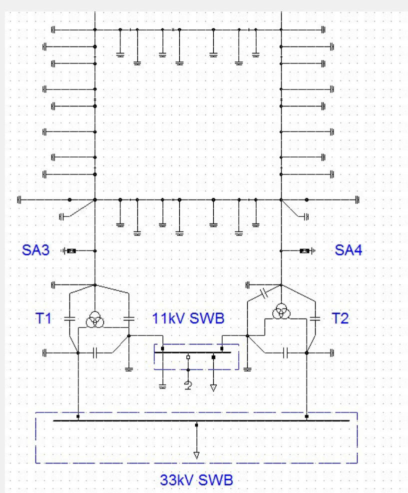
- Transmission Line Model
- Equipment's Stray Capacitance
- Surge Arrester.
- Current Dependant Characteristic of Tower Footing Resistance
- Tower Surge Impedance.
- Time Dependant Characteristic of Insulator Strength.
- Stroke Current Model.
- Determination of Critical Stroke Current's Parameters.

Network Component Models – Transmission Line



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

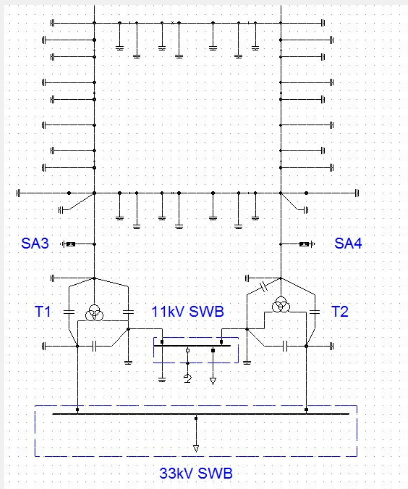
Network Component Models – Equipment's Stray Capacitance



Typical data of equipment's stray capacitance

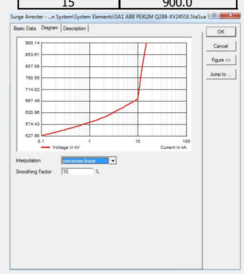
Equipment	Capacitance to Ground
Capacitive Potential Transformer	6000pF
Magnetic Potential Transformer	600pF
Current Transformer	350pF
Disconnector	120pF
Circuit breaker	150pF
Bus Support Insulator	100pF
70MVA Transformer HV	2700pF
60MVA Transformer LV	2350pF
10MVA Transformer TV	2000pF
Between Transformer winding	30pF

Network Component Models – Surge Arrester Model

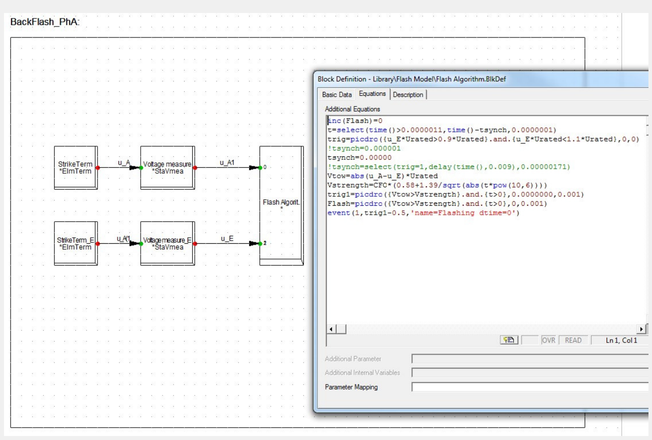


Typical Discharge Current vs Residual Voltage Characteristic of 220kV Surge Arrester.

Discharge Current(kA)	Max Residual Voltage(kV)
0.1	527.9
0.4	558.4
1	582.0
2	602.4
5	643.0
10	676.8
12	791.9
13	832.5
15	900.0



Network Component Models – String Insulator Model



$$\frac{V_B}{CFO} = 0.58 + \frac{1.39}{\sqrt{t}}$$

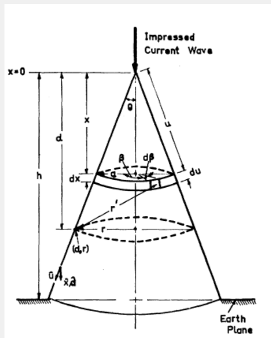
where

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 result in a 50% probability of flash over if applied to the insulation.)

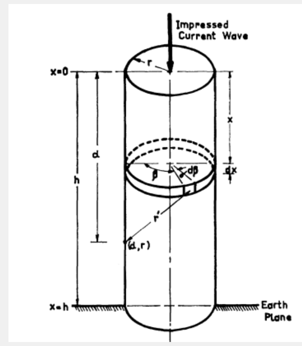
Network Component Models – Tower Surge Impedance



Conical Tower (Sargenet A.M.)

$$Z_T = 60 \ln \frac{\sqrt{2}}{\sin\theta}$$

where θ is the sine of the half angle of the cone



Cylindrical tower (Sargenet A.M.)

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

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

Network Component Models – Tower Footing Resistance(1)

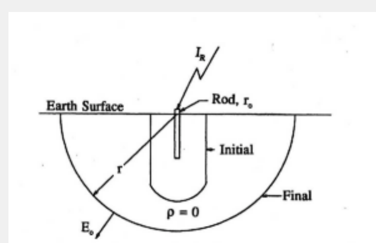
- Current to initiate sufficient soil ionization

$$I_g = \frac{1}{2\pi}\frac{\rho E_0}{R_0^2}$$

- Tower Footing Resistance

$$R_i = \frac{R_0}{\sqrt{1 + I_R / I_g}}$$

where
R_i : Surge tower footing resistance
$R_0 = 100\Omega$ is assumed to be low current resistance for transmission tower footing resistance and $R_0 = 10\Omega$ for earth resistance inside substation (worst case).
$E_0 = 400kV/m$: assumed soil ionization gradient
I_R : lightning current through the footing impedance
ρ : soil resistivity.



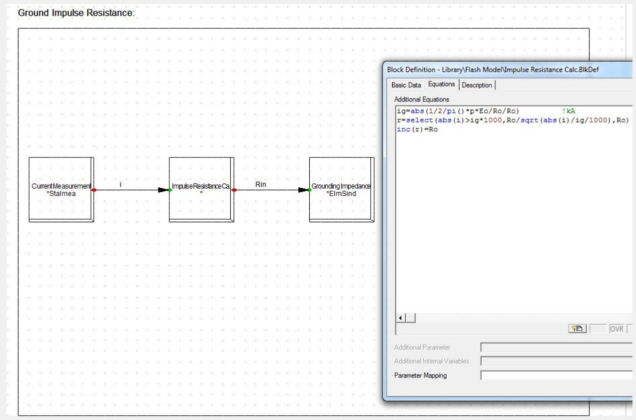
Network Component Models – Tower Footing Resistance(2)

- Current to initiate sufficient soil ionization

$$I_g = \frac{1}{2\pi} \frac{\rho E_0}{R_0^2}$$

- Tower Footing Resistance

$$R_i = \frac{R_0}{\sqrt{1 + I_R / I_g}}$$



Stroke Current Model – Heidler Function

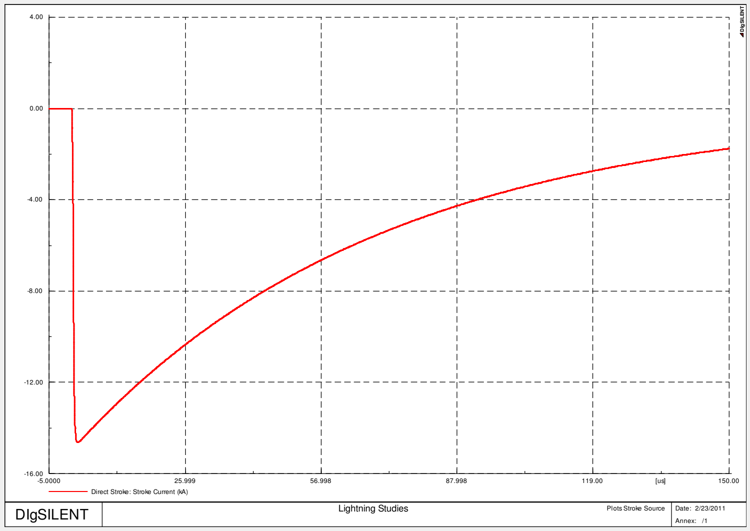
Mathematical Model - Heidler function

$$I = \frac{I_o}{\eta} * x(t) * y(t) = \frac{I_o}{\eta} \frac{\left(\frac{t}{T_1}\right)^n}{1 + \left(\frac{t}{T_1}\right)^n} e^{-\frac{t}{T_2}}$$

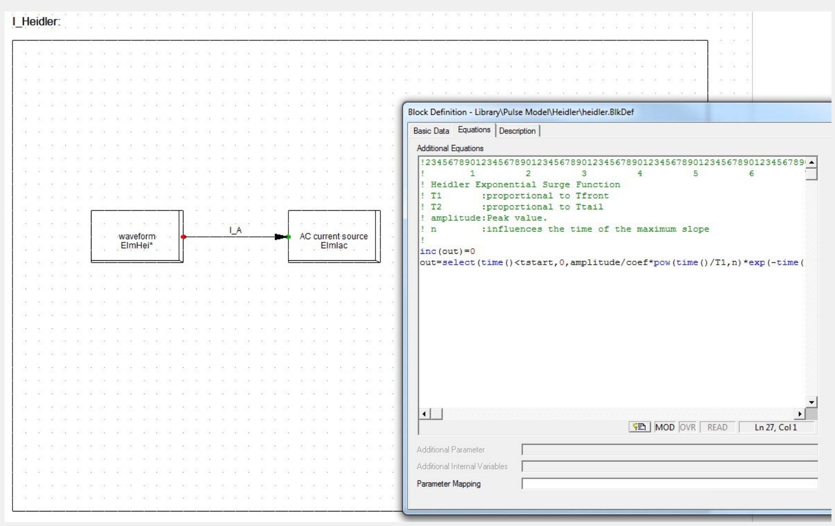
where

- T_1 : proportional to t_{front}
- T_2 : proportional to t_{tail}
- I_0 : Peak value.
- η : correction factor of peak current
- n : influences the time of the maximum slope

Stroke Current Model – Heidler Function



Stroke Current Model – Heidler Function



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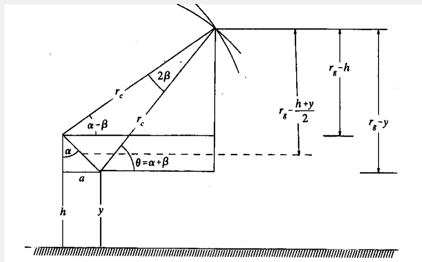
Stroke Current Model – Direct Strokes



Geometric Model of Tower for Lightning Study

The maximum shielding failure current I_m is calculated by:

$$I_m = \left[\frac{r_{gm}}{A}\right]^{\frac{1}{b}}$$

where approximation of r_{gm} is calculated by:

$$r_{gm} = \frac{(h+y)}{2(1-\gamma \sin\alpha)}$$

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)

$\gamma = 444/(462-h)$ for h>18m;
$\gamma = 1$ for h<=18m.

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

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Stroke Current Model – Back Flashover Rate(BFR)

$$BFR = \frac{1}{d_m MTBS}$$ flashes over per 100km-years

where d_m is the distance from gantry to the first

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

$$P(I > I_S) = \frac{1}{0.6 d_m N_L MTBS}$$

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:

$$f(I) = \frac{1}{\sqrt{2\pi}\beta I} e^{-\frac{1}{2}Z^2}$$

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

M :probability distribution median and β is the log standard distribution obtained from Berger's data [1]

We have:

$$1 - P(I > I_S) = 1 - \frac{1}{2\pi}\int_{I_S}^{\infty} e^{-\frac{1}{2}Z^2} dZ$$

$$1 - P(I > I_S) = \frac{1}{2\pi}\int_{-\infty}^{I_S} e^{-\frac{1}{2}Z^2} dZ$$

From table of Cumulative Normal Distribution Function, finding the approximate value of Z. The critical stroke current is then calculated:

$$I_c = Me^{Z\beta}$$

Stroke Current Model – Front Time Median

Front Time Median

$$t_f = 0.207 I_c^{0.53}$$

(Conditional Lognormal Distributions from Berger's Data)

Stroke Current Model – Tail Time Median

Determining the tail time constant is an iterative process, whereby the following formula is applied in the sequence, as suggested by Bewley (Hilemen pp397):

$$R_e = \frac{R_i Z_g}{Z_g + 2R_i}$$

$$I_R = \frac{R_e}{R_i} I_S$$

$$I_g = \frac{1}{2\pi} \frac{E_0 \rho}{R_0^2}$$

$$R_i = \frac{R_0}{\sqrt{1 + I_R / I_g}}$$

Z_g is the surge impedance of earth wire conductor(s).

Iteration no.	$R_i(\Omega)$	$R_e(\Omega)$	$I_R(kA)$	$R_i(\Omega)$
1	10	9.70717	259.054	6.99351
2	7	6.85524	261.35	6.96

Calculation Example

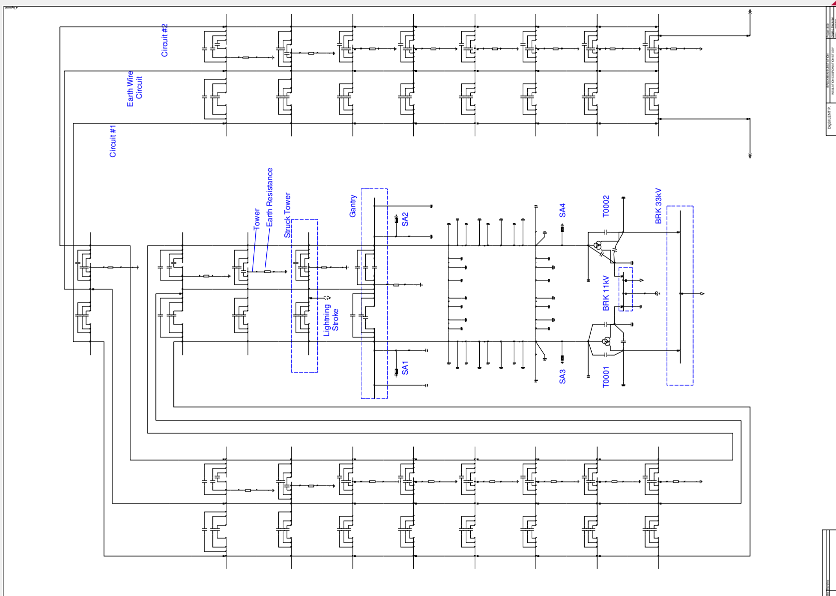
Stroke Current Model – Tail Time Median

Tail Time Median

$$\tau = \frac{Z_g}{R_i} T_S$$

Where $\mathbf{T_s}$ is to be time travel of surge for the first span length.

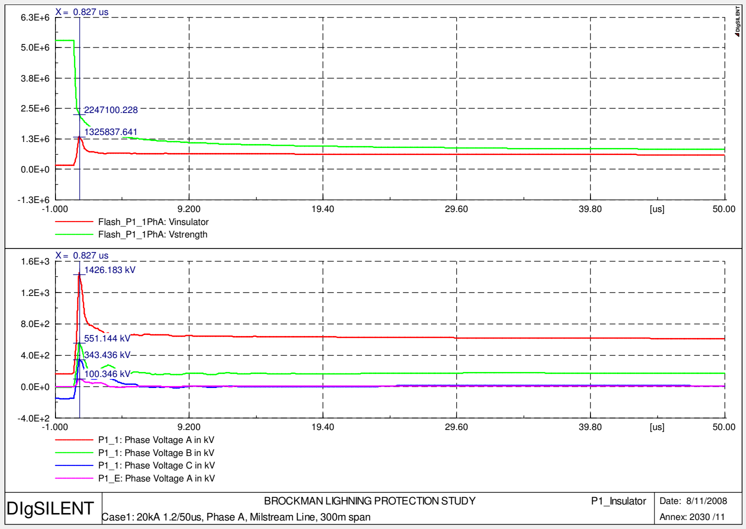
Case Studies



Case Studies – Stroke Current Waveform Summary

Test Case	Current Waveform	η	Heidler Function T_1	T_2	n
Direct Stroke	20 kA 1.2/50 us	0.98	7.51035E-07	6.8117E-05	8
Ideal First Stroke(AS 1768)	150 kA 4.6/40 us	0.88	3.9549E-06	4.2941E-05	13
250yrs MTBF design	112 kA 2.5/91 us	0.97	1.91343E-06	0.000122304	13

Case 1 Results - Direct Stroke



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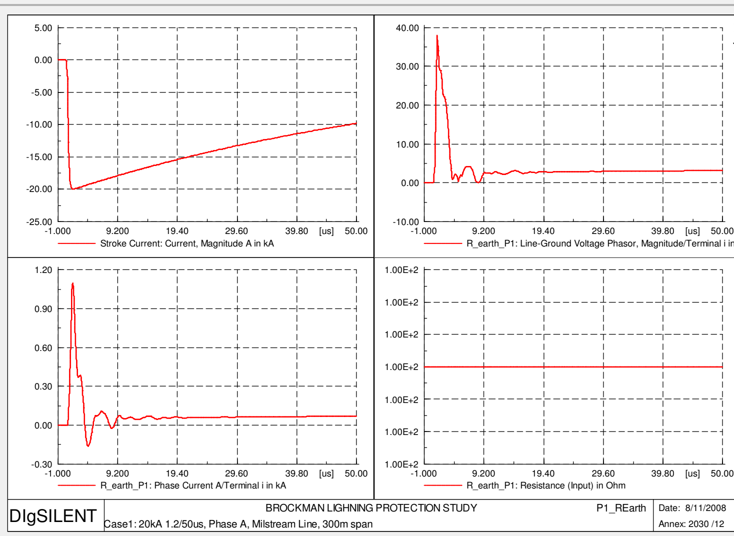

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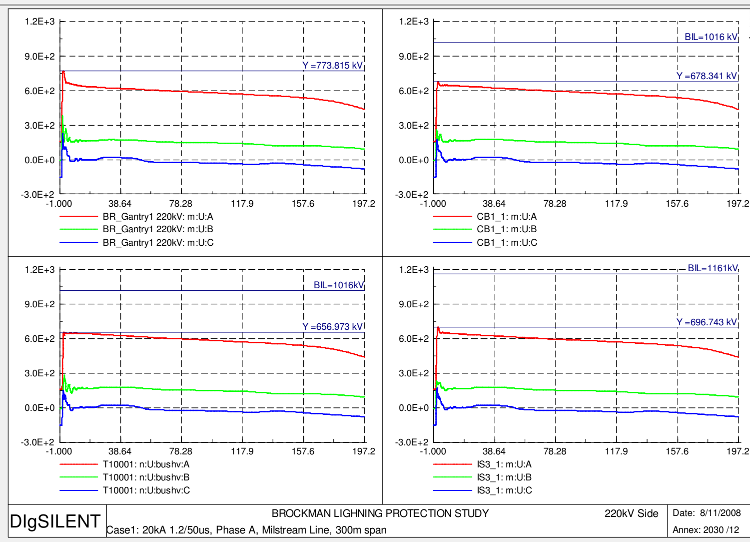

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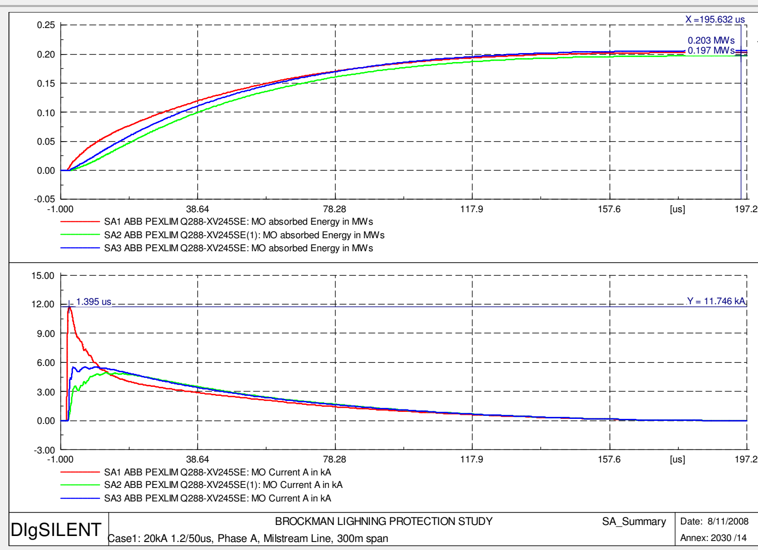
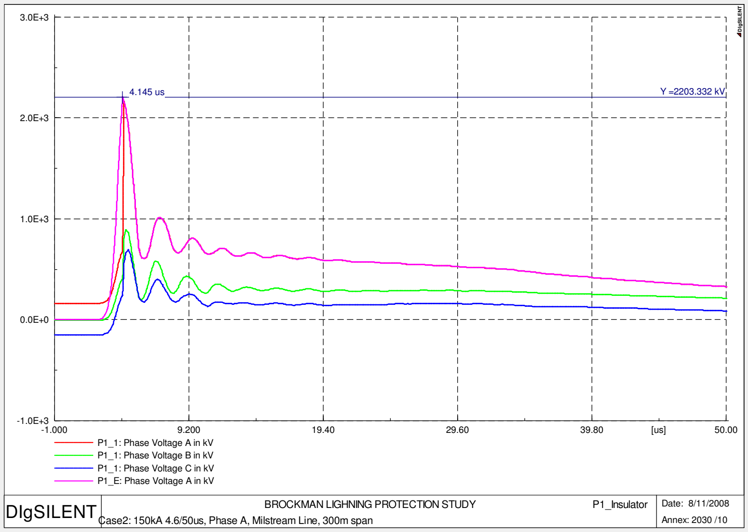


Case 2 Results - Ideal Stroke 1*50 kA 4.6/40us*



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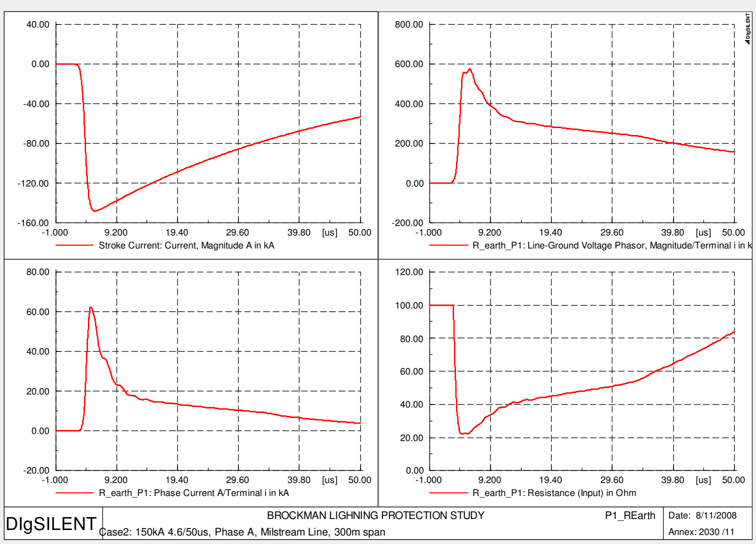
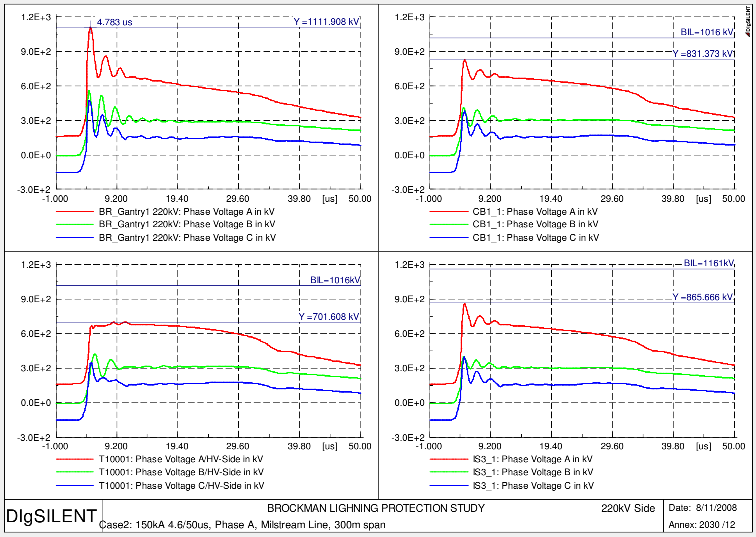


Case 2 Results - Ideal Stroke 150 kA 4.6/40us



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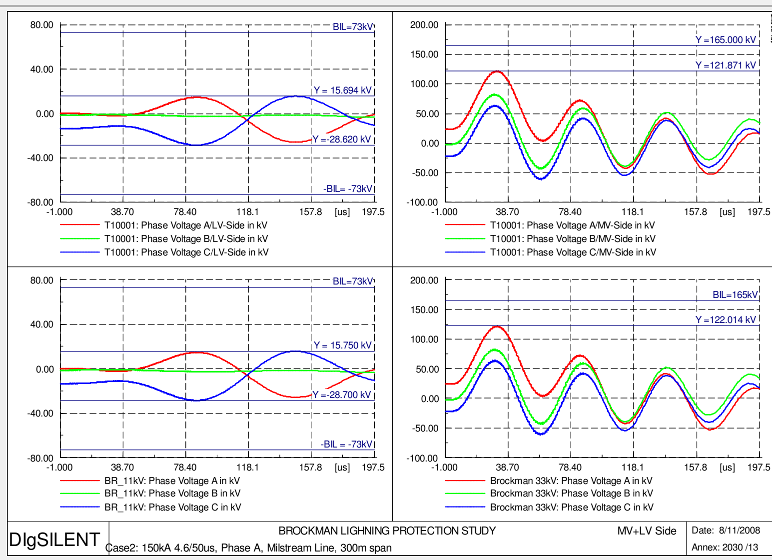

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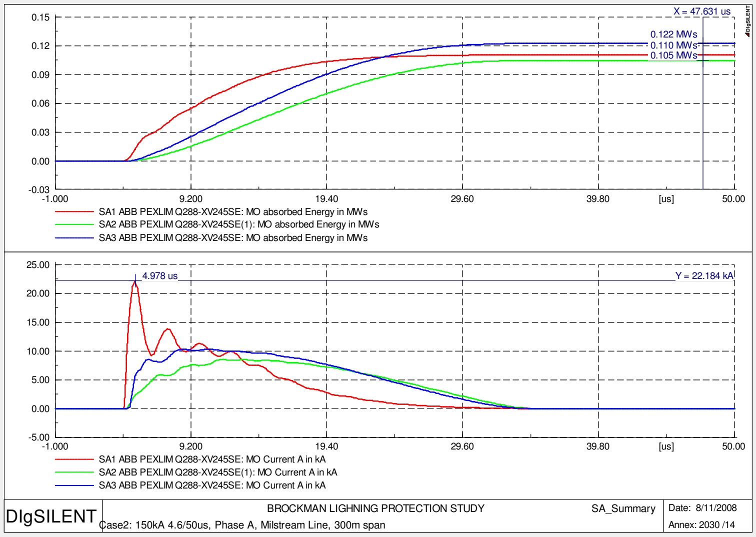
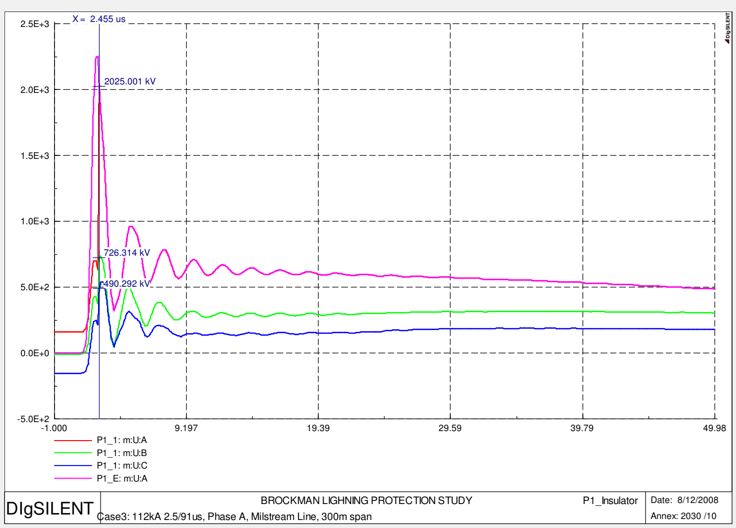


Case 3 Results - *Earth Wire Stroke 112 kA 2.5/91us*



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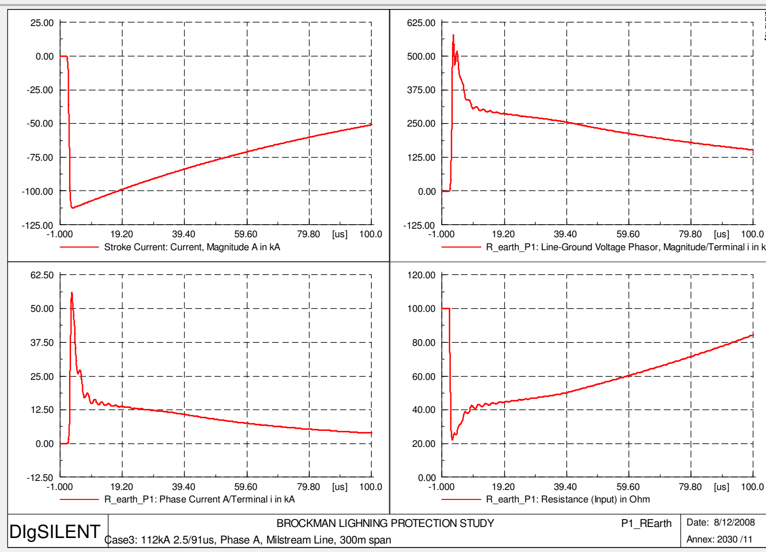

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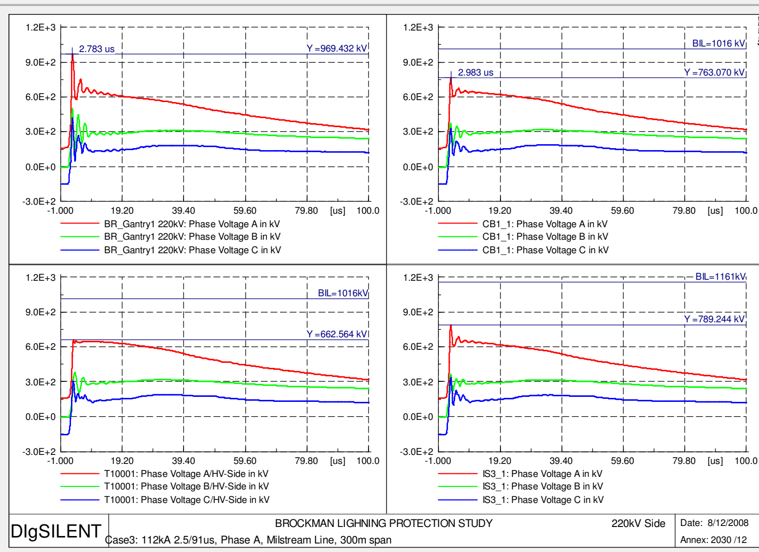

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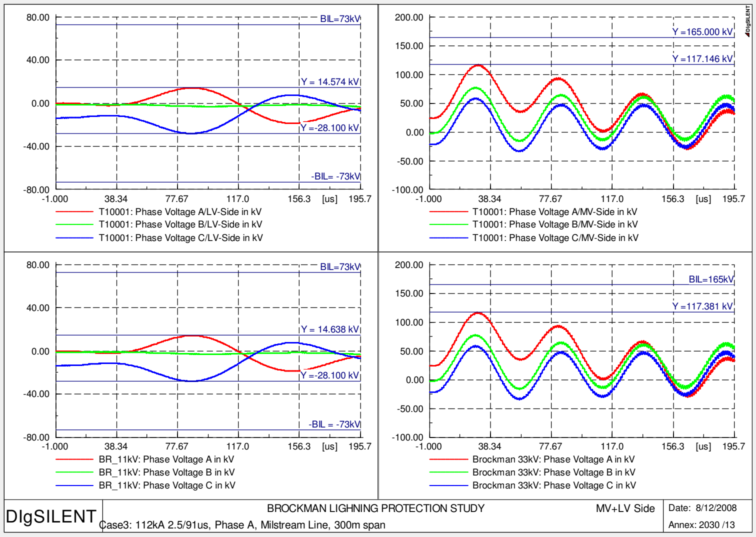

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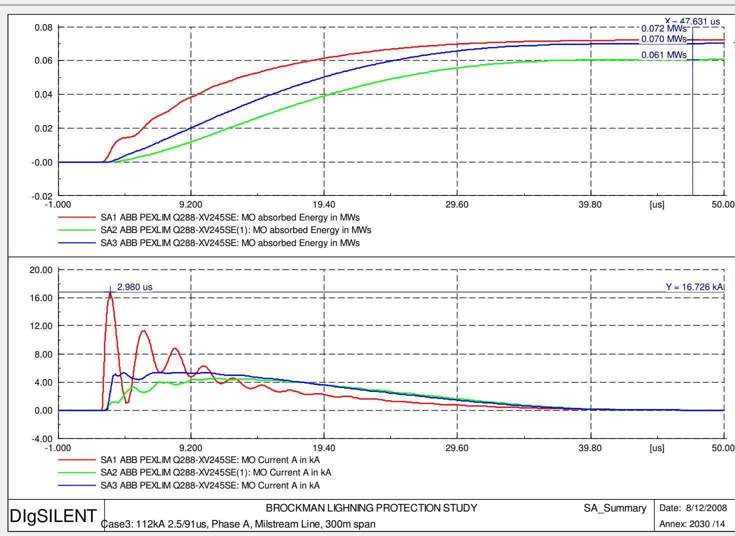

Conclusions

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

Thank you