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Lightning Flashover Rate of an Overhead Transmission Line Protected by Surge Arresters

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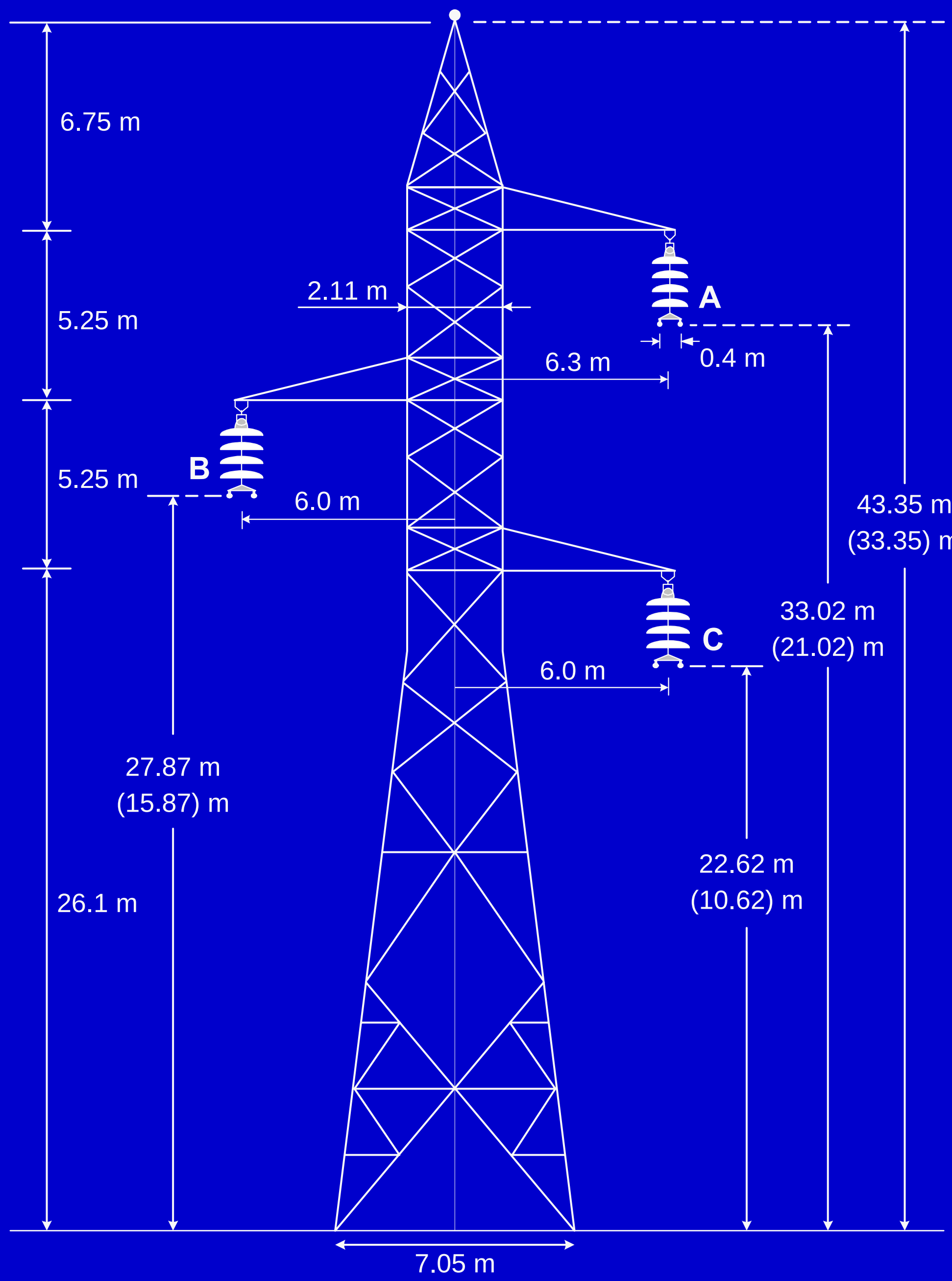
Introduction

- Surge arresters improve the lightning performance of lines with a poor shielding or with very high tower footing impedances
- Arresters must be selected taking into account energy discharge stresses
- Aim of this paper: analyzing the lightning performance improvement of a shielded transmission line after installing surge arresters
- The study will be also aimed at estimating the energy absorption capability of arresters
- A statistical approach must be used due to the random nature of lightning

Contents

- Description of the test line
- Modeling guidelines
- Features of the Monte Carlo based method
- Line and lightning parameters
- Lightning flashover rate without arresters
- Arrester energy study
- Lightning flashover rate with arresters

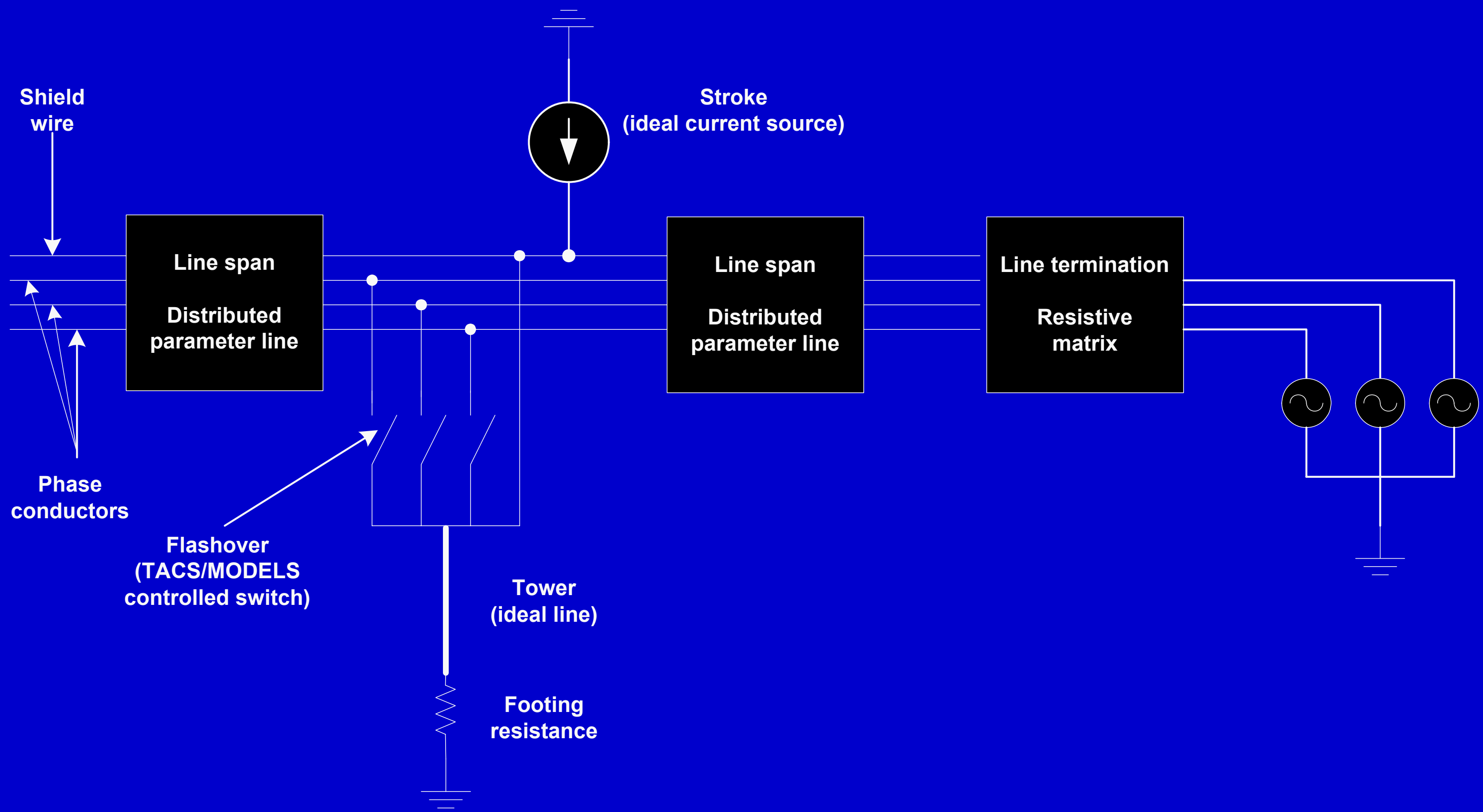
Test line (400 kV)



Modeling guidelines

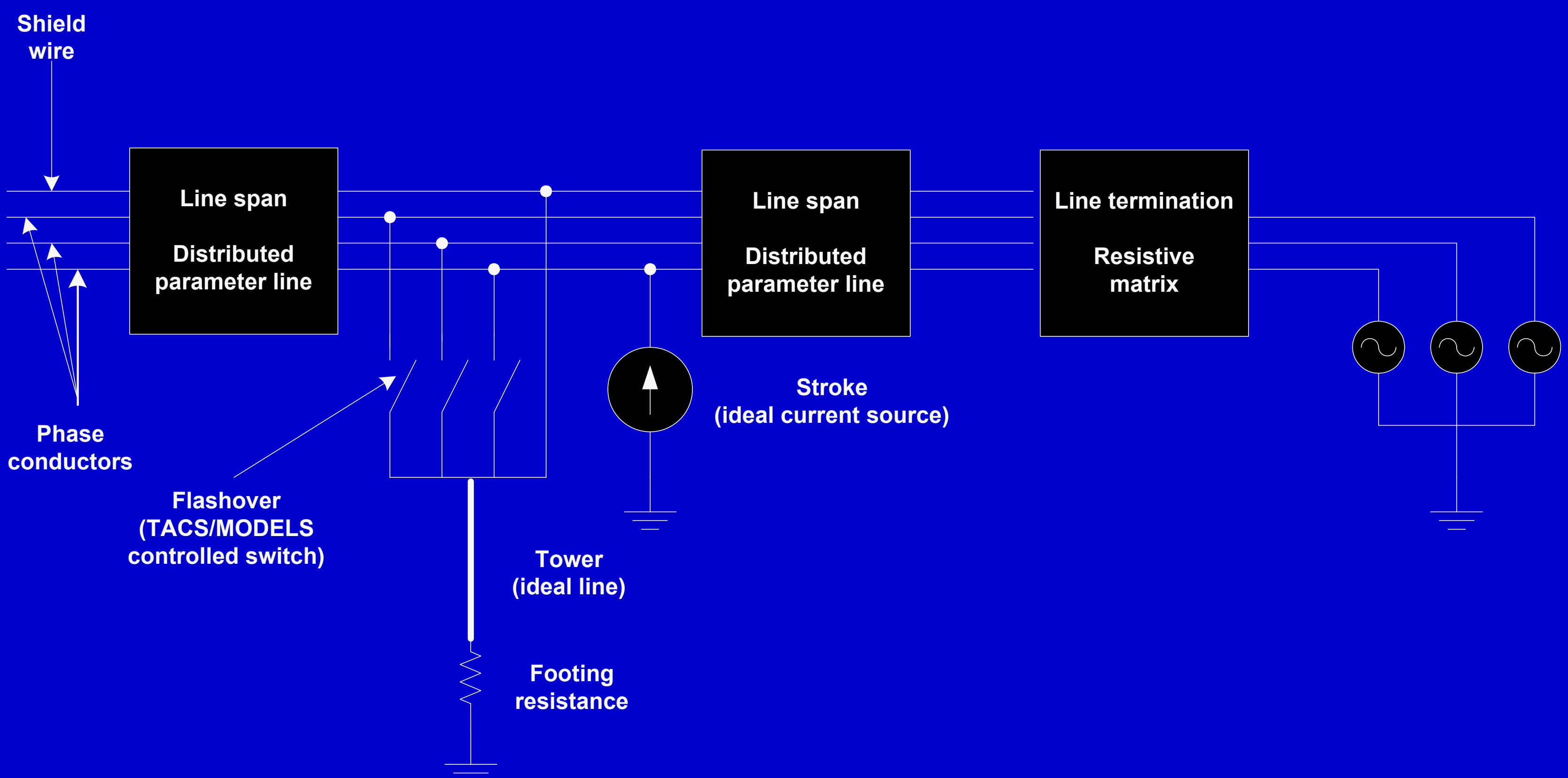
- Line span model
- Line termination
- Insulator strings
- Towers
- Footing impedance
- Power frequency phase conductor voltages
- Line surge arresters
- Return stroke – Waveform, parameters

Modeling guidelines



Overvoltages originated by strokes to shield wires

Modeling guidelines



Overvoltages originated by strokes to conductors

Lightning stroke parameters

- Return stroke waveform
  - Concave waveform - Heidler model

$$i(t) = \frac{I_p}{\eta} \frac{k^n}{1+k^n} e^{-t/\tau_2}$$

I_p is the peak current

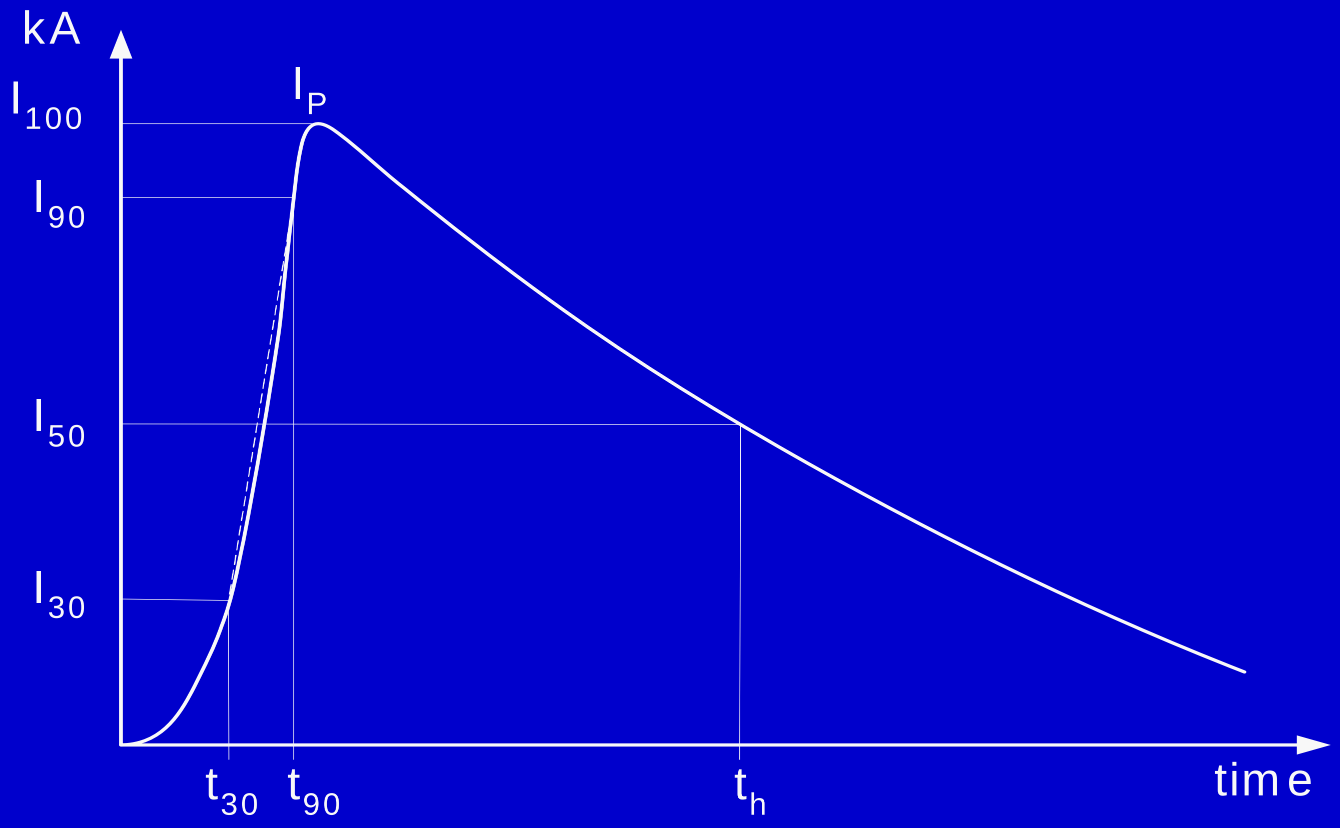
η is a correction factor of the peak current

n is the current steepness factor

$k=t/\tau_1$, (τ_1, τ_2 time constants determining current rise and decay-time, respectively)

Lightning stroke parameters

Return stroke waveform



Lightning stroke parameters

- Return stroke waveform
  - Parameters used to define this waveform
    - the peak current magnitude, I_{100}
    - the rise time, t_f (= $1.67\ (t_{90} - t_{30})$)
    - the tail time, t_h (time interval between the start of the wave and the 50% of peak current on tail)
  - The main difficulty to synthesize a concave waveform is the determination of the parameters to be specified in the current expression from those of the return stroke (I_{100}, t_f, t_h)

Insulator strings

- Based on the leader progression model (LPM)
- When the applied voltage exceeds the corona inception voltage, streamers propagate along the insulator string; if the voltage remains high enough, these streamers will become a leader channel
- A flashover occurs when the leader crosses the gap between the cross-arm and the conductor
- The total time to flashover can be expressed as follows

$$t_t = t_c + t_s + t_l$$

t_c is the corona inception time (it is usually neglected)
t_s is the streamer propagation time

$$t_s = \frac{E_{50}}{1.25E - 0.95E_{50}}$$

E_{50} is the average gradient at the critical flash-over voltage
E is the maximum gradient before breakdown

Insulator strings

- The leader propagation time, t_l, can be obtained from the following equation

$$\frac{dl}{dt} = k_l V(t) \left[\frac{V(t)}{g - l} - E_{l0} \right]$$

$V(t)$ is the voltage across the gap
g is the gap length
l is the leader length
E_{l0} is the critical leader inception gradient
k_l is a leader coefficient

- The leader propagation stops if the gradient in the un-bridged part of the gap falls below E_{l0}

Monte Carlo procedure

- Calculation of random values (lightning stroke parameters, leader channel location, phase conductor voltages, footing resistance, insulator strength)
- Application of the electrogeometric model
- Overvoltage calculations
- If a flashover occurs, the counter is increased and the flashover rate updated
- Convergence of the Monte Carlo method

Line and lightning parameters

- Models were created using ATP capabilities
- Line represented by means of 390-m spans plus a 30-km section as line termination at each side of the point of impact
- Tower surge impedance calculated according to the expression suggested by CIGRE
- Parameters of insulator equation

$$k_I = 1.3E\text{-}6\ m^2/(V^2s)\ ;\ E_{I0} = 570\ kV/m$$

- Insulator string striking distance 3.066 m
- Only negative single stroke flashes (represented by the Heidler model) were considered

Line and lightning parameters

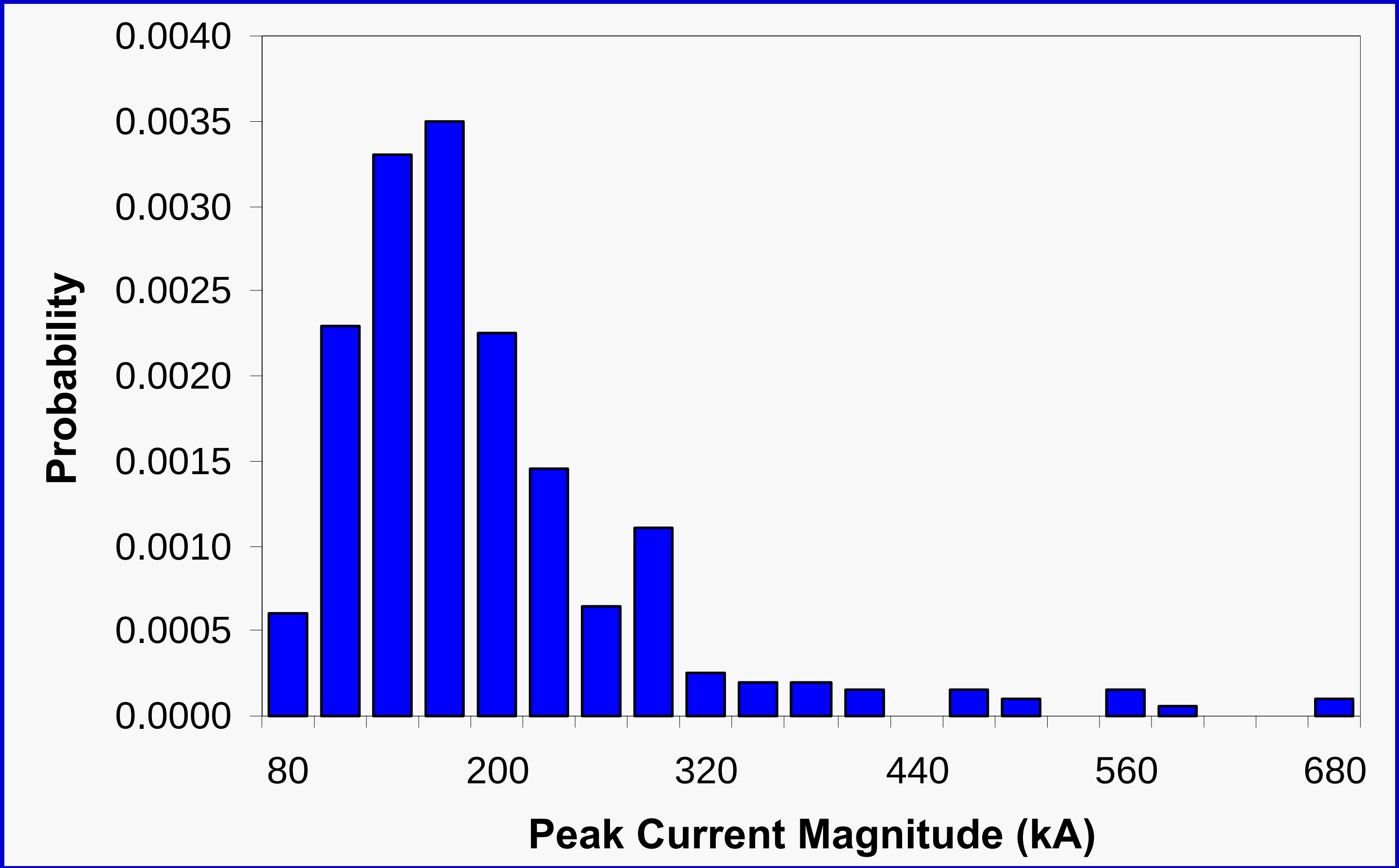
Probability distributions assumed

- Stroke parameters determined assuming a log-normal distribution
- The reference angle had a uniform distribution, between 0 and 360 degrees
- Insulator string parameters determined according to a Weibull distribution, with a standard deviation of 5% for all parameters.
- The footing resistance had a normal distribution with a mean value of 50 Ω and a standard deviation of 5 Ω (soil resistivity = 200 Ω.m)
- The stroke location was obtained by assuming a uniform ground distribution of the leader

Flasshover rate without arresters

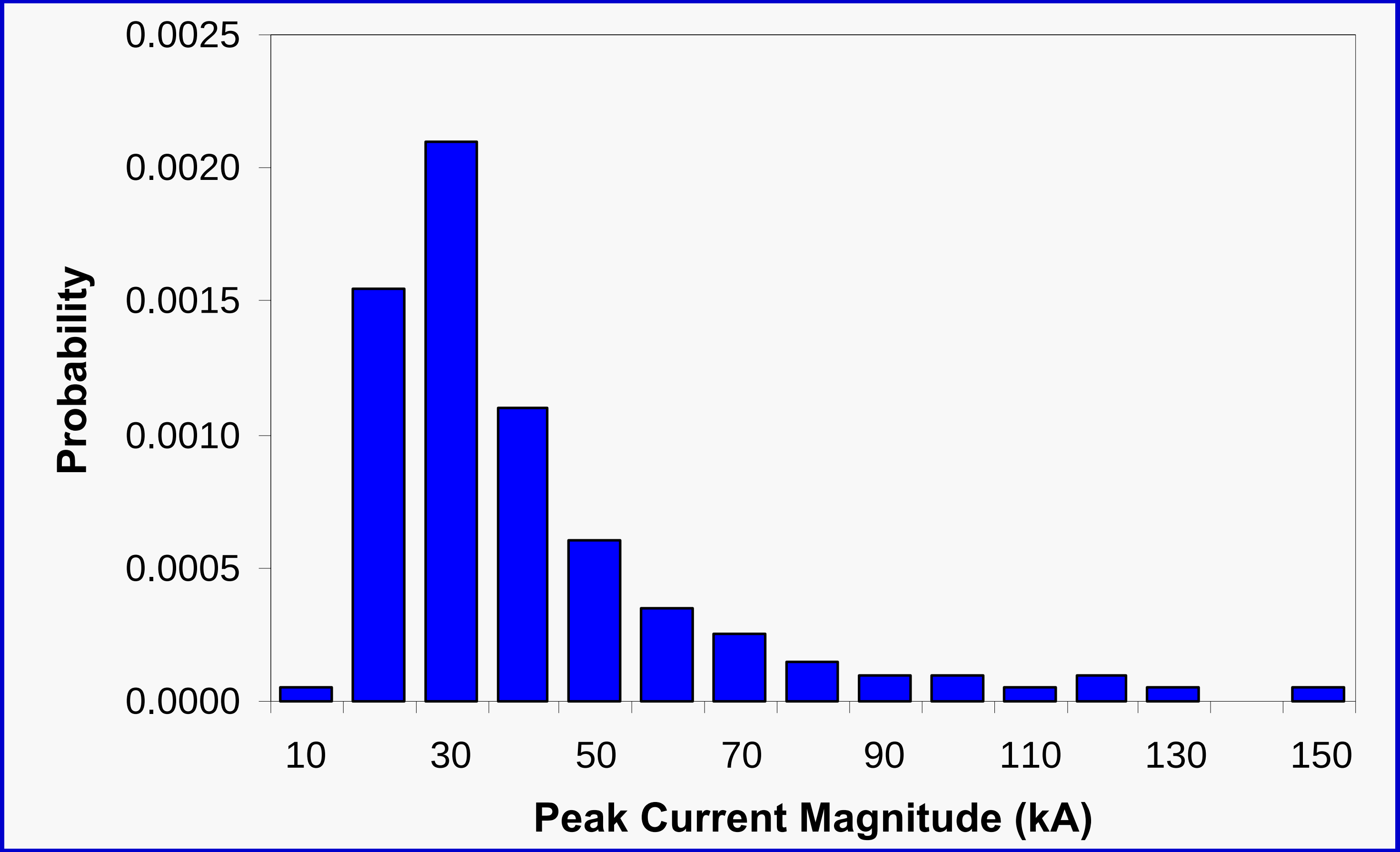
- Flashover rates after 20000 runs
  - backflashovers = 1.65 per 100 km-year
  - shielding failures = 0.66 per 100 km-year
- The total flashover rate was 2.31per 100 km-year
- Values obtained N_g = 1 fl/km^2-year
- Too high rate for a transmission line

Simulation results



Strokes to shield wires that caused flashover

Simulation results

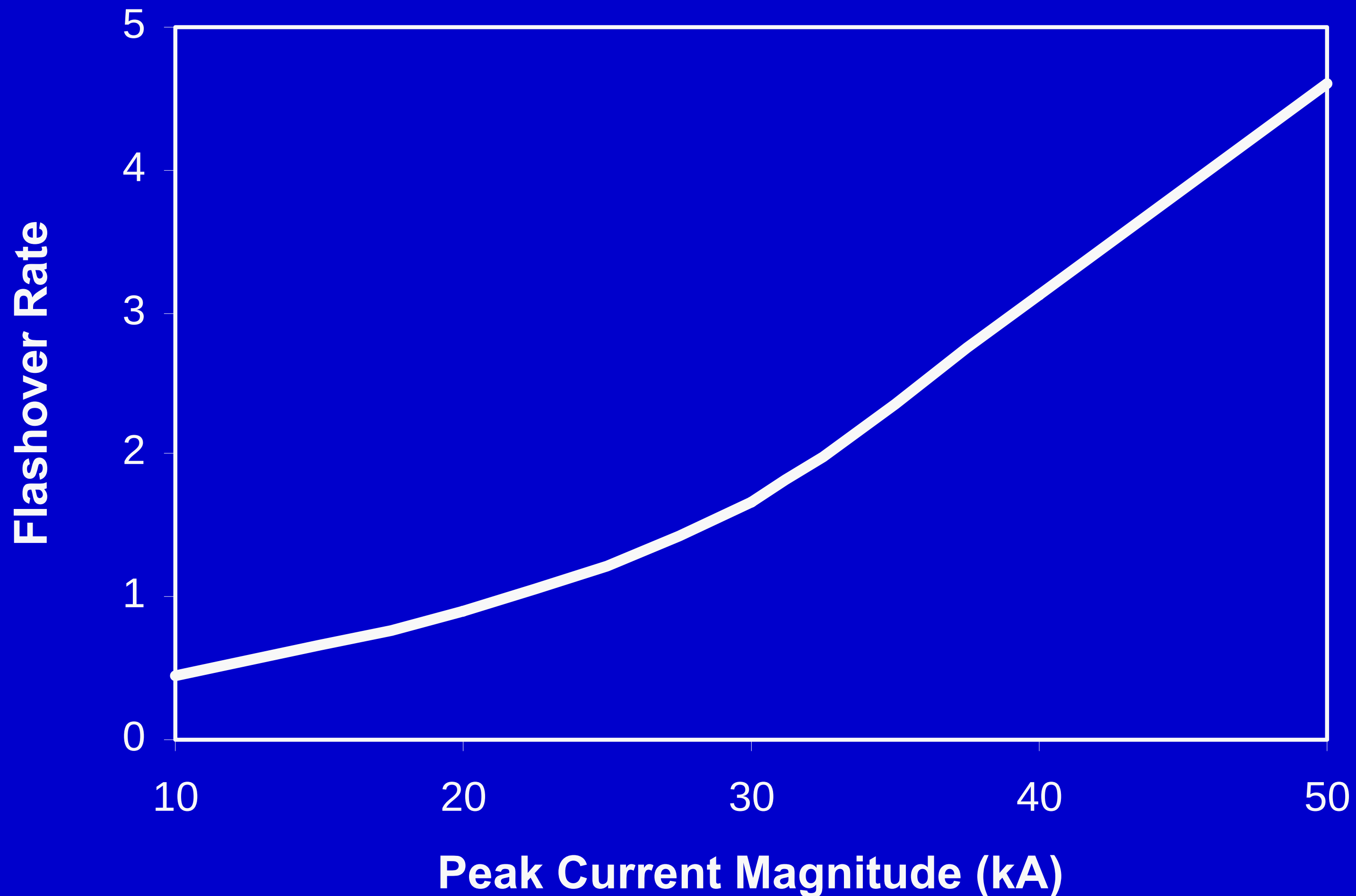


Strokes to phase conductors that caused flashover

Sensitivity analysis

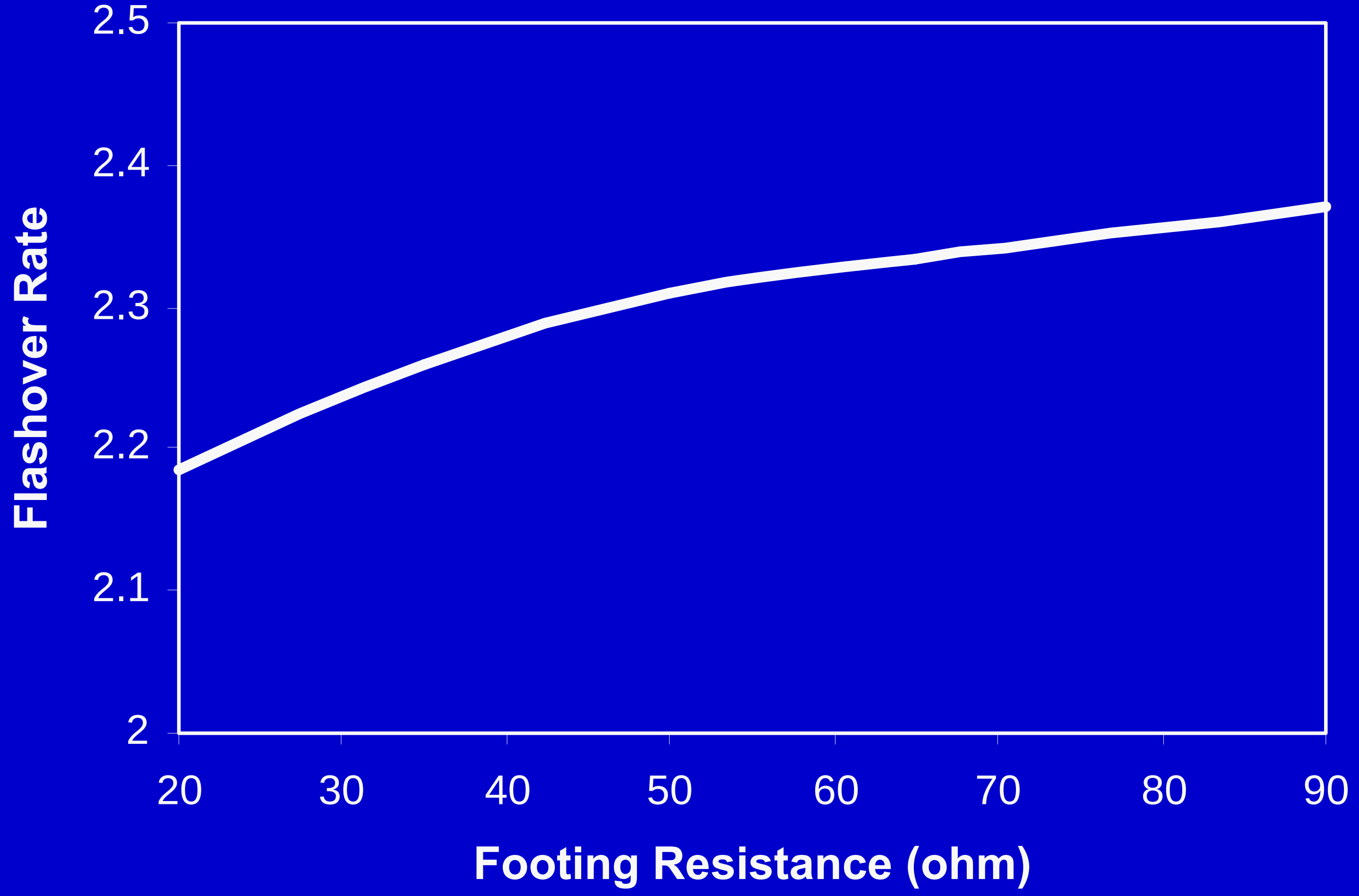
- Performed to find out the relationship between the flashover rate of the test line and some parameters
  - the median value of the peak current magnitude
  - the rise time of lightning strokes
  - the mean value of the footing resistance at low current and low frequency

Flashover rate vs. peak current magnitude
(t_f= 2 µs, t_h= 77.5 µs, R_0= 50 Ω, ρ= 200 Ω.m, N_g= 1 fl/km^2-y)



Flashover rate vs. footing resistance

(I_{100}= 34 kA, t_f= 2 μs, t_h= 77.5 μs, ρ= 200 Ω.m, N_g= 1 fl/km^2-y)



Arrester energy studies

Modeling guidelines

- Spans must be represented as multi-phase untransposed frequency-dependent distributed-parameter line sections
- No less than 7 spans at both sides of the point of impact have to be included in the model for arrester energy evaluation
- The effect of the arrester lead is negligible when strokes hit either a tower or a phase conductor
- The tail time of the return stroke current has a strong influence; the effect of the rise time very small, or even negligible for low peak current values

Arrester energy studies

Arrester model and parameters

- Model recommended by IEEE
- Values used to obtain the arrester model:
  - voltage for a 10 kA, 8/20 μs current, V_{10} = 1007 kV
  - switching surge discharge voltage for 1 kA, 30/60 μs current, V_{ss} = 735 kV
  - height of the arrester, d = 3.72 meters
  - number of parallel columns of MO disks, n = 1
- Rated voltage selected for the test arrester is 378 kV

Arrester energy studies

Maximum energy discharged by surge arresters

Arresters per tower	Stroke to a tower [1]	Stroke to a phase conductor [2]
A – B – C	96.4 kJ	645.8 kJ
A – B	101.2 kJ	645.8 kJ
B – C	81.7 kJ	651.7 kJ
C – A	90.8 kJ	645.8 kJ
A	97.3 kJ	645.8 kJ
B	88.8 kJ	651.7 kJ

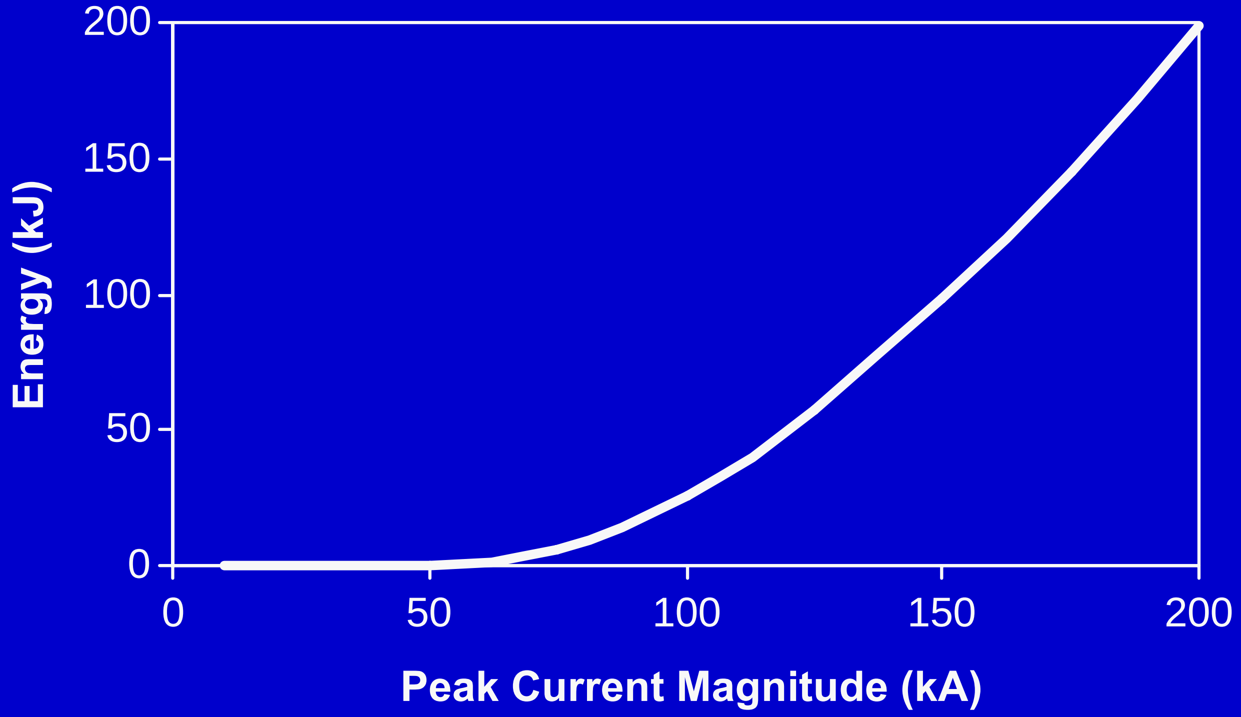
(1) Waveform of the stroke to a tower = 150 kA, 2/50 μs

(2) Waveform of the stroke to a conductor = 50 kA, 2/50 μs

Footing resistance: R_0 = 50 Ω; ρ = 200 Ω.m

Arrester energy studies

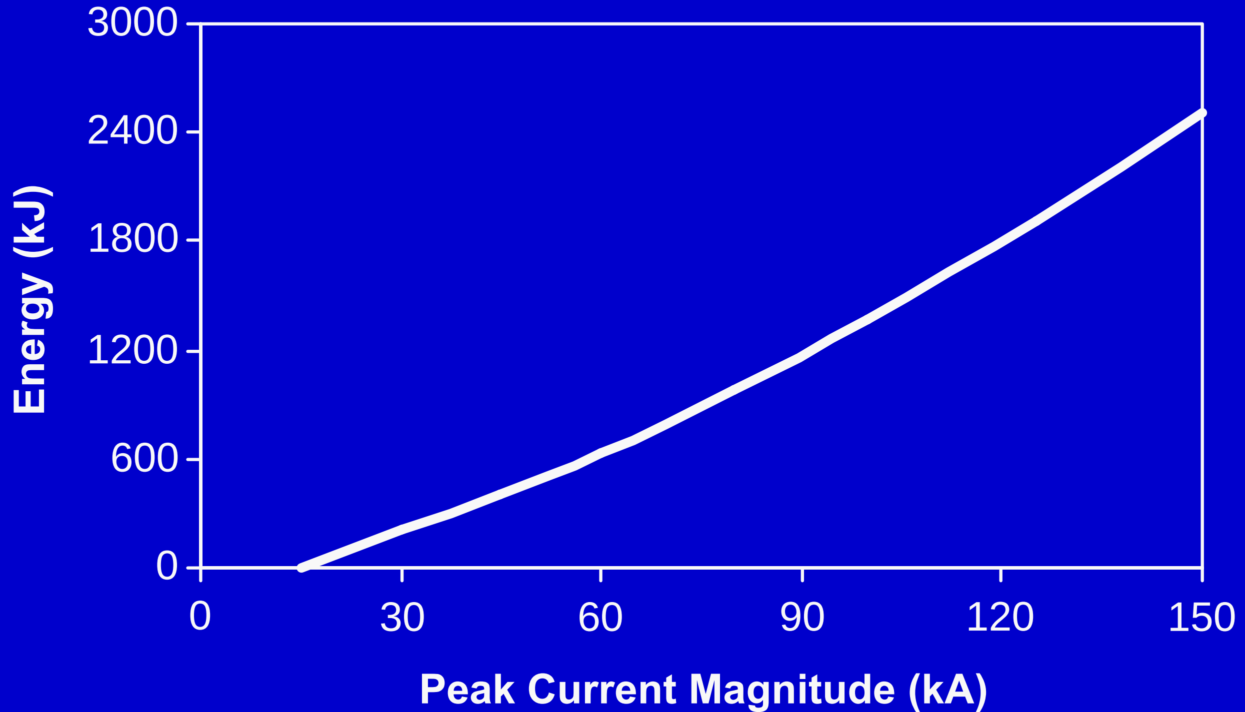
Maximum energy discharged by surge arresters



Stroke to a tower - Footing resistance: R_0 = 50 Ω; ρ = 200 Ω.m

Arrester energy studies

Maximum energy discharged by surge arresters



Stroke to a tower - Footing resistance: R_0 = 50 Ω; ρ = 200 Ω.m

Flashover rate with arresters

- Goal: estimate the improvement of the flashover rate that can be achieved by installing surge arresters at all towers of the test line, but not at all phases
- Conclusions derived from the previous results:
  - The line has a poor lightning performance, mainly due to an abnormal shielding failure rate
  - Arrester failures can be caused by a stroke to a phase conductor, unless arresters with a large energy absorption capability were installed
- The flashover rate of the test line with the different combinations of arresters was estimated; it was as-sumed that arresters with a large enough energy absorption capability were installed

Flashover rate with arresters

Flashover rate with arresters (per 100 km-year)

Arrester Protection	BFOR	SFFOR	Total flashover rate
A – B – C	0	0	0
A – B	0.245	0	0.245
B – C	0.670	0.560	1.230
C – A	0.505	0.100	0.605
A	0.740	0.105	0.845
B	1.000	0.560	1.560

Conclusions

- The paper has presented the lightning performance improvement of a 400 kV line with a poor shielding
- The study has shown that
  - a different degree of improvement can be achieved by installing arresters at all or only some of the line phases
  - the improvement can be very significant when arresters are installed at two phases
  - with the installation of a single arrester per tower, an important reductions of the FR is achieved
  - the installation of arresters with a high energy absorption capability is advisable