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

Juan A. Martinez  
Univ. Politècnica Catalunya  
Barcelona, Spain

Ferley Castro-Aranda  
Universidad del Valle  
Cali, Colombia
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
- \( \eta \) is a correction factor of the peak current
- \( n \) is the current steepness factor
- \( k = t/\tau_1 \)
- \( \tau_1, \tau_2 \) time constants determining current rise and decay-time, respectively
Lightning stroke parameters

Return stroke waveform

- $I_{100}$
- $I_{90}$
- $I_{50}$
- $I_{30}$
- $I_P$
- $t_{30}$
- $t_{90}$
- $t_h$

$kA$ vs. time
Lightning stroke parameters

- **Return stroke waveform**
  - Parameters used to define this waveform
    - the peak current magnitude, $I_{100}$
    - the rise time, $t_r (= 1.67 (t_{90} - t_{30}))$
    - 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 ($I_{100}$, $t_r$, $t_h$)
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

\[ t_f = t_c + t_s + l \]

- \( t_c \) 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
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 unbridged part of the gap falls below $E_{l0}$. 

**Insulator strings**
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
  \[ k_I = 1.3 \times 10^{-6} \, \text{m}^2/(\text{V}^2\text{s}) \quad \text{and} \quad E_{I0} = 570 \, \text{kV/m} \]
- 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
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 2.31 per 100 km-year

Values obtained $N_g = 1 \text{ fl/km}^2\text{-year}$

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

![Graph showing probability distribution of peak current magnitude](image)
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
($t_f = 2 \mu s$, $t_h = 77.5 \mu s$, $R_0 = 50 \Omega$, $\rho = 200 \Omega\cdot m$, $N_g = 1 \text{ fl/km}^2\cdot\text{y}$)
Flashover rate vs. footing resistance

\( (I_{100} = 34 \text{ kA}, t_f = 2 \mu\text{s}, t_h = 77.5 \mu\text{s}, \rho = 200 \Omega\cdot\text{m}, N_g = 1 \text{ fl/km}^2\cdot\text{y}) \)
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 is 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

<table>
<thead>
<tr>
<th>Arresters per tower</th>
<th>Stroke to a tower (1)</th>
<th>Stroke to a phase conductor (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – B – C</td>
<td>96.4 kJ</td>
<td>645.8 kJ</td>
</tr>
<tr>
<td>A – B</td>
<td>101.2 kJ</td>
<td>645.8 kJ</td>
</tr>
<tr>
<td>B – C</td>
<td>81.7 kJ</td>
<td>651.7 kJ</td>
</tr>
<tr>
<td>C – A</td>
<td>90.8 kJ</td>
<td>645.8 kJ</td>
</tr>
<tr>
<td>A</td>
<td>97.3 kJ</td>
<td>645.8 kJ</td>
</tr>
<tr>
<td>B</td>
<td>88.8 kJ</td>
<td>651.7 kJ</td>
</tr>
</tbody>
</table>

(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: $R_0 = 50 \, \Omega; \ \rho = 200 \, \Omega.m$
Arrester energy studies

Maximum energy discharged by surge arresters

Stroke to a tower - Footing resistance: \( R_0 = 50 \, \Omega \); \( \rho = 200 \, \Omega \cdot m \)
Arrester energy studies

Maximum energy discharged by surge arresters

Stroke to a tower - Footing resistance: \( R_0 = 50 \Omega; \rho = 200 \Omega.m \)
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 assumed that arresters with a large enough energy absorption capability were installed
## Flashover rate with arresters

### Flashover rate with arresters (per 100 km-year)

<table>
<thead>
<tr>
<th>Arrester Protection</th>
<th>BFOR</th>
<th>SFFOR</th>
<th>Total flashover rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – B – C</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A – B</td>
<td>0.245</td>
<td>0</td>
<td>0.245</td>
</tr>
<tr>
<td>B – C</td>
<td>0.670</td>
<td>0.560</td>
<td>1.230</td>
</tr>
<tr>
<td>C – A</td>
<td>0.505</td>
<td>0.100</td>
<td>0.605</td>
</tr>
<tr>
<td>A</td>
<td>0.740</td>
<td>0.105</td>
<td>0.845</td>
</tr>
<tr>
<td>B</td>
<td>1.000</td>
<td>0.560</td>
<td>1.560</td>
</tr>
</tbody>
</table>
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.