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Lightning overvoltage protection of combined overhead line and underground cable distribution network

Božidar Filipović-Grčić, PhD
Prof. Ivo Uglešić
Faculty of Electrical Engineering and Computing
University of Zagreb, Croatia

Presentation outline

- Introduction
- Model of distribution network in EMTP-ATP
- Simulation of lightning overvoltages including direct lightning stroke to tower and phase conductor
- Simulation results
- Analysis of data from lightning location system
- Conclusions

Introduction (1)

- The increasing demand of utility customers for stability of the power supply has stressed the importance of improving the **reliability** and **power quality** in the distribution network.

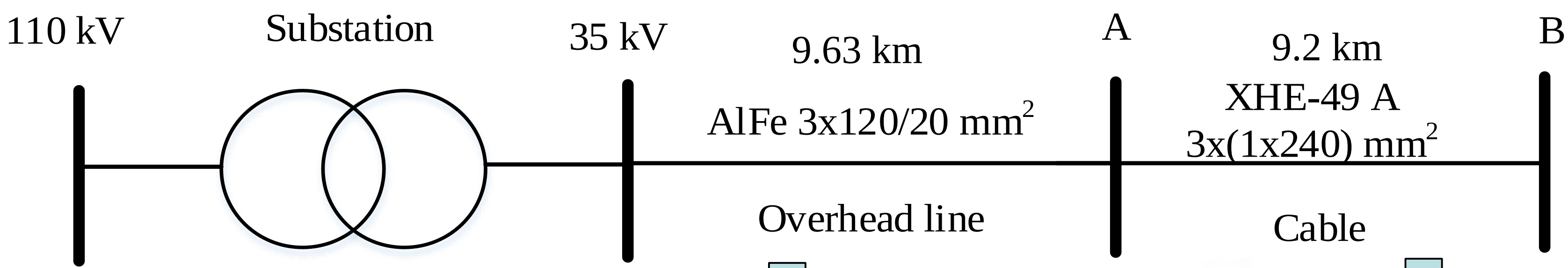
- **Lightning is a major cause of faults on overhead lines**, so it is essential to evaluate the lightning electromagnetic environment in order to mitigate its effects and improve the power system reliability.

- Transient faults are usually acceptable by the consumers, except in cases where the loads are very sensitive to short time interruptions or voltage dips.

Introduction (2)

- Lightning overvoltages in a 35 kV distribution network were calculated by using the EMTP-ATP software.
- Mixed overhead line and underground cable distribution network supplying an industrial consumer.
- An open end of a cable was considered in the simulations as the most unfavorable switching configuration.
- An optimal overvoltage protection was selected which significantly improves the overvoltage protection of the cable.

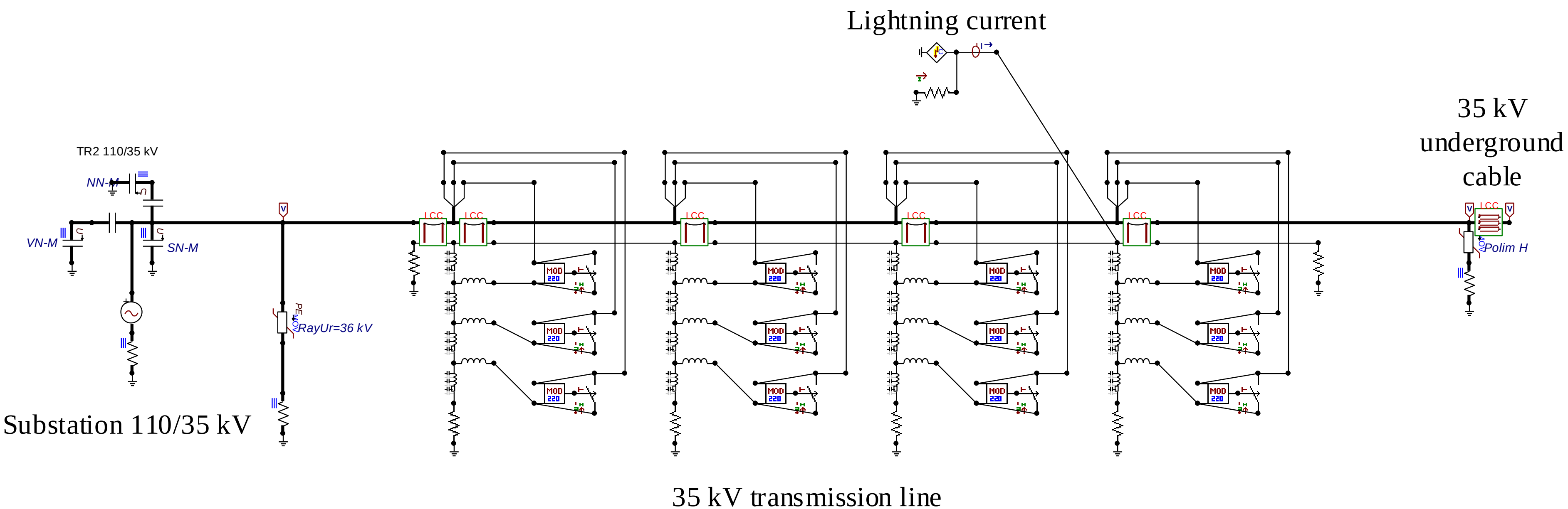
Combined overhead line and underground cable distribution network



35 kV overhead line with steel lattice towers and a single shield wire

35 kV cable with cross-linked polyethylene (XLPE) insulation

Model of distribution network in EMTP-ATP

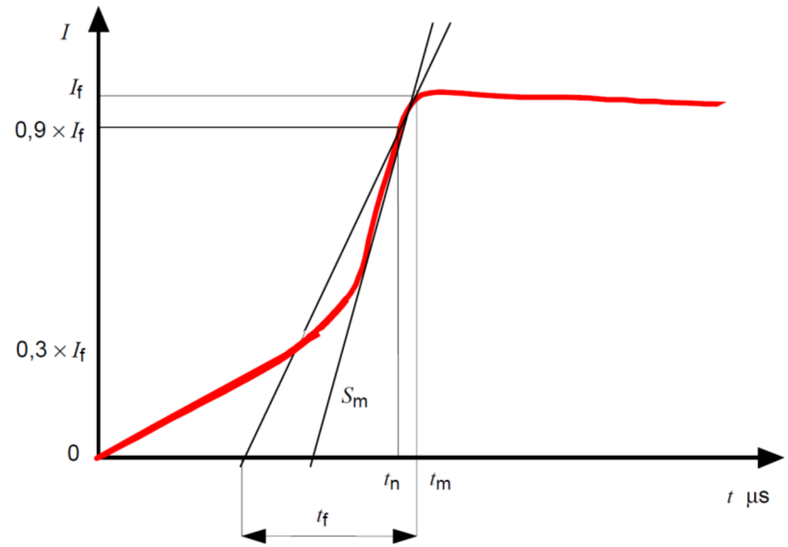


- The overhead line and cable were represented by the frequency-dependent model in EMTP-ATP.

- The equipment in high voltage substation were represented by surge capacitances obtained from manufacturer’s data.

Lightning current

- The lightning stroke (hitting a tower or a phase conductor) was represented by a CIGRE concave shape.



- The peak current magnitude and the tail time are important when observing the arrester energy. Front time is an important parameter with regard to the insulator flashover.
- The CIGRE shape represents more accurately the concave front of a lightning stroke and usually gives more realistic results.

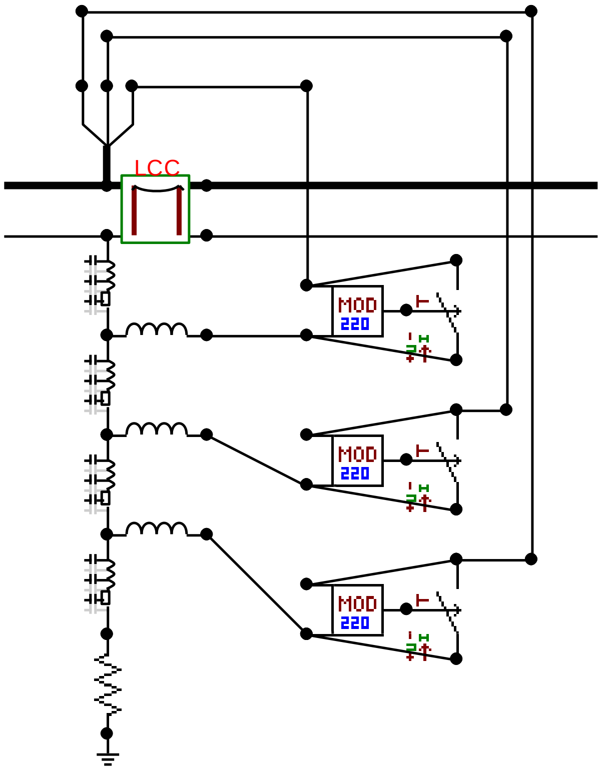
Transmission line tower model

- The tower surge impedance depends on the direction of wave propagation and the shape of a lightning current.

- An approximation of surge impedance equation is determined by equivalently replacing the tower with a cylinder:

$$Z = 60 \cdot \left\{ \ln\left(\frac{H}{R}\right) - 1 \right\}$$

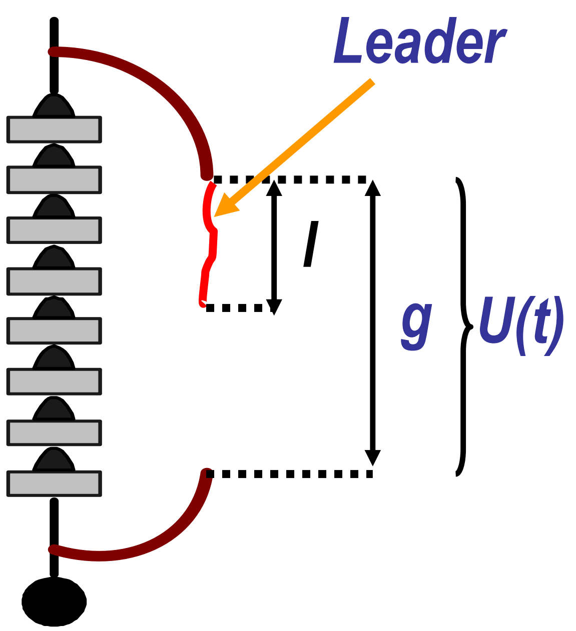
where *H* represents the tower height and *R* the equivalent radius of a tower base.



Insulator flashover - Leader Propagation Model

- The flashover mechanism of the overhead line insulators was represented with differential equation of the leader propagation model recommended by the CIGRE WG 33-01:

$$v = \frac{dl}{dt} = k_l\, U(t)\left[\frac{U(t)}{g-l} - E_{10}\right]$$

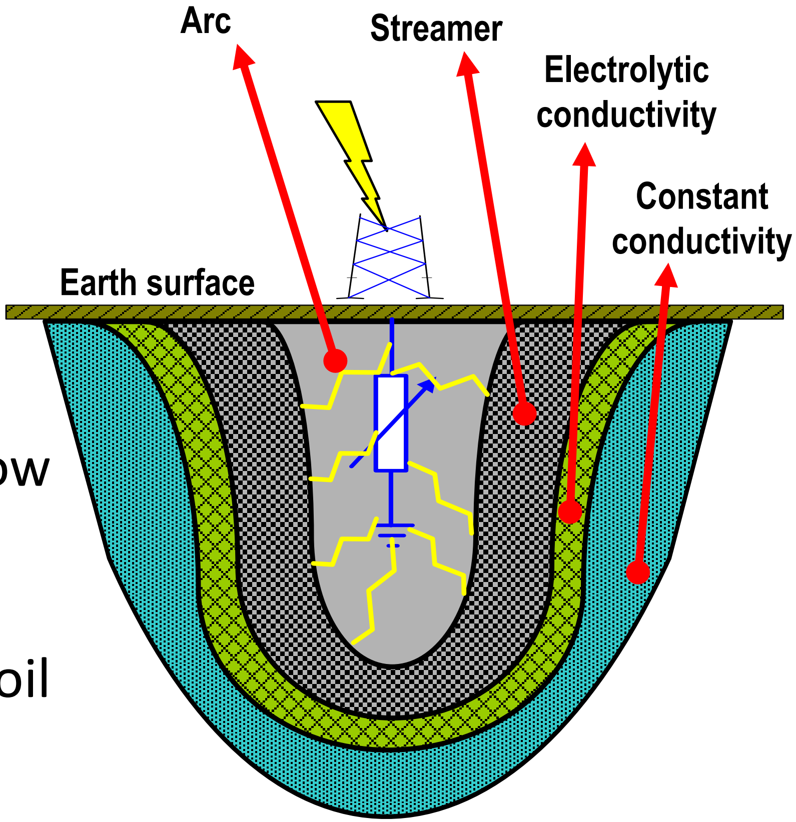


v – leader velocity (m/s);
U(t) - voltage across the gap (kV);
g - gap length (m);
l - leader length (m);
E_{10} - critical leader inception gradient (kV/m);
k_l - leader coefficient ($m^2V^{-2}s^{-1}$).

Tower footing resistance model – soil ionization

- The ionization model takes into account the soil ionization caused by the lightning currents.
- Tower grounding non-linear resistor should be represented as:

$$R_i = \frac{R_0}{\sqrt{1+\left(\frac{I}{I_g}\right)}}$$



R_0 - footing resistance at low current and low frequency, i.e. 50 or 60 Hz;

I - stroke current through the resistance;

I_g - limiting current to initiate sufficient soil ionization.

Tower footing resistance model – soil ionization

- Limiting current to initiate sufficient soil ionization:

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

ρ- soil resistivity (Ωm);
E_0 - is the soil ionization gradient, recommended value: 400 (kV/m).

- Tower grounding was represented as a non-linear resistor using MODELS language and TACS-controlled time-dependent resistor in EMTP-ATP.

Gapless type surge arresters (SA)

- SAs with continuous operating voltage U_c=30 kV, rated voltage U_r=37.5 kV and energy class 4 (13.3 kJ/kV(U_c)) were considered in simulations.

- *U-I* characteristic of SA for impulse current waveform 8/20 µs:

Current [kA]	2	5	10	20	40
Voltage [kV]	79.5	83.4	87.0	94.9	106.2

- The SA leads were represented by the inductance of 1 µH/m taking into account the effects of additional voltage rise across the lead inductance.

Simulation of different overvoltage protection scenarios

- Lightning strikes the upper phase conductor and a shield wire at the first tower close to the beginning of the cable section.

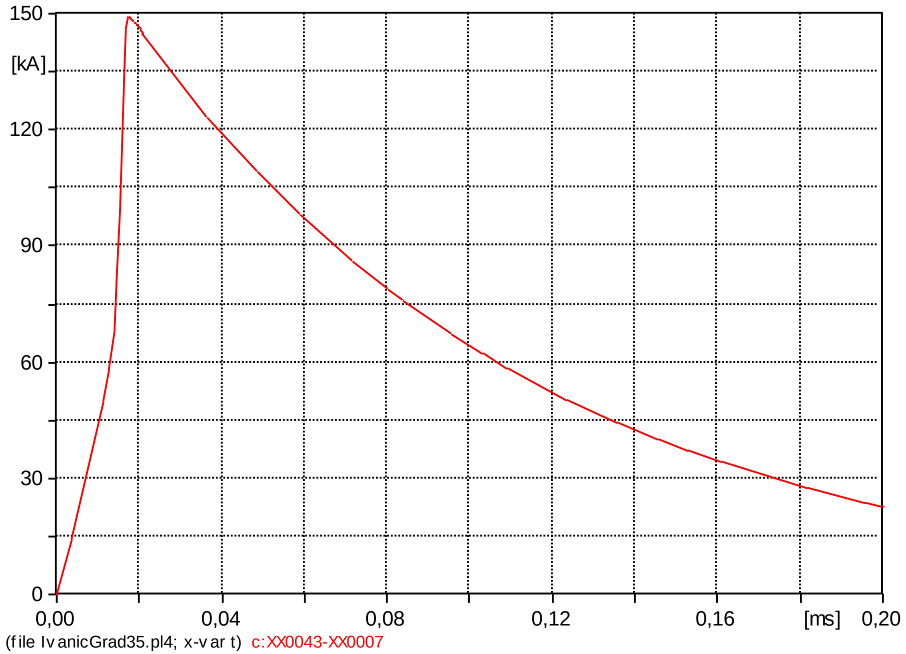
- Three different overvoltage protection scenarios were analyzed:

  1) no SAs installed;
  2) SAs installed at the beginning of a cable;
  3) SAs installed at the beginning and at the end of a cable.

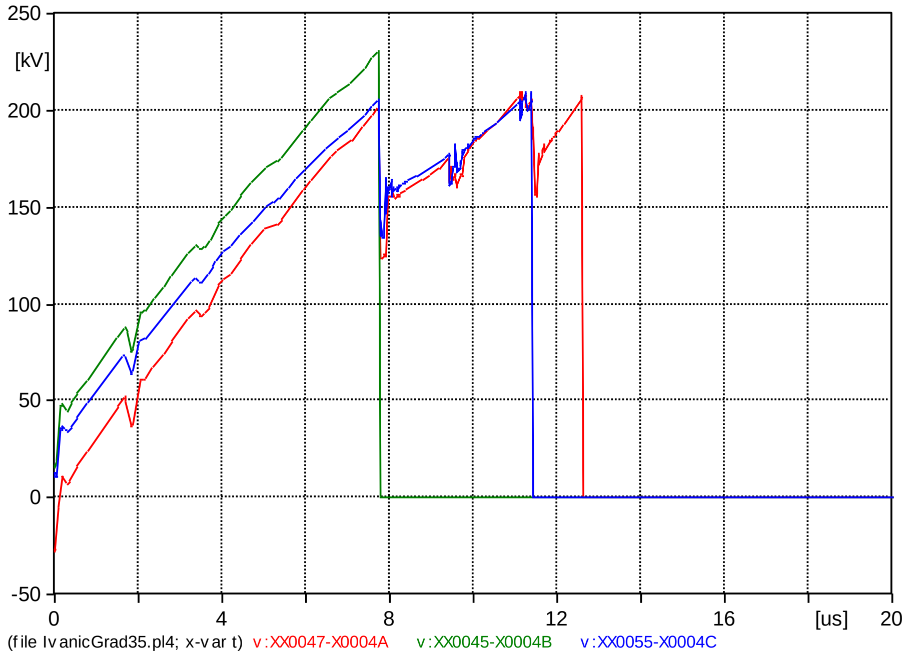
- The most severe switching condition was considered: opened circuit breaker at the end of cable.

Simulation results
Lightning stroke to tower

Scenario 1): no SAs installed



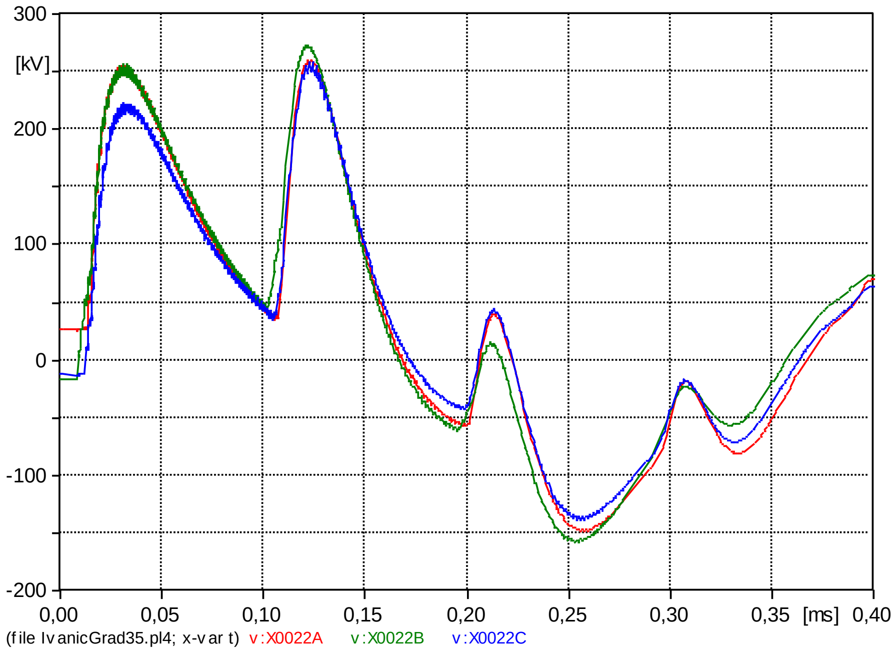
Lightning current
150 kA, 9.8/77.5 µs



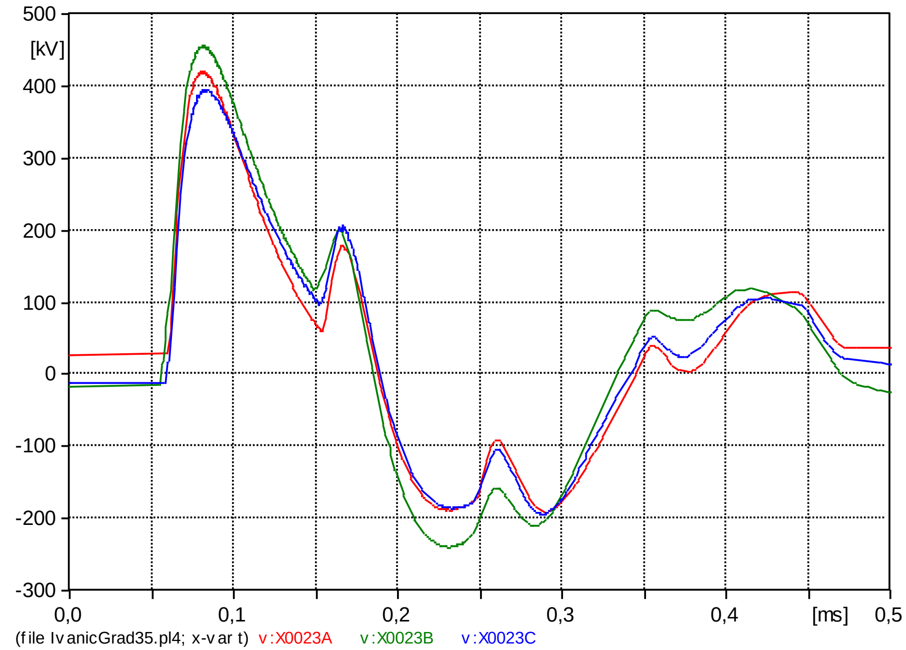
Overvoltages on the insulator strings of the struck tower (flashover in all phases)

Scenario 1): no SAs installed

- Lightning-impulse withstand voltage of the cable: **142 kV**.



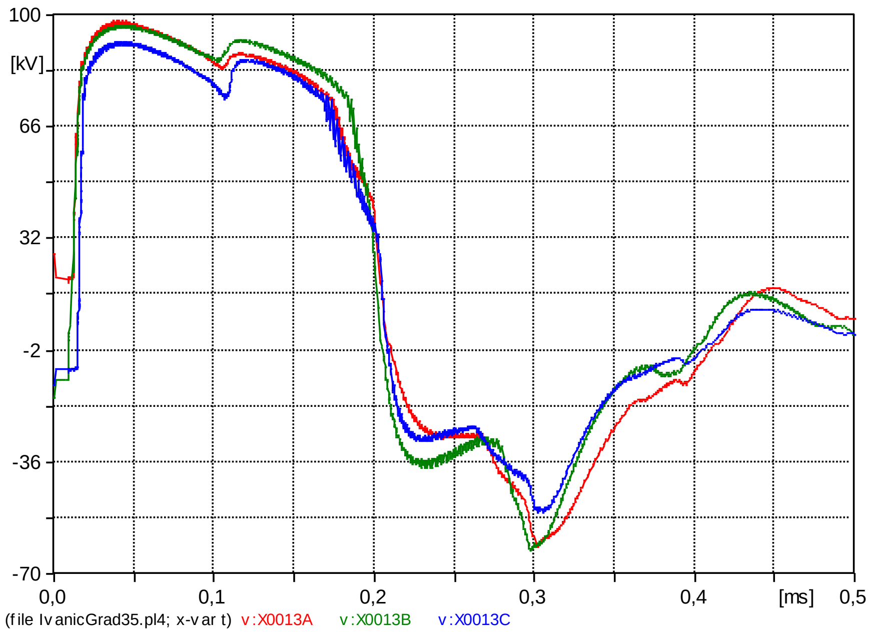
Overvoltages at the beginning of the cable
(U_{max}=272.8 kV)



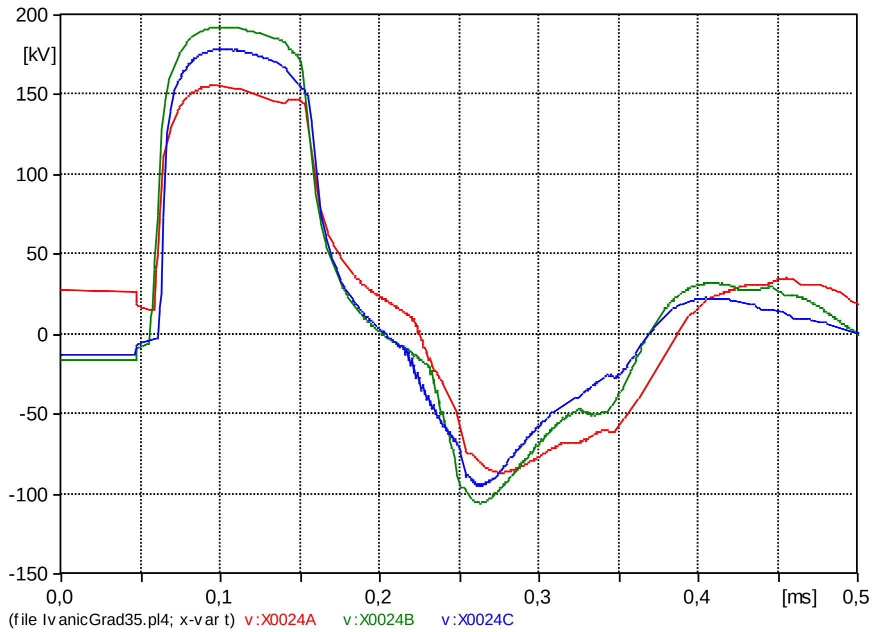
Overvoltages at the end of the cable
(U_{max}=456.0 kV)

Scenario 2): SAs installed at the beginning of a cable

- Lightning-impulse withstand voltage of the cable: **142 kV**.



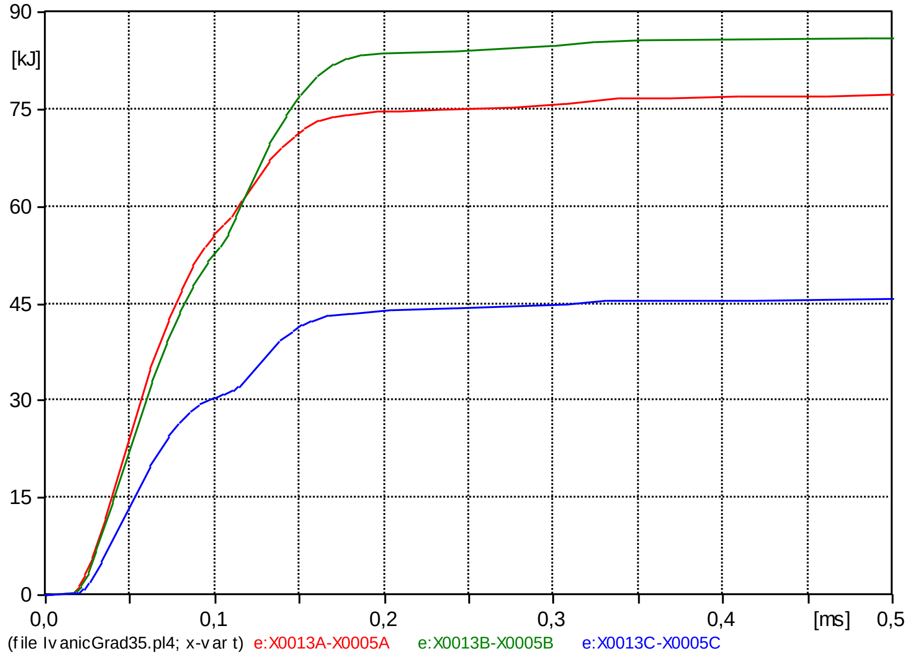
Overvoltages at the beginning of the cable (U_{max}=98.3 kV)



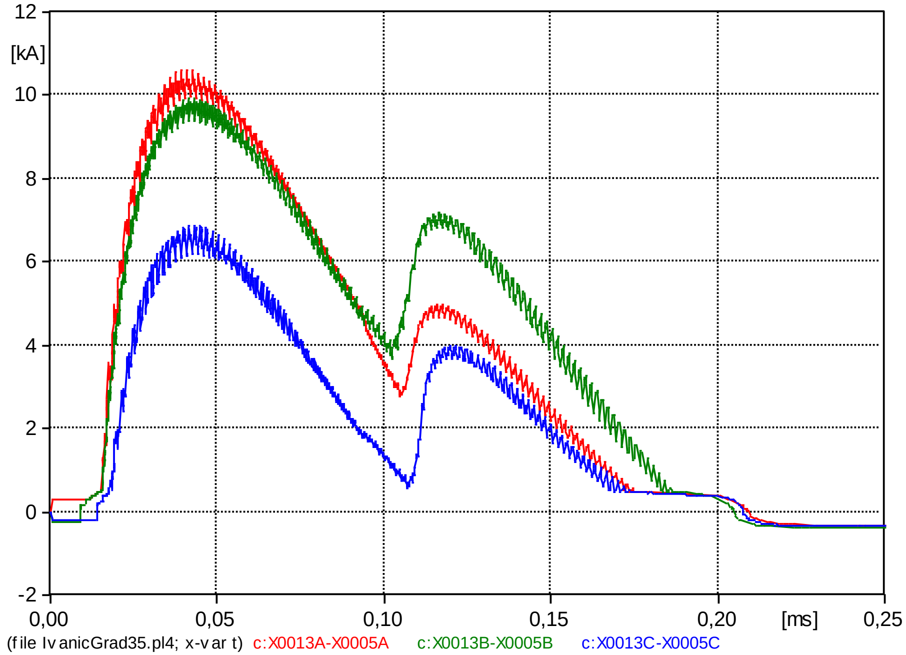
Overvoltages at the end of the cable (U_{max}=192.7 kV)

Scenario 2): SAs installed at the beginning of a cable

- Surge arrester energy capability: 13.3 kJ/kV(U_c) = **399 kJ**



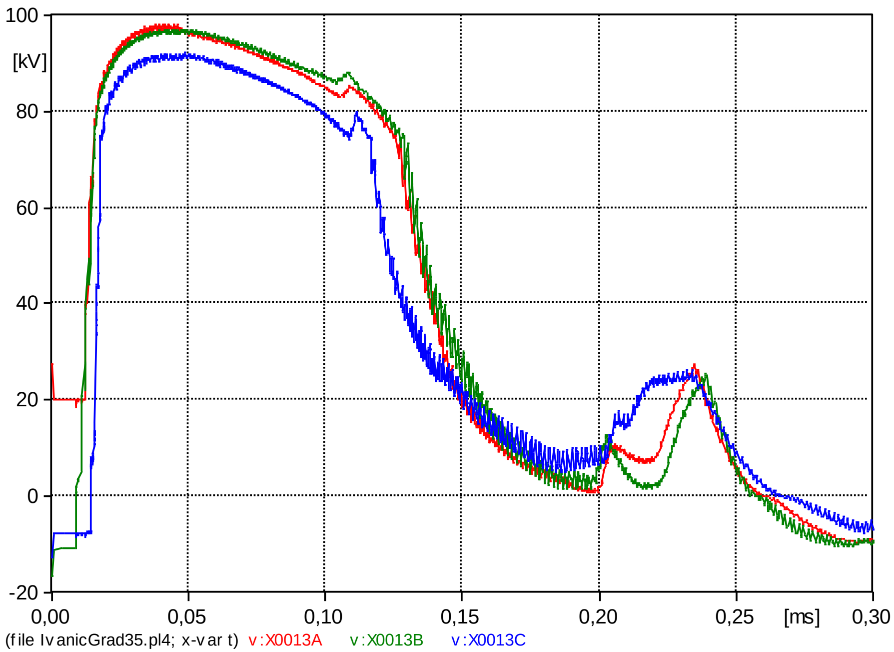
SA energy
(E_{max}=85.9 kJ)



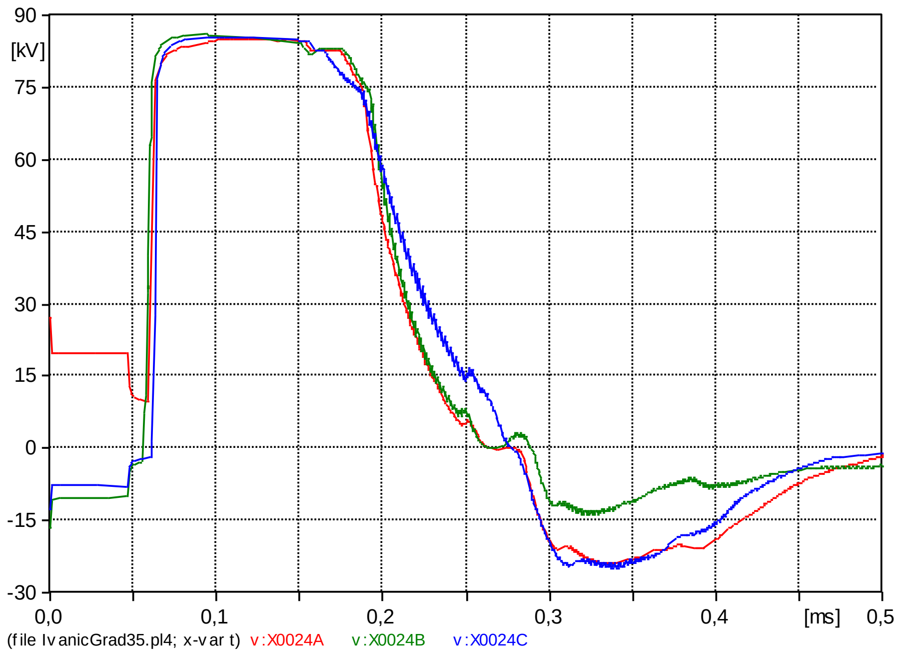
SA currents
(I_{max}=10.6 kA)

Scenario 3): SAs installed at both cable ends

- Lightning-impulse withstand voltage of the cable: **142 kV**.



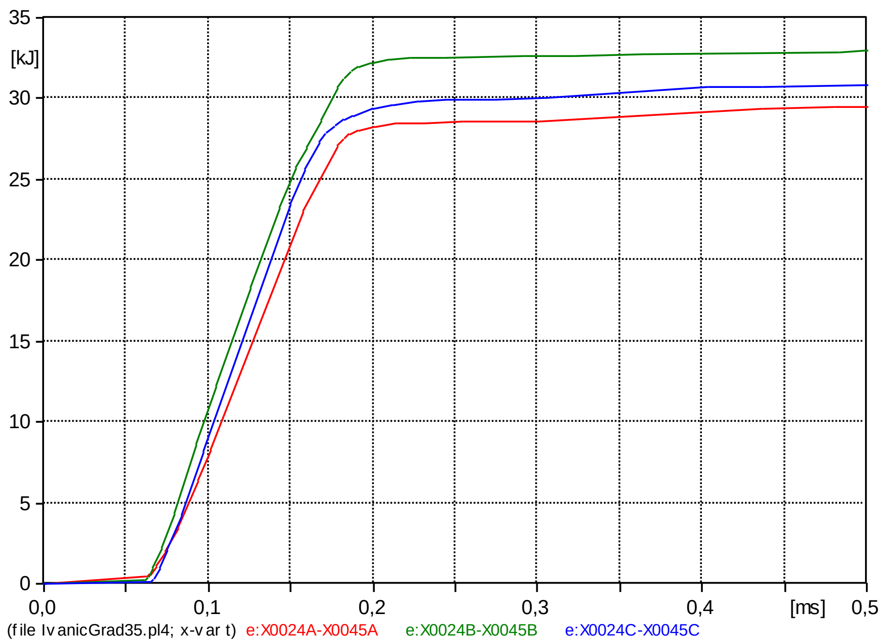
Overvoltages at the beginning of the cable
(U_{max}=98.3 kV)



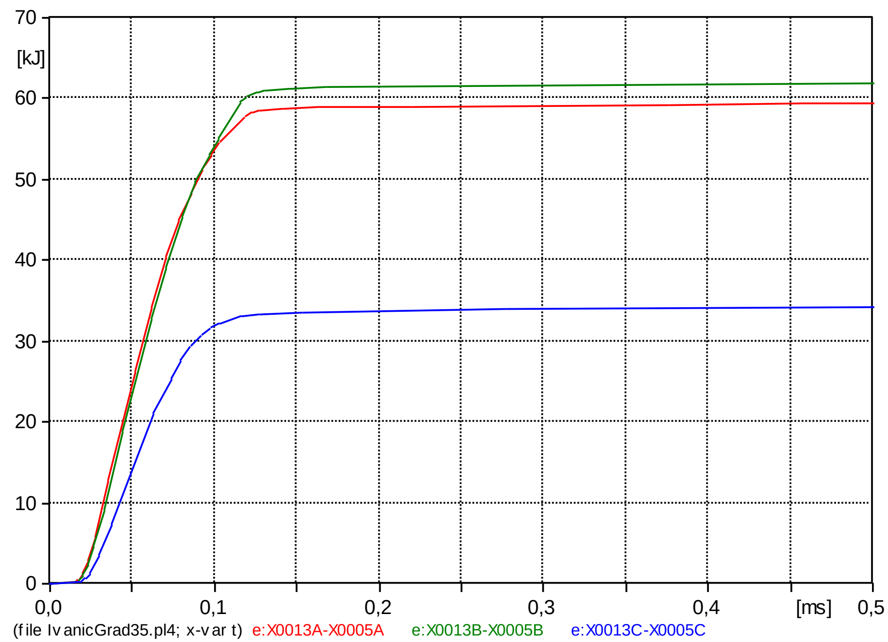
Overvoltages at the end of the cable
(U_{max}=86.3 kV)

Scenario 3): SAs installed at both cable ends

- Surge arrester energy capability: 13.3 kJ/kV(U_c) = **399 kJ**



SA energy at the beginning of the cable (E_{max}=32.9 kJ)



SA energy at the end of the cable (E_{max}=61.9 kJ)

Simulation results – lightning stroke to tower

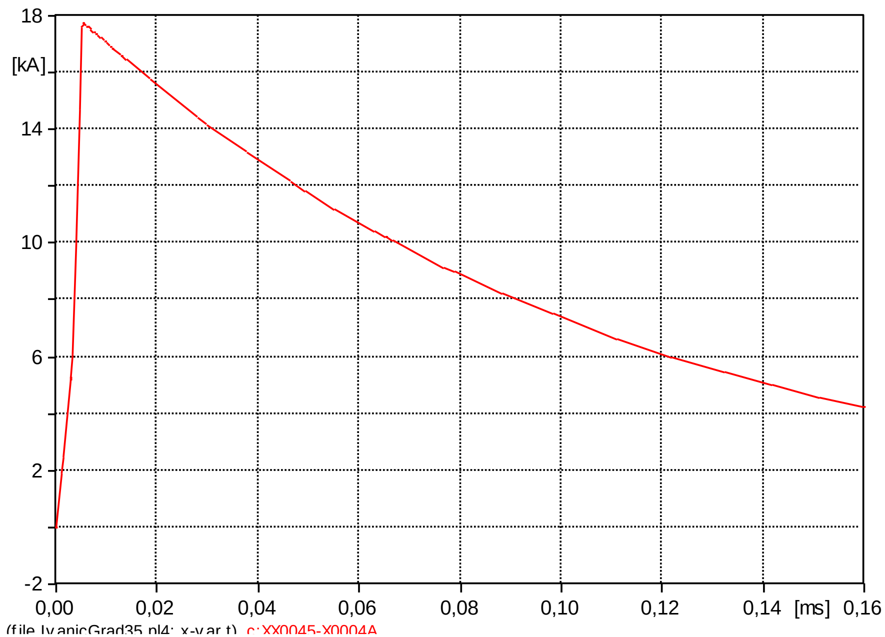
- Lightning-impulse withstand voltage of the cable: 142 kV.

Scenario	Insulator flashover at the struck tower	Overvoltages at the beginning of the cable	Overvoltages at the end of the cable	SA energy at the beginning of the cable	SA energy at the end of the cable
1) No SAs installed	Yes, phases A, B, C	272.8 kV	456.0 kV	-	-
2) SAs at the beginning of a cable	Yes, phases A, B, C	98.3 kV	192.7 kV	85.9 kJ	-
3) SAs at the beginning and at the end of a cable	Yes, phases A, B, C	98.3 kV	86.3 kV	61.9 kJ	32.9 kJ

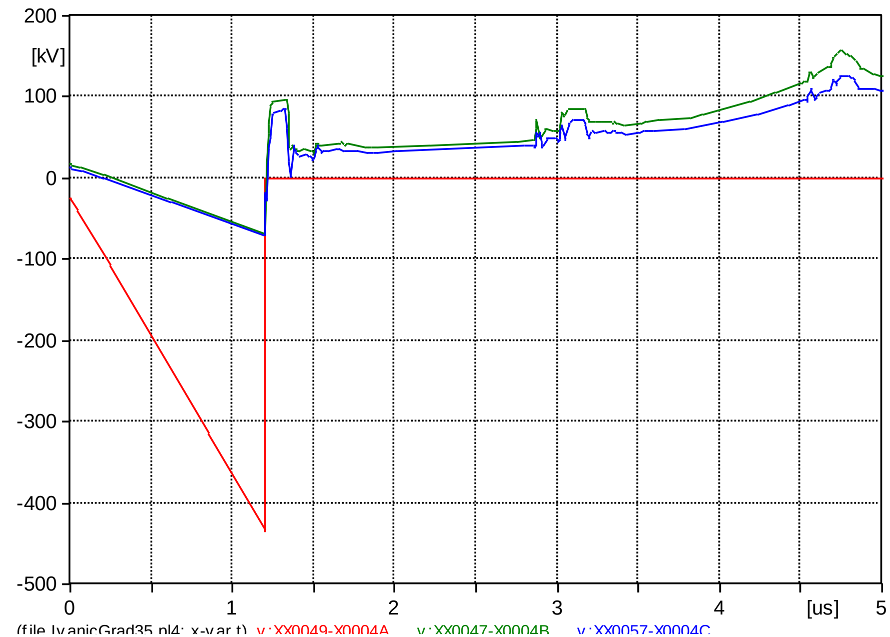
Simulation results
Lightning stroke to upper phase conductor

Lightning stroke to upper phase conductor

- According to the electro-geometric model of the overhead line the highest (critical) lightning current that can hit the upper phase conductor is 17.8 kA.



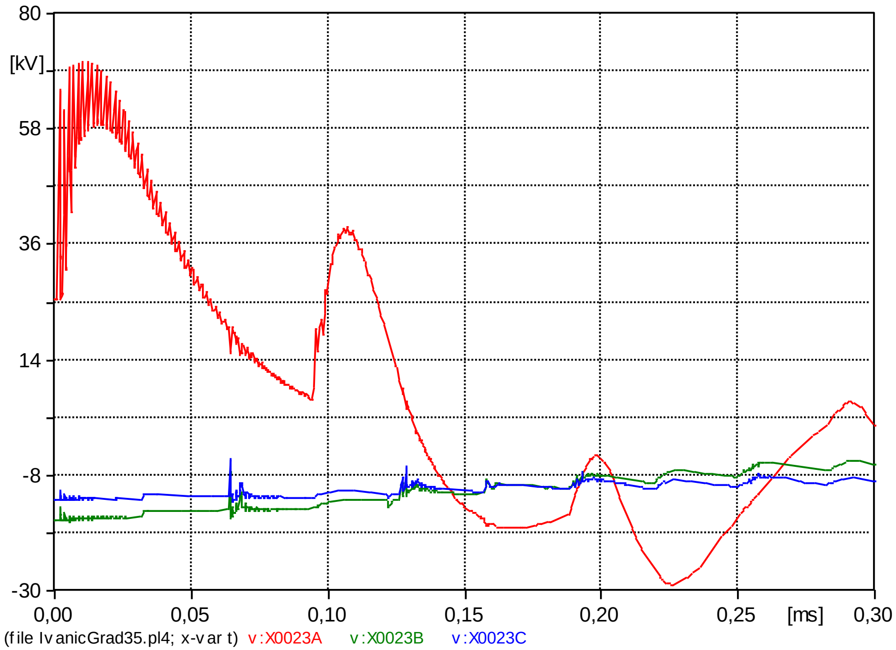
Lightning current
17.8 kA, 3/77.5 µs



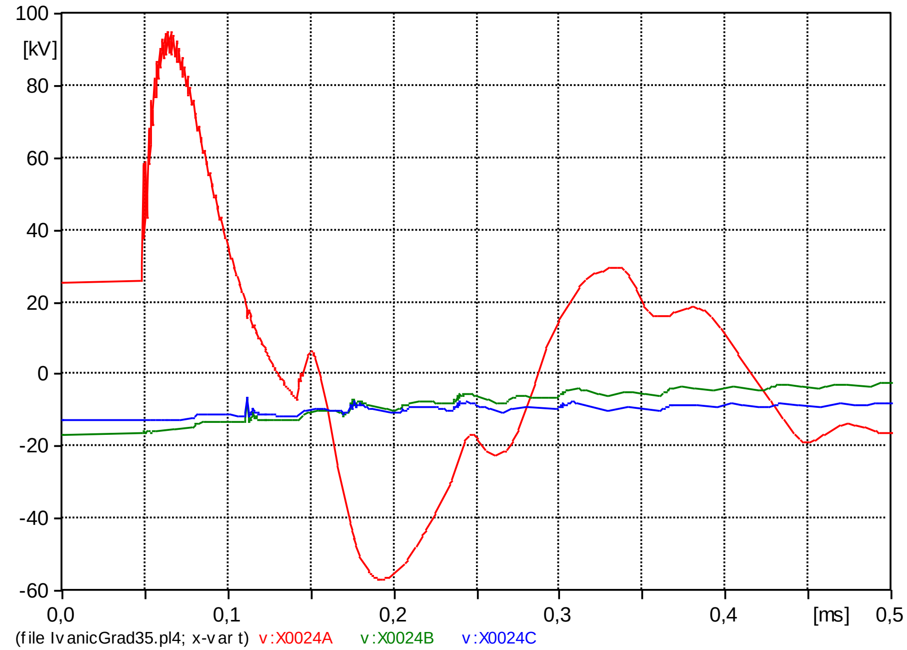
Overvoltages on the insulator strings of the struck tower (flashover in upper phase A)

Lightning stroke to upper phase conductor

- No SAs installed.
- Lightning-impulse withstand voltage of the cable: **142 kV**.



Overvoltages at the beginning of the cable (U_{max}=70.8 kV)



Overvoltages at the end of the cable (U_{max}=95.04 kV)

Simulation results – lightning stroke to upper phase conductor

Scenario	Insulator flashover at the struck tower	Overvoltages at the beginning of the cable	Overvoltages at the end of the cable	SA energy at the beginning of the cable	SA energy at the end of the cable
1) No SAs installed	Yes, phases A, B, C	70.8 kV	95.0 kV	-	-
2) SAs at the beginning of a cable	Yes, phases A, B, C	64.4 kV	85.5 kV	1.9 kJ	-
3) SAs at the beginning and at the end of a cable	Yes, phases A, B, C	64.4 kV	73.5 kV	1.4 kJ	1.9 kJ

Data from lightning location system (1)

- The lightning activity around 35 kV overhead line (9.63 km long) was observed for a 7 year period within an alarm zone radius of 2 km (surface of 50.71 km^2).

- The data were obtained from the LINET lightning location system (LLS).

- An algorithm was developed to group lightning strokes into flashes (lightning stroke multiplicity) in order to determine the current probability distribution of the first and subsequent CG strokes.

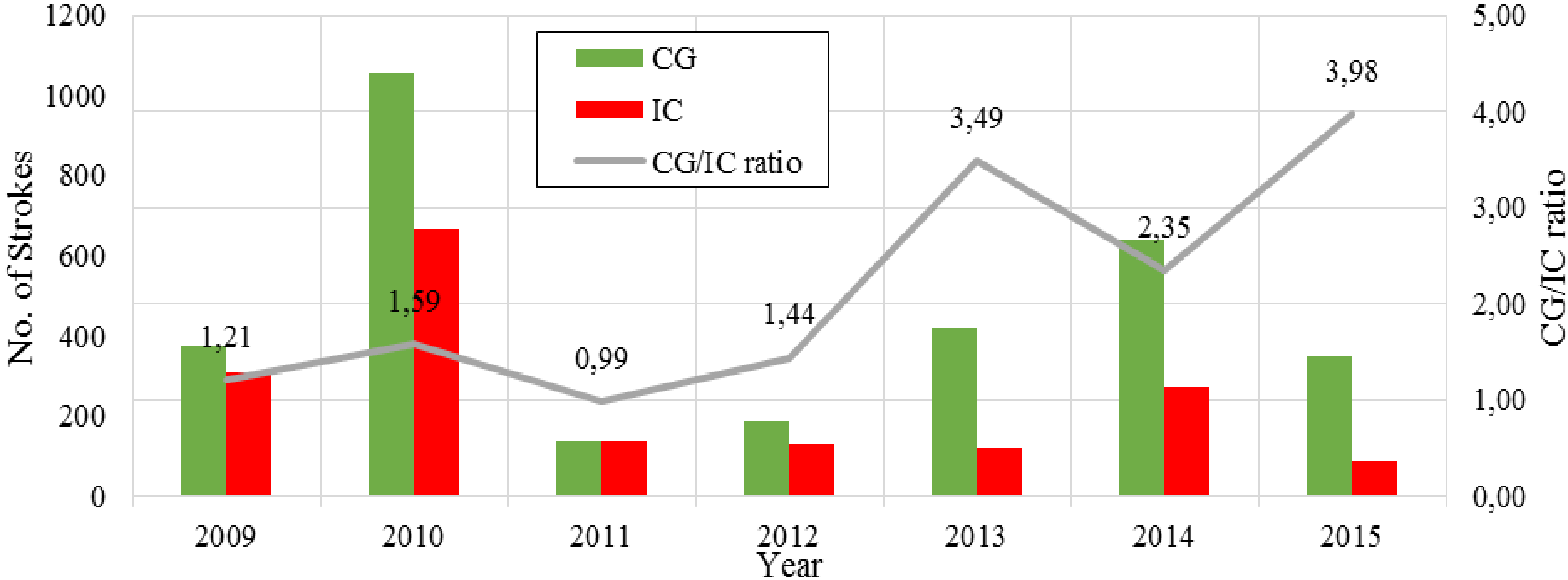
- The multiplicity was calculated for a maximum temporal separation of **200 ms** and a maximum lateral distance of **2 km** between successive strokes.

Data from lightning location system (2)

Year	Flash	Stroke	FMF	CG	CG-	CG+	CG-/CG+ ratio	N_{gf}	N_{gs}
2009	283	374	1.32	374	281	93	3.02	5.58	7.38
2010	704	1059	1.50	1059	746	313	2.38	13.88	20.88
2011	117	137	1.17	137	87	50	1.74	2.31	2.70
2012	151	189	1.25	189	116	73	1.59	2.98	3.73
2013	269	422	1.57	422	306	116	2.64	5.30	8.32
2014	435	639	1.47	639	386	253	1.53	8.58	12.60
2015	266	350	1.32	350	159	191	0.83	5.25	6.90
Total	**2225**	**3170**	**1.42**	**3170**	**2081**	**1089**	**1.91**	**6.27**	**8.93**

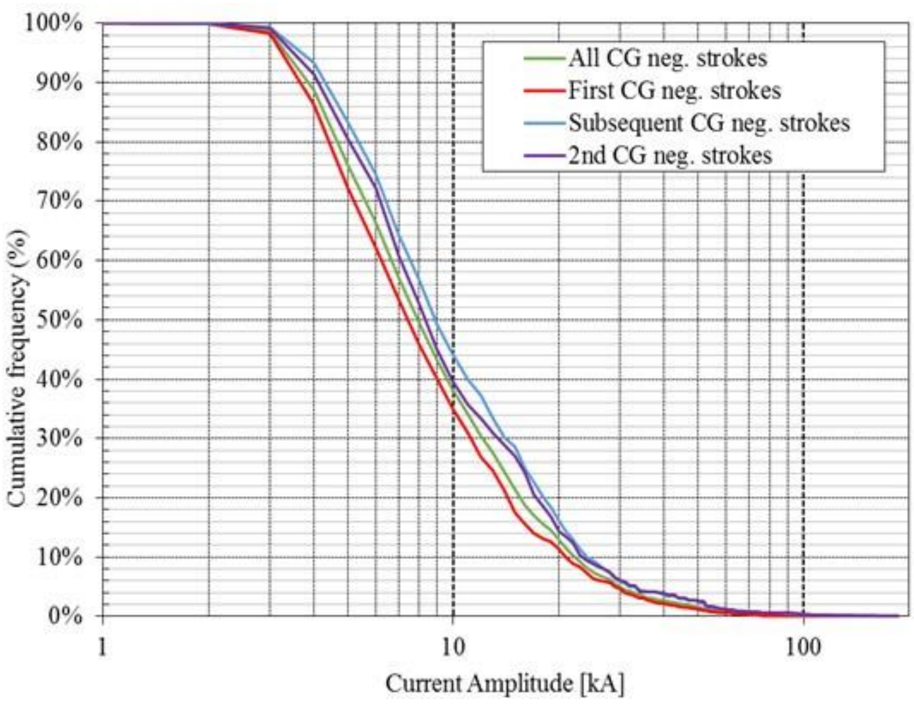
FMF - Flash Multiplicity Factor;
N_{gf} - the lightning flash density;
N_{gs} - the lightning stroke density.

Data from lightning location system (3)

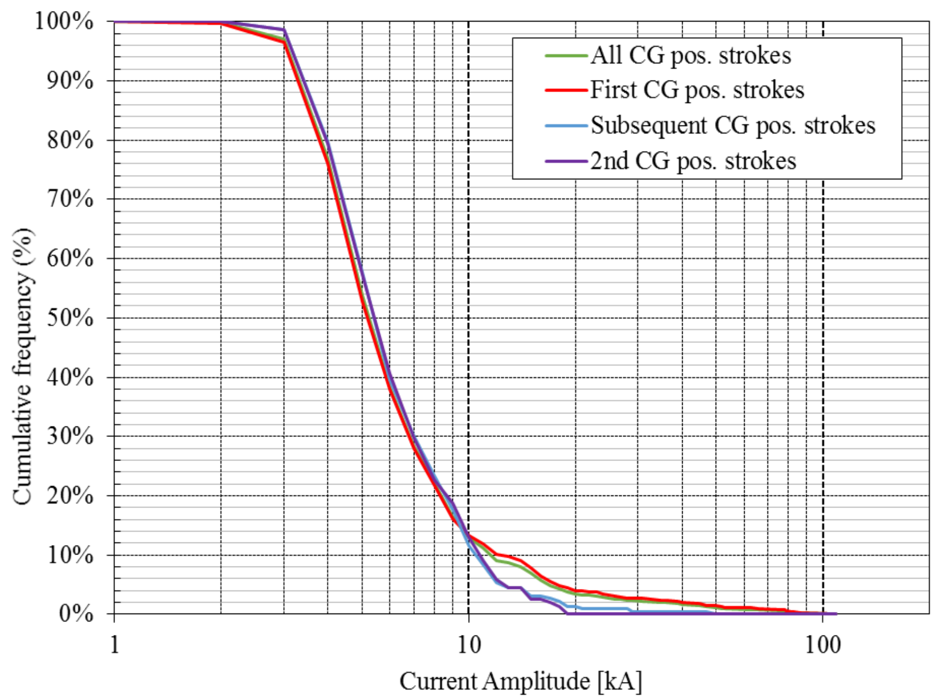


Number of CG and IC lightning strokes detected by LLS around 35 kV overhead line

Data from lightning location system (4)



CG negative lightning strokes



CG positive lightning strokes

Data from lightning location system (5)

- There is a significantly higher probability of lightning strokes occurrence with lower current amplitudes, compared to CIGRE data.

- This difference is caused by the sensitivity of LLS which is capable of detecting multiple CG strokes with low current amplitudes.

- LLS gives lower median values of current amplitudes both for first and subsequent strokes.

Conclusions (1)

- An optimal overvoltage protection was selected including the installation of surge arresters at both cable ends which significantly improves the overvoltage protection of the cable.

- Lightning parameters derived from the LINET lightning location system were analyzed and compared to the ones used in literature.

- The analysis of the LLS data showed that the lightning current parameters used in the simulations were conservative and on the “safe side”.

Conclusions (2)

- The selected surge arrester with U_c=30 kV, U_r=37.5 kV and energy class 4 can withstand energy stress caused by multiple lightning strokes with relatively high amplitudes and long tail times.
- Induced overvoltages were not analyzed but in some cases they may also cause an insulator flashover.
- This can be prevented by installing line surge arresters (LSAs) in order to reduce the number of overhead line outages.

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Božidar Filipović-Grčić, PhD

Prof. Ivo Uglešić

Faculty of Electrical Engineering and Computing

University of Zagreb, Croatia