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

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SUMMARY

This paper presents the analysis of lightning overvoltages in a mixed overhead line and underground cable distribution network supplying an industrial consumer. Different overvoltage protection scenarios were discussed, including the installation of surge arresters at both cable ends. Lightning overvoltages in 35 kV distribution network were calculated by using EMTP-ATP software. Open end of a cable was considered in simulations as the most unfavourable switching configuration. Lightning parameters derived from LINET lightning location system observations around 35 kV overhead line were analysed and compared to the ones used in literature and standards. Lightning flash multiplicity was taken into account in order to determine the probability distribution of lightning current amplitude of the first and subsequent cloud-to-ground strokes. The energy absorbed by surge arresters was determined and an optimal overvoltage protection of the underground cable was proposed.

KEYWORDS

Lightning overvoltages, overhead line, cable, distribution network, overvoltage protection, lightning location system.

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INTRODUCTION

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. As lightning is a major cause of faults on overhead lines, it is essential to evaluate the lightning electromagnetic environment in order to mitigate its effects and improve the power system quality [1]. Transient faults are usually acceptable by the consumers, except in cases where the loads are very sensitive to short time interruptions or voltage dips. Lightning can produce overvoltages when it hits either the phase conductors or the shielding wire (direct strokes) or a point in the vicinity of the distribution network (indirect strokes). The majority of direct strokes can cause multi-phase insulation breakdown on distribution overhead lines which leads to opening and reclosing operation of circuit breakers (line tripping).

This paper deals with lightning overvoltages in a mixed overhead line and underground cable distribution network supplying an industrial consumer. Only direct lightning strokes to overhead line were analysed in this paper, since they are more critical with regard to overvoltage amplitudes and surge arresters (SA) energy stress. Induced overvoltages were not analysed 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 [2].

MODEL OF DISTRIBUTION NETWORK IN EMTP-ATP

Fig. 1 shows an electrical scheme of a combined overhead line and underground cable distribution network analysed in this paper.

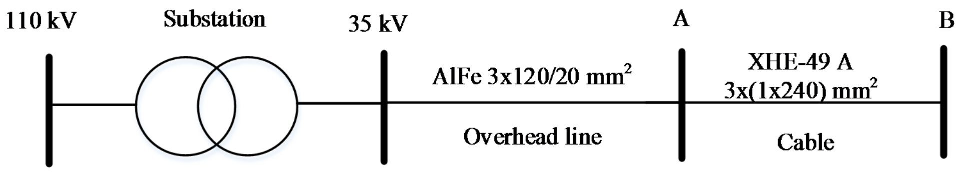

Fig. 1 Electrical scheme of a network

The network consists of substation 110/35 kV, overhead line and underground cable. A lightning stroke at the first tower in the vicinity of location A (Fig. 1), which represents the beginning of the cable section, was considered. An industrial consumer is connected at the end of the cable – location B. The overhead line with a single shield wire (Fig. 2) is 9.63 km long and the cable (Fig. 3) is 9.2 km long.


Fig. 2 35 kV overhead line with steel lattice towers and a single shield wire (Al/Fe 3x120/20 mm^2)


Fig. 3 35 kV cable with cross-linked polyethylene (XLPE) insulation (3x1x240 mm^2)

Fig. 4 shows a model of 35 kV network in EMTP-ATP for the calculation of lightning overvoltages.

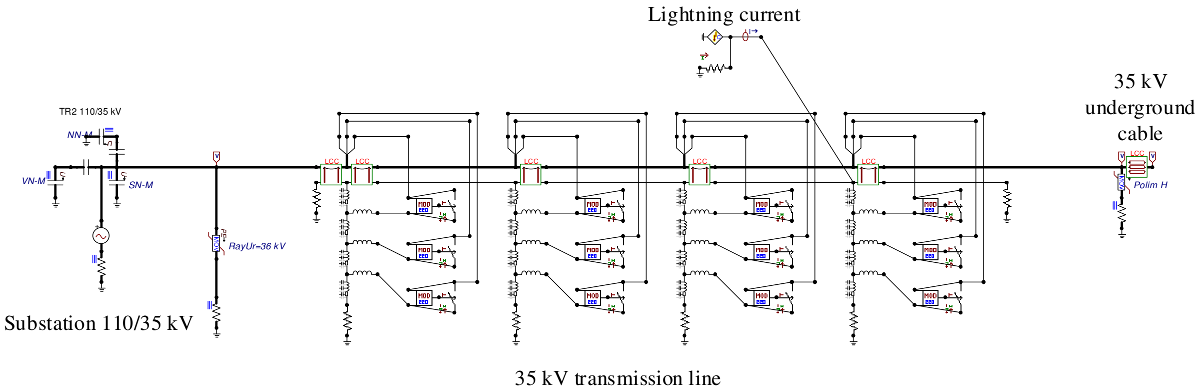

Fig. 4 Model of 35 kV overhead line and cable in EMTP-ATP for the calculation of lightning overvoltages

Parameters of 110 kV equivalent network were calculated from short circuit currents by using the following expressions:

$$Z_d = \frac{c \cdot U_n}{\sqrt{3} \cdot I_{sc3}} \quad , \tag{1}$$

$$Z_0 = \frac{c \cdot U_n}{\sqrt{3}} \cdot \left(\frac{3}{I_{sc1}} - \frac{2}{I_{sc3}} \right) , \tag{2}$$

where:
I_{sc1}, I_{sc3} – single-phase and three-phase short circuit currents; U_n – rated voltage; c – factor = 1.1.

The overhead line and cable were represented by the frequency-dependent model in EMTP-ATP and four spans close to the beginning of the cable section were taken into account. The rest of the overhead line entering 110/35 kV substation was also taken into account in the model. Surge impedances of the overhead line towers [3] were determined by using the expression (3):

$$Z = 60 \cdot \left\{ \ln\left(\frac{H}{R} \right) - 1 \right\}, \tag{3}$$

where H represents the tower height and R the equivalent radius of a tower base. Each tower was divided in four parts: the first part from tower top to upper arm, the second one from upper arm to middle arm, the third part from middle arm to lower arm and the last part from lower arm to the ground. Thus it was possible to calculate transient voltages of tower arms. Tower footing resistances were modelled taking into account soil ionization [3] caused by lightning current. Tower grounding was represented as a non-linear resistor using MODELS language and TACS-controlled time-dependent resistor. The value of tower grounding resistance at low current and low frequency (50 Hz) is 10 Ω. Grounding resistance in the substation 110/35 kV is 0.3 Ω, while the grounding resistance at locations A and B is 1 Ω.

The important parameter for the behaviour of overhead line insulation subjected to lightning overvoltages is its corresponding flashover voltage, which depends on the voltage level and insulation clearances. The flashover mechanism of the overhead line insulators was represented with differential equation (4) of the leader progression model selected by the CIGRE WG 33-01[4].

$$v(t) = k_L u(t)\left[\frac{u(t)}{x} - E_0\right] \tag{4}$$

In the expression (4), $u(t)$ is the voltage as a function of time, x is the distance of the unbridged gap, E_0 is the gradient at which the breakdown process starts, and k_L is a constant [5]. Insulator flashover was modelled using MODELS language in EMTP-ATP.
The equipment in high voltage substation was represented by surge capacitances obtained from manufacturer's data. The model of gapless type SA includes non-linear which was represented by *U-I* characteristics. The arrester leads were represented by the inductance of 1 µH/m taking into account the effects of additional voltage rise across the lead inductance. 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 [6] for impulse current waveform 8/20 µs is shown in Table 1.

Table 1. Residual voltage 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 lightning stroke hitting a tower or a phase conductor was represented by a CIGRE concave shape [3] shown in Fig. 5.

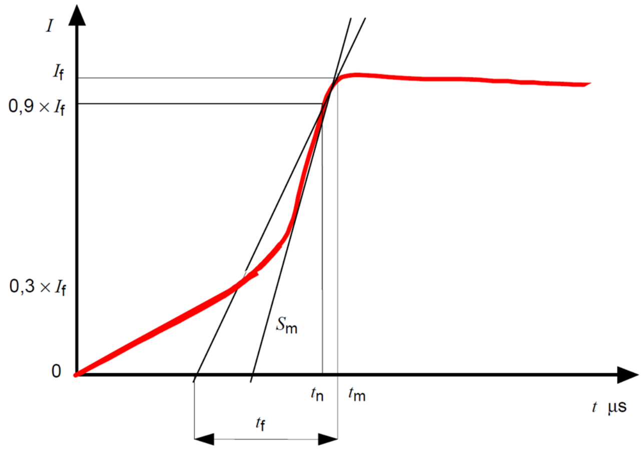

Fig. 5 CIGRE concave shape (I_f is the crest current, S_m is the maximum front steepness, t_f is the equivalent front duration)

The peak current magnitude and the tail time are important when observing the SA energy, while the influence of the rise time is hardly noticeable in such a case. In contrast, the current wave front is an important parameter with regard to the insulator flashover. The CIGRE concave shape shown in Fig. 5 represents more accurately the concave front of a lightning stroke and usually gives more realistic results.

SIMULATION RESULTS

The calculations of lightning overvoltages were carried out in cases when lightning strikes the upper phase conductor and a shield wire at the first tower close to the beginning of the cable section (location A). The most severe switching condition was considered including the open end of the cable (opened circuit breaker at location B).

In cases when a SA is connected at the cable end, it will limit the overvoltage to the level that is equal to the SA's protective level plus the voltage drop of the connecting leads. Sometimes it is necessary to provide SAs at both ends of the cable, if the opposite cable end could be disconnected (eg. due to line tripping).

Typically, the SA is installed at the beginning of the cable (at the transition from overhead line to cable). When a lightning overvoltage reaches the underground cable through the overhead line, it will propagate along the cable and it will reflect and increase when it arrives at an open end of the cable. If this overvoltage is below the lightning impulse withstand voltage of the cable, no additional protection is required. However, the lightning impulse withstand voltage of typical cable in distribution network is relatively low (in this particular case 142 kV was selected according to [7]). In most cases, if a cable is protected with the SA at the beginning of the cable, it is possible that the overvoltage at the open end of the cable exceeds the lightning impulse withstand voltage of the cable and equipment in the cable bay, which can cause the equipment failure.

Three different overvoltage protection scenarios were analysed:

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

For the first scenario (no SAs installed), Figs. 6-9 show the simulation results in cases when lightning current 150 kA, 9.8/77.5 μs hits the first tower in the vicinity of location A.

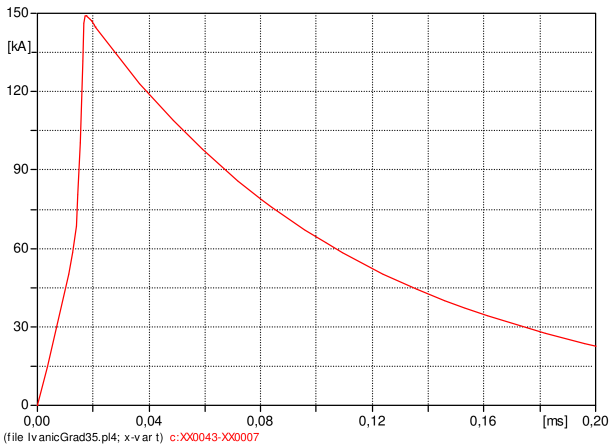

Fig. 6 Lightning current 150 kA, 9.8/77.5 μs

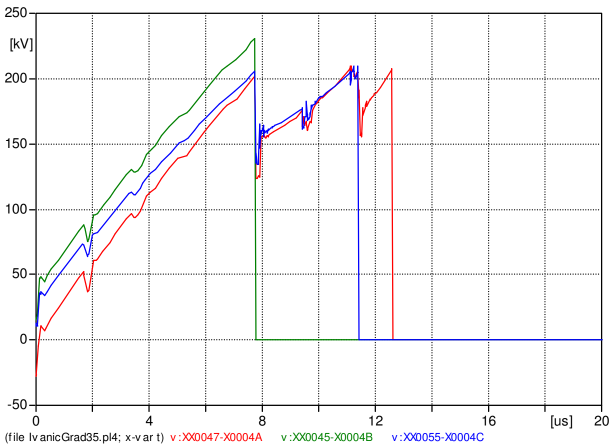

Fig. 7 Overvoltages on the insulator strings of the struck tower (flashover in all phases)

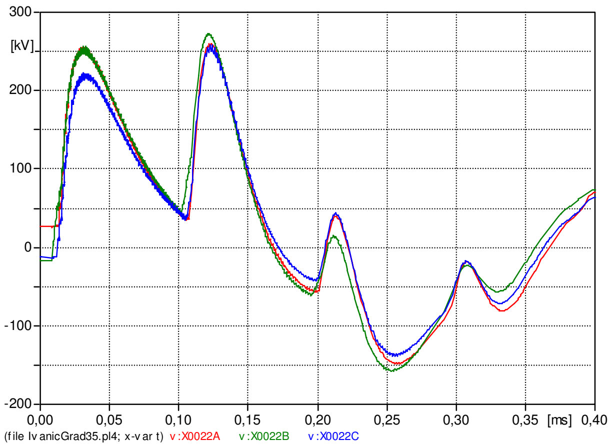

Fig. 8 Overvoltages at the beginning of the cable (U_{max}=272.8 kV)

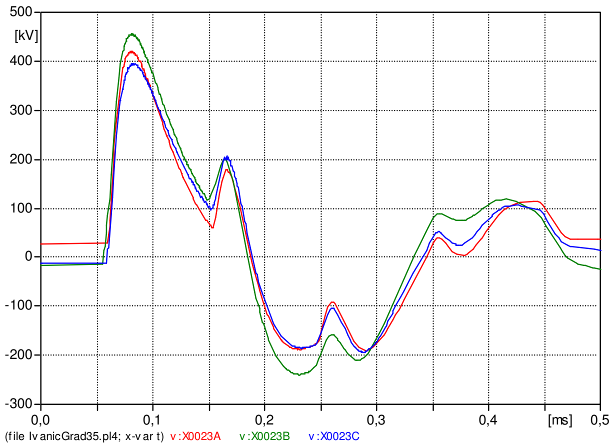

Fig. 9 Overvoltages at the end of the cable (U_{max}=456.0 kV)

Figs. 10-13 show the simulation results for the second scenario (SAs installed only at the beginning of a cable).

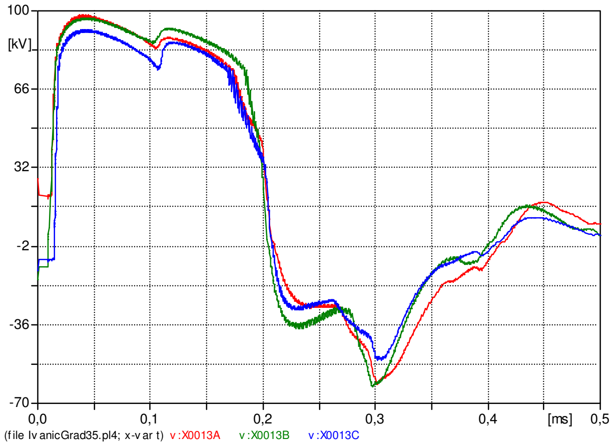

Fig. 10 Overvoltages at the beginning of the cable (U_{max}=98.3 kV)

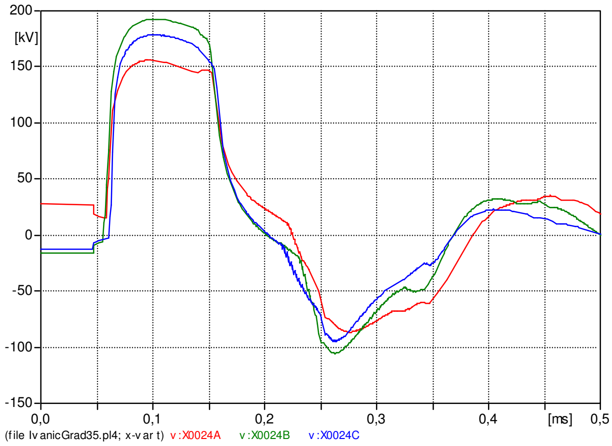

Fig. 11 Overvoltages at the end of the cable (U_{max}=192.7 kV)

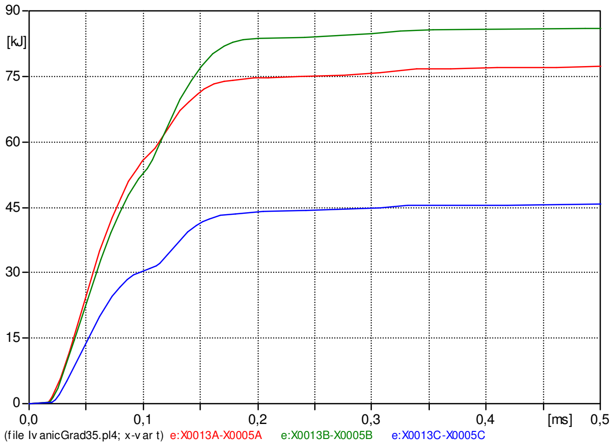

Fig. 12 SA energy (E_{max}=85.9 kJ)

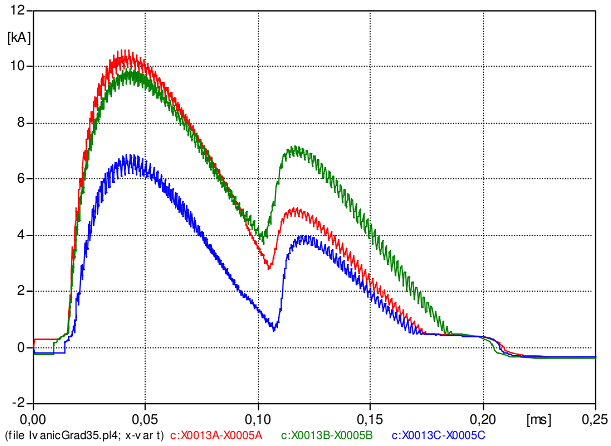

Fig. 13 Currents through SAs (I_{max}=10.6 kA)

Figs. 14-17 show the simulation results for the third scenario - SAs installed at the beginning (location A) and at the end of a cable (location B).

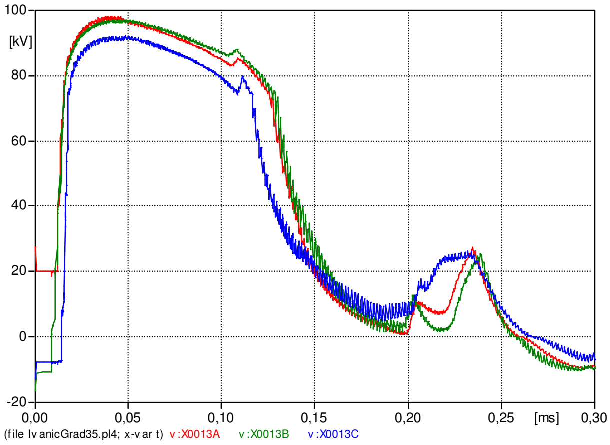

Fig. 14 Overvoltages at the beginning of the cable (U_{max}=98.3 kV)

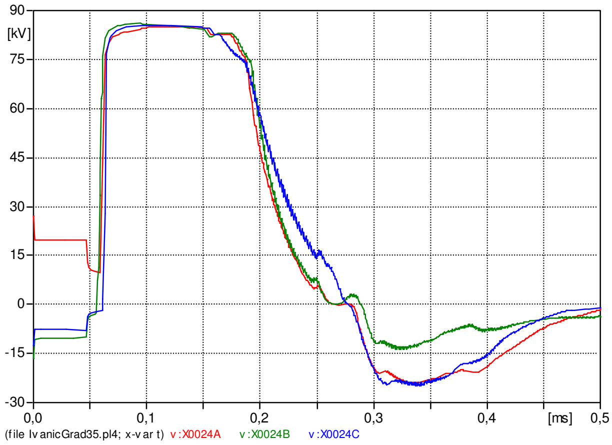

Fig. 15 Overvoltages at the end of the cable (U_{max}=86.3 kV)

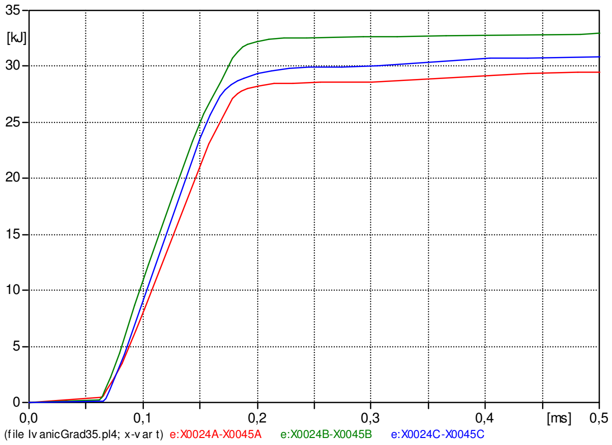

Fig. 16 SA energy at the beginning of the cable (E_{max}=32.9 kJ)

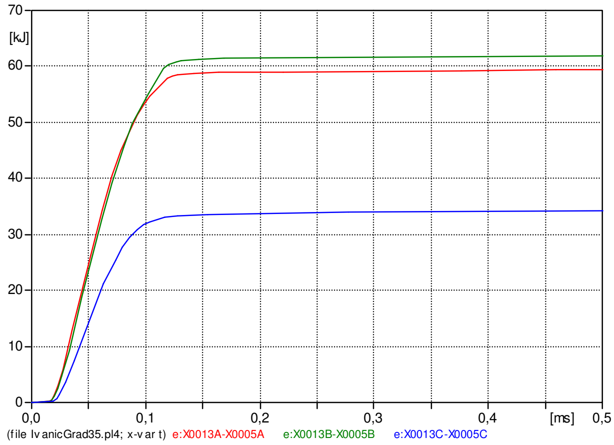

Fig. 17 SA energy at the end of the cable (E_{max}=61.9 kJ)

Maximum lightning overvoltage amplitudes and SA energies in cases of lightning stroke to tower are shown in Table 2.

Table 2. Overvoltage amplitudes and SA energy in case of lightning stroke to tower

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

It can be seen that the lightning overvoltage amplitudes exceed the lightning impulse withstand voltage of the cable for scenarios 1) and 2) (values marked red in Table 2). Even for lower lightning current amplitudes the overvoltages at the end of the cable may exceed the critical value. The SA energy is lower than the critical value of 399 kJ.

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. For the first scenario (no SAs installed), Figs. 18-21 show the simulation results in cases when lightning current 17.8 kA, 3/77.5 μs hits the upper phase conductor of first tower in the vicinity of location A.

Maximum lightning overvoltage amplitudes and SA energies in cases of lightning stroke to tower are shown in Table 3. From the simulation results it can be seen that the lightning overvoltage amplitudes do not exceed the lightning impulse withstand voltage of the cable for all scenarios and that the SA energy is lower than the critical value.

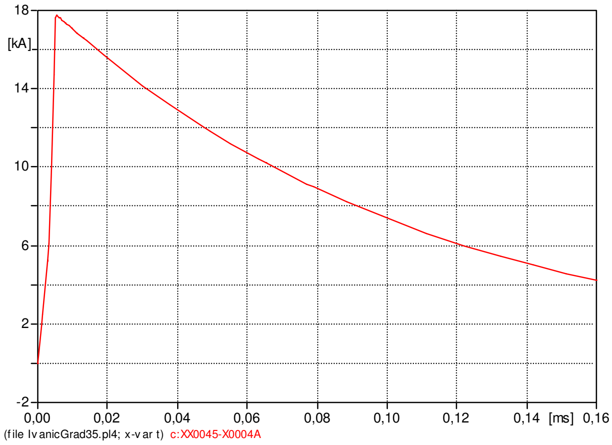

Fig. 18 Lightning current 17.8 kA, 3/77.5 µs

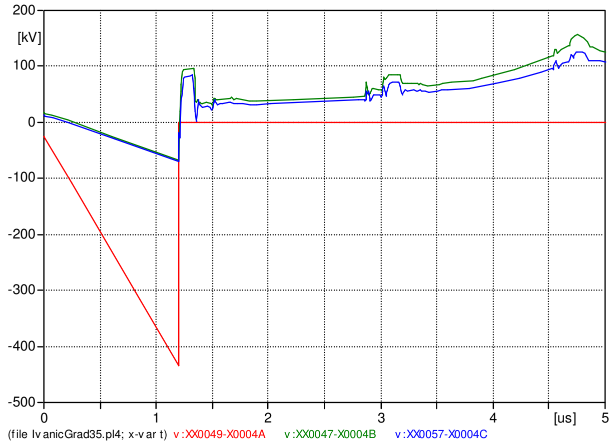

Fig. 19 Overvoltages on the insulator strings of the struck tower (flashover in upper phase A)

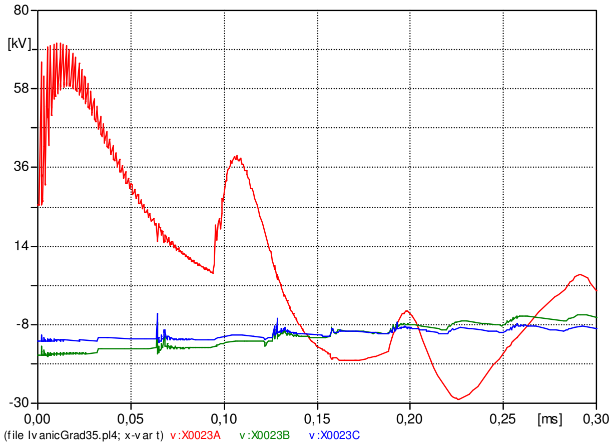

Fig. 20 Overvoltages at the beginning of the cable (U_{max}=70.8 kV)

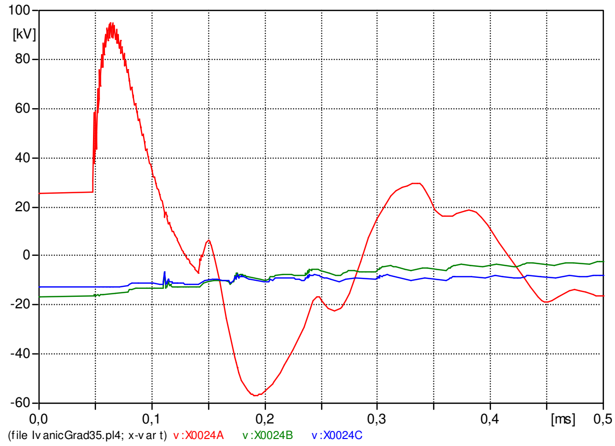

Fig. 21 Overvoltages at the end of the cable (U_{max}=95.04 kV)

Table 3. Overvoltage amplitudes and SA energy in case of 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 OBTAINED FROM THE LIGHTNING LOCATION SYSTEM

The lightning activity around 35 kV overhead line 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) [8-10], which is capable of detecting multiple-stroke flashes where every stroke is represented by individual set of data (current amplitude, discharge time, location, etc.). Cloud-to-ground (CG) flashes consist of one or several strokes coming in very short temporal intervals and close spatial proximity. The common method for grouping stroke data into flashes is to use the thresholds for maximum temporal separation and maximum lateral distance between successive strokes. For this purpose, an algorithm was developed to group lightning strokes into flashes (assessment of the 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 [9].
Fig. 21 shows a number of CG and inter-cloud (IC) lightning strokes detected by LLS around 35 kV overhead line during a 7 year period.

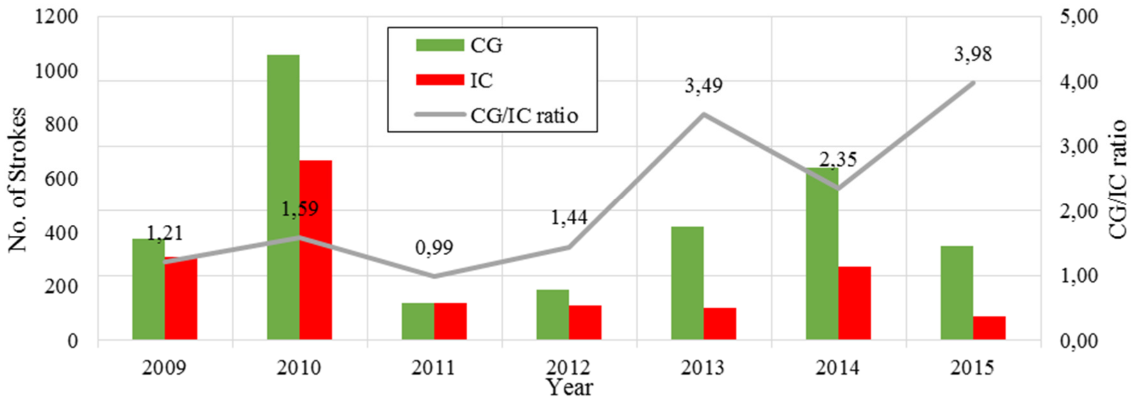

Fig. 21 Number of CG and IC lightning strokes detected by LLS around 35 kV overhead line

Table 4 shows the information on the CG lightning strokes detected around the overhead line, where FMF represents the Flash Multiplicity Factor, N_{gf} the lightning flash density and N_{gs} the lightning stroke density.

Table 4. CG lightning strokes detected around the overhead line

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**

A total of 3170 CG strokes were detected, with an average stroke multiplicity of 1.42 strokes per flash. Table 5 shows the multiplicity of CG lightning strokes. A lightning flash with a maximum number of 17 lightning strokes was detected by LLS. The majority (70.6 %) of lightning flashes are unipolar while 29.4 % are bipolar.

Table 5. Multiplicity of CG lightning strokes

Number of strokes per flash	Number of flashes
1	1708
2	315
3	105
4	44
5	23
6	13
7	6
8	5
9	3
10	1
12	1
17	1

The cumulative amplitude distributions for CG negative strokes and CG positive strokes are shown in Figs 22-23.

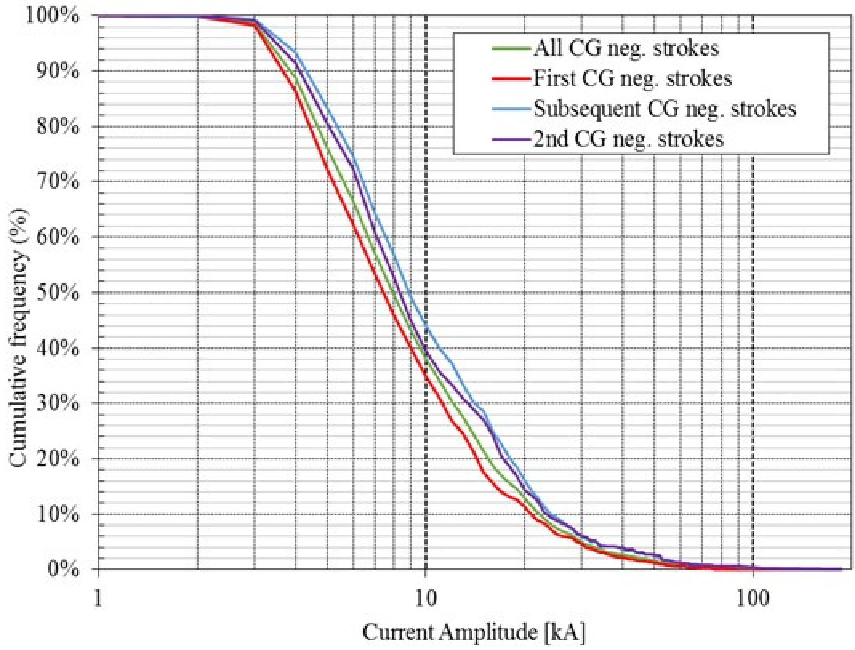

Fig. 22 Cumulative amplitude distribution of CG negative lightning strokes

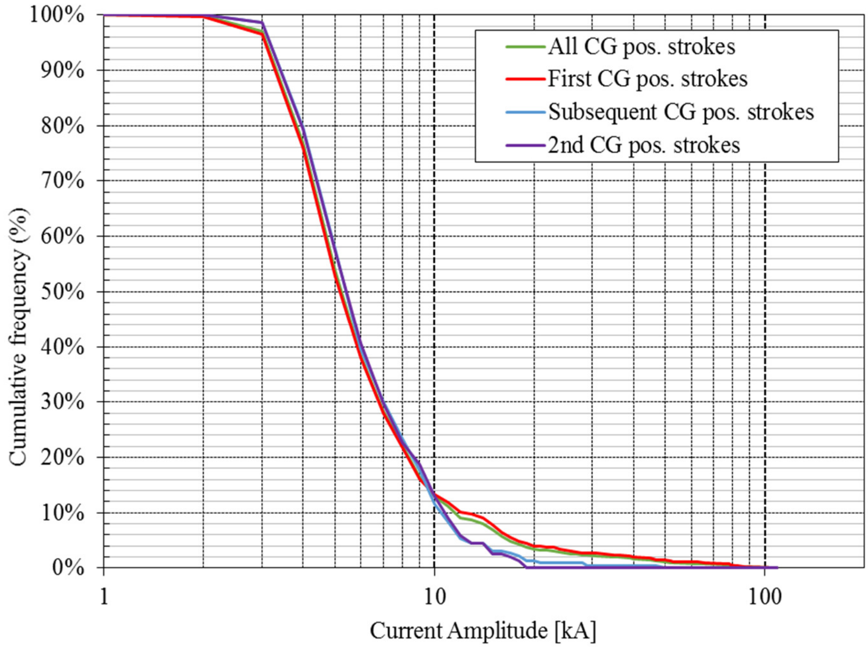

Fig. 23 Cumulative amplitude distribution of CG positive lightning strokes

According to the data from LLS, there is a significantly higher probability of lightning strokes occurrence with lower current amplitudes, compared to CIGRE [4] data. This difference is caused by the sensitivity of LLS which is capable of detecting multiple CG strokes with low current amplitudes. LLS data gives lower median values of current amplitudes both for first and subsequent strokes.

CONCLUSIONS

This paper deals with lightning overvoltages in a mixed overhead line and underground cable distribution network supplying an industrial consumer. Lightning overvoltages in a 35 kV distribution network were calculated by using the EMTP-ATP software. The open end of cable was considered in simulations as the most unfavourable switching configuration. 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 analysed 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". Therefore, 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.

ACKNOWLEDGEMENTS

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