Lightning Overvoltage Analysis for a 380-kV Gas-Insulated Line

M. Kizilcay, C. Neumann

***Abstract*--A new double-circuit 380-kV gas-insulated line (GIL) of length 1 km was installed in Germany. The connection between the overhead line and gas-insulated substation (GIS) is realized by the GIL instead of a XLPE cable. The lightning performance of the overhead line and the GIL has been studied in this paper. Lightning overvoltages along the GIL caused by the lightning strokes to the towers or to the ground wire and direct strokes to the phase conductors of the overhead line are computed. Various electrogeometric models of the phase conductors and ground wire are taken into consideration to determine maximum lightning current amplitude for a direct stroke to a phase conductor. In particular, the requirement of additional surge arrester set at the GIS interface of the GIL is investigated**

***Keywords*: flashover, back-flashover, lightning stroke, lightning surge, surge arrester, gas-insulated line, EMTP.**

I. INTRODUCTION

For the transmission of high power underground gas-insulated transmission lines (GIL) are a good technical alternative to an underground XPLE cable [1]. The GIL has the advantage of low resistive losses because of large cross section of the conductor and enclosure. GIL is environmentally friendly with regard to low field emissions. The return current over the enclosure is almost as high as the current of the conductor and therefore the resulting magnetic field outside of the GIL is very low. Besides, because of gaseous dielectric with the capacitive load is relatively low. As insulating gas a mixture of SF6 (20 %) and nitrogen (80 %) is used.

A double-circuit 380-kV underground gas-insulated transmission line (GIL) was installed to connect a double-circuit 380-kV overhead line with a metal-enclosed gas-insulated substation (GIS). The length of the GIL is 1 km. The power transmission capacity amounts to 1800 MVA per circuit. The GIL is directly buried [2].

The lightning overvoltage stress and protection of that 380-kV GIL has been analyzed in this paper. The lightning overvoltages caused both by back-flashover over the line insulator and by direct lightning strokes to upper phase conductor are taken into consideration. First, the simulation model created using [3], [4] is described. The results of various scenarios obtained using EMTP-ATP [5] are discussed in the second part of the paper.

Mustafa Kizilcay is with the University of Siegen, Department of Electrical and Computer Engineering, Siegen, Germany (e-mail of corresponding author: kizilcay@ieee.org).
Claus Neumann is with the Amprion GmbH (TSO), Dortmund, Germany (e-mail: claus.neumann@amprion.net)

Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011

II. SYSTEM MODELING

The configuration of the connection of the 380-kV GIS by overhead line and GIL is shown in Fig. 1. The surge arresters shown at left are installed at the gantry, where one circuit of the double circuit line is taken into consideration in the simulation model for the lightning overvoltage analysis. Behind the gantry 5 towers are modeled. When the circuit breakers indicated by “x” in Fig. 1 at the receiving end are in open position, the lightning overvoltage protection of the GIL and also of the open circuit breaker may be insufficient. The aim of this study is to determine whether or not additional surge arrester set is required at the receiving end of the GIL, if the circuit breakers “x” are open. In the following, the models of the components including flashover model are briefly described.

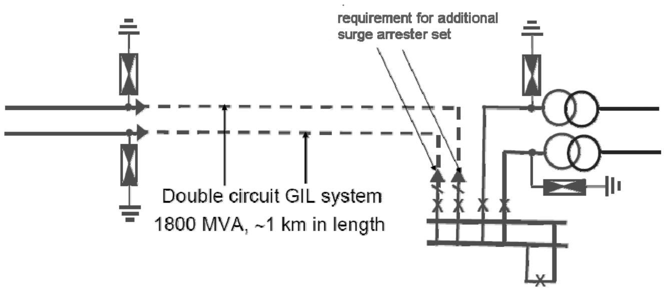


Fig. 1. Connection of the 380-kV gas-insulation substation by overhead line and GIL

A. Tower Model

The simplified layout of the first tension tower of the 380-kV double-circuit overhead line is shown in Fig. 2 with dimensions in m. The position of the conductors at the other tower is similar to the first tower. The towers are represented by loss-less Constant-Parameter Distributed Line (CPDL) model [5]. The propagation velocity of a traveling wave along a tower is taken to be equal to the light velocity [6], [7]. The surge impedance of the tower is calculated according to the formula given in [7] for the “waisted” tower shape [8] (see Fig. 3):

$$Z_{t-waist} = 60 \cdot \ln\left[\cot\left\{0.5 \cdot \tan^{-1}\left(\frac{R}{h}\right)\right\}\right] \tag{1}$$

where $R = \dfrac{r_1 h_2 + r_2 h + r_3 h_1}{h}$ and $h = h_1 + h_2$.

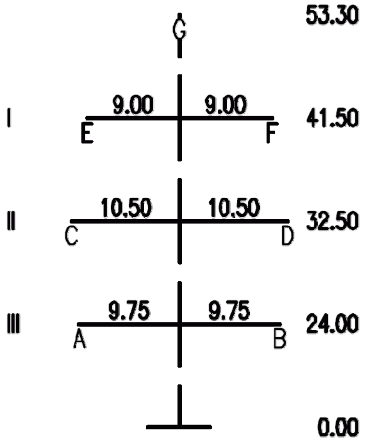
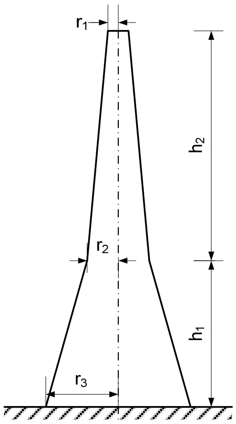


Fig. 2. Layout of the first tension tower



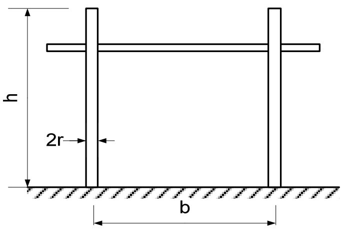


Fig. 3. „Waisted“ tower model Fig. 4. Simplified model of the gantry

The surge impedance of the gantry is calculated according to Eq. (2) referring to Fig. 4 [9].

$$Z_{s\text{-}g} = \frac{Z_s + Z_m}{2} \tag{2}$$

where

$$Z_s = 60\ln(h/r) + 90\cdot(r/h) - 60$$

$$Z_m = 60\ln(h/b) + 90\cdot(b/h) - 60$$

The calculated surge impedance of the modeled towers is given in Table 1. The cross-arms are modeled as considering them like bundle conductors with an average surge impedance of 265 Ω. The propagation velocity is taken equal to the light velocity. The tower footing impedance is assumed to be a constant resistance of 10 Ω.

TABLE 1
SURGE IMPEDANCE OF THE TOWERS

tower	type	surge impedance (Ω)
0	gantry	127.2
1	tension	207.8
2	tension	208.5
3	tension	204.7
4	suspension	216.1
5	suspension	216.1

B. 380-kV Overhead Line

Only one circuit of the double circuit overhead line (symmetric on both sides of the tower) is represented by the *CPDL* model at $f = 400$ kHz. Data of the conductors are:

- *phase conductors*: 4 conductors/phase, ACSR 265/35 Al/St
- *ground wire*: AY/AW 216/33 (aerial cable).

That overhead line has only one ground wire. In order to increase the shielding effect two ground wires are connected between gantry (from outer poles) and first tension tower. The average ground resistivity is given as $\rho_g = 500\,\Omega\cdot\text{m}$.

C. 380-kV Gas-Insulated Transmission Line (GIL)

The GIL consists of inner conductor and enclosure both made of Aluminium alloy. The dielectric between conductor and enclosure is a gas mixture of SF6 (20 %) and nitrogen (80 %) with the relative permittivity $\varepsilon_r \approx 1$. The outer surface of the enclosure is coated by an insulating material of thickness 5 mm as corrosion protection. Its relative permittivity is 4. The GIL data are summarized in Table 2.

TABLE 2
DATA OF THE GAS-ISULATED LINE

Conductor	
- outer diameter	180 mm
- thickness	10 mm
- resistivity	0.03571 Ω·mm²/m
Enclosure	
- inner diameter	500 mm
- thickness	8.5 mm
- resistivity	0.05714 Ω·mm²/m

The GIL is represented as *single-core cable* using CABLE PARAMETERS (CP) [5]. The line model CPDL (Bergeron model) is created at $f = 100$ kHz. At this frequency the electromagnetic waves travel almost completely in the coaxial mode, so that each gas-insulated pipe (each phase) can be modeled independently from the other phases.

The surge impedance Z_s and propagation velocity v of the coaxial mode at $f = 100$ kHz are:

$$Z_s = 61.3\,\Omega;\quad v = 299.4\ \text{m}/\mu\text{s}.$$

The GIL has been divided into 5 sections of length 200 m. The reason for this representation is to enable the observation of the voltage wave propagation along the GIL. The highest voltage may occur anywhere along the GIL.

D. Strain Insulator String and Flashover Model

Double strain insulator strings are used at the last three tension towers, for which a flashover model will be developed. The 50 % sparkover volt-time characteristic of the insulator is calculated according to [10] using the flashover distance of 2.97 m:

$$u_{flo}(t) = 400 \cdot l + 710 \cdot l \cdot t^{-0.75} \qquad (3)$$

Based on the positive experience in the past works [11], [12], [13], where a comparison was made between leader development methods [15], [16] and the equal-area criterion by Kind [7], [14] on similar tower structures, Kind method is used as flashover model. The criterion by Kind requires two parameters, U_0 and F, and it is tested simply by evaluating the following integral numerically:

$$\int_0^{t_{flo}} \left[u(t) - U_0\right] dt \geq F \qquad (4)$$

where $u(t)$ is the voltage waveform across the insulator.

When the time integral of the voltage difference ($u - U_0$) becomes greater than the value of F, then at $t = t_{flo}$ the flashover occurs. The unknown parameters U_0 and F can be obtained from the 50 % sparkover volt-time characteristic of the insulator. The unknown parameters in (4) are determined according to [14]:

$U_0 = 1095.6\ \text{kV}$, $F = 0.726\ \text{Vs}$.

In case of flashover the arc channel is represented by the self inductance of 1 µH/m.

E. Lightning Stroke

The lightning stroke is modeled by a current source and a parallel resistance of 1 kΩ, which represents the lightning-path impedance [6]. Two different lightning current wave-forms are used to represent a stroke to the top of the tower or ground wire:

a) CIGRE waveform [7] of concave shape with front time, $T_f = 3\ \mu\text{s}$ and time to half value, $T_h = 77.5\ \mu\text{s}$. Constant current peak value: 200 kA.
b) Linear ramp waveform with $T_f = 1\ \mu\text{s}$ and $T_h = 70\ \mu\text{s}$. Constant current peak value: 150 kA.

For a lightning stroke to the upper phase conductor, the crest current is determined using various electrogeometric models (EGM) for the ground and phase conductors. The front time T_f of the CIGRE model is calculated using the correlation between the final crest current I_F and t_{30} for the first negative downward stroke in the range $I_F > 20\ \text{kA}$ [7]:

$$t_{30} = 0.906 \cdot I_F^{0.411} \quad (I_F \text{ in kA; } t_{30} \text{ in µs}) \qquad (5)$$

The maximum rate of rise S_m is also dependent on the crest current I_F and calculated according to (6). The time to half value $T_h = 77.5\ \mu\text{s}$ is kept as constant.

$$S_m = 6.50 \cdot I_F^{0.376} \quad (I_F \text{ in kA; } S_m \text{ in kV/µs}) \qquad (6)$$

Additionally, to represent subsequent strokes a linear ramp waveform (1/30 µs) is used for comparison purpose.

F. 380-kV Surge Arresters

Line-to-ground surge arresters with $U_r = 336\ \text{kV}$ are specified by the power utility. The voltage-current characteristic of the surge arrester is shown in Fig. 5. They are represented using the simplified IEEE model [17] - [19] by two non-linear resistors A_0 and A_1 for the slow and fast surges (see Fig. 6). The inductances L_0 and L_1 in Fig. 6 are calculated according to [18], [19]. A lead wire of total 5 m connects the surge arrester with the phase conductor and grounding point, which is modeled by a lumped inductance of 1 µH/m.

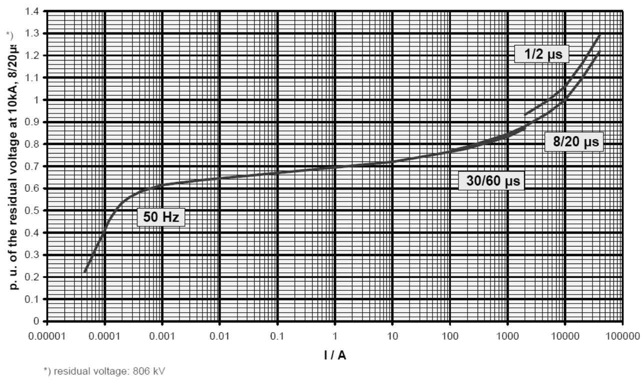


Fig. 5. Voltage-current characteristic of the surge arrester

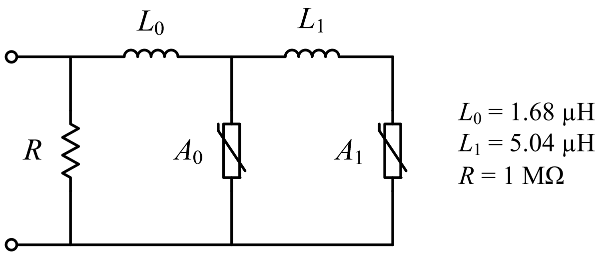


Fig. 6. Surge arrester model [17]

III. Computation Results

The lightning overvoltages caused by

– lightning strokes to the tower or ground wire and subsequent back-flashover across the line insulator,
– direct lightning strokes to the upper phase conductor with or without flashover

are computed. At first step the requirement for an additional surge arrester set at the receiving end of the GIL (connection to GIS) is evaluated, in case the circuit-breaker or disconnector at this location (see Fig. 1) is open.

The standard rated lightning impulse withstand voltage for the highest voltage for equipment, $U_m = 420\ \text{kV}$ is 1425 kV (peak value) for the 380-kV transmission system in question [20]. Taking the recommended safety factor, $K_s = 1.15$, for internal insulation into consideration, following limiting value for the lightning overvoltages is applicable:

$$u_{\lim} = \frac{1425\ \text{kV}}{K_s} = 1239\ \text{kV} \qquad (7)$$

The schematic diagram of the modeled transmission system for lightning surge computations is shown in Fig. 7. Three-phase conductors and ground wire are considered in the simulation model. The power frequency system voltage is represented by a three-phase voltage source behind the last line section, length of which is chosen as 6 km, so that time-domain simulation with a total period, $T_{\max} = 40\ \mu\text{s}$ is allowed without any disturbing effects due to refractions and reflections. Five towers and corresponding line sections behind the gantry are modeled in detail.

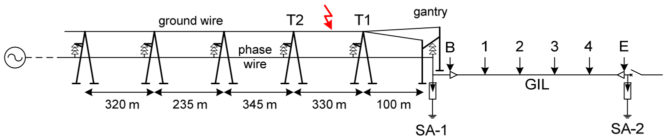


Fig. 7. Schematic diagram of the modeled overhead line and GIL

A. Lightning Stroke to the Tower or Ground Wire

Following locations for the lightning stroke are selected:

- top of tension tower T1
- top of tension tower T2
- ground wire between gantry and tower T1, distance to T1 50 m
- ground wire between gantry and tower T1, distance to T1 20 m.

Unlike in Fig. 7 only one ground wire between gantry and T1 is taken into consideration in the simulation model.

In the case without surge arrester set SA-2 at the open end of the GIL most of the cases produce voltage amplitudes at the open GIL end that are higher than u_{lim} given in (7). A back-flashover is expected at the towers T1 and T2 depending on the location of the lightning stroke, i. e. a lightning stroke to the top of T2 causes back-flashover at T1 and T2. Thereby the power frequency system voltage in phase A at $t = 0$ is assumed to be

$$u_A(0) = -\hat{u}_{m\mathrm{Y}} = -\sqrt{\frac{2}{3}} \cdot U_m = -343\ \text{kV} \qquad (8)$$

as the worst case for a lightning stroke current with a positive sign.

The highest peak voltage of 1744 kV is expected at the open end of the GIL in phase A for a lightning stroke, 200 kA, Cigre waveform (3/77.5 µs), to top of T2. The back-flashover occurs only in phase A. The voltage waveforms along the GIL are shown for this case in Fig. 8. The lightning voltage is limited by the surge arrester set SA-1 at the beginning of GIL to approx. 700 kV. At the open end the voltage surge reaches more than the twice of the limited value by SA-1.

The same case with additional surge arrester set SA-2 at the open end of GIL is no longer critical as shown in Fig. 9. The maximum voltage along the GIL is lower than u_{lim}.

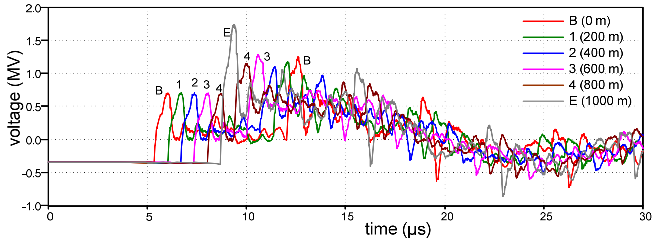


Fig. 8. Voltage waveforms along the GIL between core and enclosure in 200 m distances. Only surge arrester set SA-1 in operation

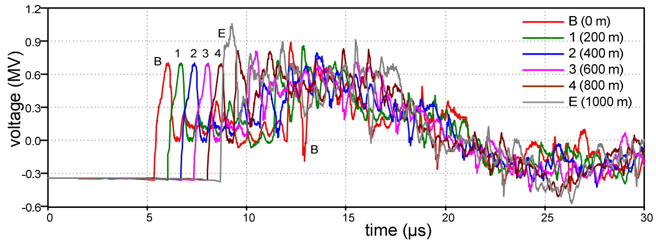


Fig. 9. Voltage waveforms along the GIL between core and enclosure in 200 m distances with additional surge arrester set SA-2

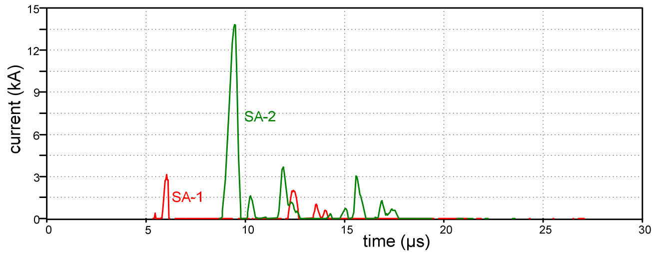


Fig. 10. Phase A current of surge arresters SA-1 and SA-2 for the voltage curves in Fig. 9

The current of the surge arresters in phase A for the case with both surge arrester sets in operation is shown in Fig. 10.

B. Direct Lightning Stroke to a Phase Conductor

In case of a direct lightning stroke to a phase conductor the maximum lightning stroke current is determined by the electrogeometric model (EGM) of the phase and ground wires. The striking distance of a downward leader is defined as a function of stroke current. The intersection of the family of striking distance curves between ground wire and upper phase wire, and upper phase wire and ground delivers the maximum lightning stroke current that would hit the phase conductor [7]. Fig. 11 shows as an example those curves for the span between tower T1 and T2. The intersection of the red curve (striking distance boundary curve between shield wire and the upper phase wire) and of the green curve (striking distance boundary curve between the upper phase wire and ground) corresponds to a stroke current amplitude of $I_{peak} = 45.2$ kA. This means the phase wire may be hit directly by a lightning stroke with this maximum amplitude.

For comparison purpose, following EGMs are applied to different locations along the overhead line for a direct lightning stroke [7], [21]:

Love; Young, et al.; Armstrong/Whitehead; Brown/Whitehead; IEEE WG [7]; IEEE-Guide [21].

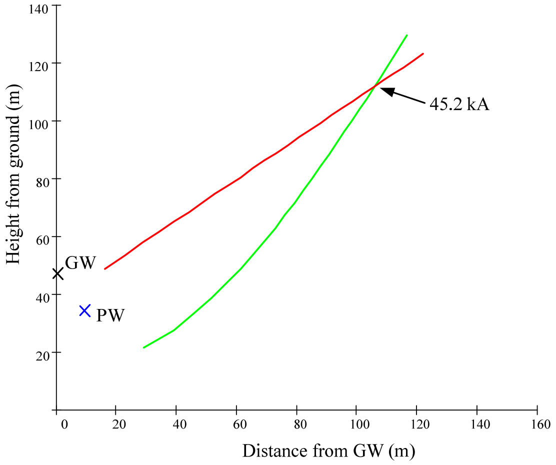


Fig. 11. EGM for the overhead line between tower T1 and T2 according to the model Brown/Whitehead [7] (crosses: ground wire “GW” and phase wire “PW”)

The general equations for the lightning current dependent striking distances are given as follows:

– phase and ground wires: $r_c = A_c \cdot I^{b_c}$ (9)

– ground: $r_g = A_g \cdot I^{b_g}$ (10)

The locations for a direct lightning stroke selected are:

(a) 10 m in front of tower T1 (direction gantry)
(b) 10 m behind tower T1 (direction T2)
(c) between towers T1 and T2 (mean conductor heights)
(d) midway between gantry and T1.

For the locations (a) and (d) and their EGM it is assumed that two ground wires between the tower T1 and two outer poles of the gantry exist (see Fig. 7). The maximum likely stroke current amplitudes determined by various EGM are summarized in Table 3 for the above locations of a lightning stroke to the upper phase conductor.

TABLE 3
MAXIMUM LIGHTNING STROKE CURRENT AMPLITUDES TO HIT THE UPPER PHASE CONDUCTOR FOR VARIOUS EGM AND DIFFERENT STROKE LOCATIONS

EGM	stroke current amplitudes (kA) at different stroke locations			
	(a)	(b)	(c)	(d)
Love	34.4	41.8	32.0	7.5
Young et al	81.6	132.7	69.8	2.8
Armstrong/Whitehead	41.2	50.4	39.2	10.1
Brown/Whitehead	47.7	59.0	45.2	10.8
IEEE [7]	72.4	92.7	68.1	13
IEEE Guide [19]	574	∞	152.1	10.2

The EGM according to IEEE Guide [19] delivers unrealistically high current amplitudes for the locations (a) to (c). With two ground wires between gantry and tower T1 a good shielding can be achieved, as indicated by the lower current amplitudes for the location (d) in Table 3.

Since the calculated maximum values of lightning stroke currents according to Table 3 vary in a wide range, the lightning current amplitudes are changed in the range (25 kA … 80 kA). For each current amplitude the overvoltage along the GIL is determined. Without surge arrester set SA-2 the overvoltages expected in the GIL are higher than the limiting value u_{lim}. For example, for the lightning stroke location (c) and Cigre waveform with $I_F = 40\ \mathrm{kA}$, $T_f = 4.13\ \mu\mathrm{s}$ and $S_m = 26\ \mathrm{kA}/\mu\mathrm{s}$ the voltage peak reaches 1995 kV at the open end of GIL as shown in Fig. 12. A flashover across the line insulator at T1 is expected for lightning currents equal and higher than 30 kA.

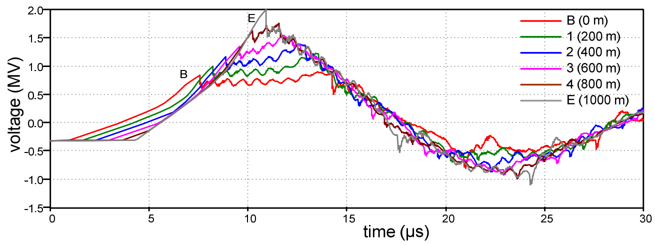


Fig. 12. Voltage waveforms along the GIL between core and enclosure in 200 m distances for $I_F = 40\ \mathrm{kA}$, CIGRE waveform. Only surge arrester set SA-1 in operation

For the same lightning stroke location (c) the overvoltages are computed by taking into consideration the additional surge arrester set SA-2 at the open end of the GIL (see Fig. 13). The simulation results with and without surge arrester set SA-2 are summarized in Fig. 14, where the limiting values for the overvoltages with and without safety factor K_s (see (7)) are indicated by horizontal lines.

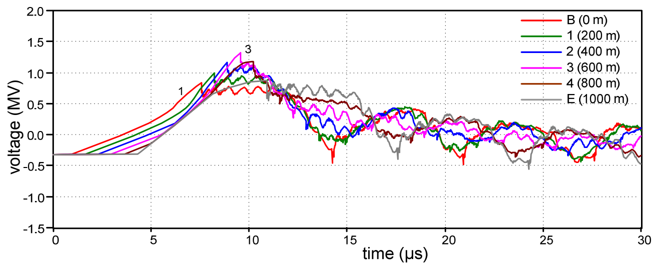


Fig. 13. Voltage waveforms along the GIL between core and enclosure for $I_F = 40\ \mathrm{kA}$, CIGRE waveform. Both surge arrester set SA-1, SA-2 in operation

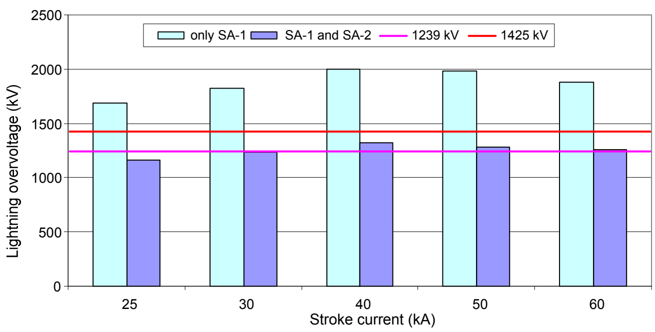


Fig. 14. Overvoltages along the GIL with and without surge arrester set SA-2 in operation for the location (c) of the lightning stroke

The overvoltages along the GIL are slightly greater than u_{lim}, but lower than 1425 kV (the standard rated lightning impulse withstand voltage). They occur at locations other than the sending and receiving end, where the surge arresters SA-1 and SA-2 are located.

IV. Conclusion

This paper deals with the lightning overvoltage study for a 1 km long 380-kV gas-insulated line that connects a double-circuit overhead line with a gas-insulated substation (GIS). The simulation model has been created using graphical pre-processor ATPDraw and the simulations have been performed using EMTP-ATP.

The lightning overvoltages caused 1) by strokes to the tower or ground wire and subsequent back-flashover of the line insulator and 2) by direct lightning strokes to upper phase conductor are taken into consideration. In both cases surge arrester sets (phase-to-ground) at the gantry and at the end of the GIL (GIS interface) are required, when the circuit-breaker or the disconnector at the end of the GIL are open. Since the GIL is relatively long (1 km), lightning voltage may rise to critical values along the GIL in spite of surge arresters installed at both ends. In the case of direct lightning stroke to the phase conductor depending on the peak value of the stroke current subsequent flashover across the line insulator is expected. The overvoltages in the GIL may reach values higher than the limiting value u_{lim} which contains 15 % safety margin according to [18]. In any case the overvoltages remain below the standard rated lightning impulse withstand voltage.

Possible measures to reduce further the lightning overvoltages in the GIL would be a) selection of surge arresters with a lower residual voltage, b) equipping the overhead line with additional ground wire at the last four towers or c) installation of an additional surge arrester set at the midway of the GIL. Measure a) implies that the continuous operating voltage of the surge arrester should be lowered which may not be feasible due to the temporary overvoltages in the system. Measures b) and c) both would cause substantial additional cost. To add a second ground wire to the existing overhead line is associated with the change of the tower design. Consequently, the present solution for the lightning protection of the GIL by means of two sets of surge arresters to be installed at both ends is regarded as sufficient taking also into consideration that the lightning phenomenon is a random process with a statistical distribution of its parameters.

V. References

[1] H. Koch, T. Hillers, "Second-Generation Gas-Insulated Line", *IEEE Power Engineering Journal*, Vol. 16, No. 3, June 2002.

[2] C. Neumann, "Gas-Insulated Lines Provide EHV Solution", *Transmission & Distribution World Magazine*, Issue February 2010, Penton Media, Inc. (available at: http://tdworld.com/ underground_transmission_distribution/gas-insulated-lines-20100201/)

[3] H. K. Høidalen, "Updates in ATPDraw version 5.4", *Proc. European EMTP-ATP Users Group Meeting*, Izmir, Turkey, Sept. 2008.

[4] H. K. Høidalen, D. Radu, D. Penkow, "Optimization of Cost Functions in ATPDraw", *Proc. of the EEUG Meeting 2009*, Delft, The Netherlands, Oct. 2009.

[5] Canadian/American EMTP User Group: *ATP Rule Book*, distributed by the European EMTP-ATP Users Group Association, 2009.

[6] A. Ametani, T. Kawamura, "A Method of a Lightning Surge Analysis Recommended in Japan Using EMTP", *IEEE Trans. on Power Delivery*, Vol. 20, No. 2, pp. 867-875, April 2005.

[7] CIGRE WG 33-01: "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines", Technical Brochure, October 1991.

[8] W. A. Chisholm, Y. L. Chow, K. D. Srivastava, "Travel Time of Transmission Towers", *IEEE Trans. on Power App. and Systems*, Vol. PAS-104, No. 10, S. 2922-2928, Oktober 1985.

[9] IEEE Working Group on Lightning Performance of Transmission Lines: A Simplified Method for Estimating Lightning Performance of Transmission Lines, *IEEE Trans. on Power App. and Systems*, Vol. PAS-104, No. 4, S. 919-927, April 1985.

[10] [IEEE Fast Front Transients Task Force, Modeling and Analysis of System Transients Working Group: Modeling Guidelines for Fast Front Transients, *IEEE Trans. on Power Delivery*, Vol. 11, No. 1, S. 493-506, 1996.

[11] M. Kizilcay, C. Neumann, "Backflashover Analysis for 110-kV Lines at Multi-Circuit Overhead Line Towers," *Proc. International Conference on Power Systems Transients* (IPST'07), Lyon, France, June 4-7, 2007. Available http://www.ipst.org

[12] M. Kizilcay, C. Neumann, "Mitigation of common mode failures at multi circuit line configurations by application of line arresters against back-flashovers," presented at the CIGRE-Symposium on Transient Phenomena in Large Electric Power Systems, , Zagreb, Croatia, April 18-21, 2007.

[13] M. Kizilcay, "Mitigation of Back-Flashovers for 110-kV Lines at Multi-Circuit Overhead Line Towers", *Proc. International Conference on Power Systems Transients* (IPST'09), Kyoto, Japan, June 2-6, 2009. Available http://www.ipst.org

[14] CIGRE WG 33.02: "Guidelines for representation of network elements when calculating transients", CIGRE Technical Brochure, No. 39, 1990.

[15] Motoyama, H.: "Experimental study and analysis of breakdown characteristics of long air gaps with short tail lightning impulse", IEEE Trans. on Power Delivery, Vol. 11, No. 2, pp. 972-979, April 1996.

[16] Pigini, A.; Rizzi, G.; Garbagnati, E.; Porrino, A.; Baldo, G.; Pesavento, G.: "Performance of large air gaps under lightning overvoltages: Experimental study and analysis of accuracy of predetermination methods", IEEE Trans. on Power Delivery, Vol. 4, No. 2, pp. 1379-1392, April 1989

[17] IEEE Working Group 3.4.11-Surge Protective Devices Committee: "Modeling of Metal Oxide Surge Arresters", *IEEE Trans. on Power Delivery*, Vol. 7, No. 1, S. 302- 309, January 1992.

[18] P. Pinceti, M. Giannettoni, "A simplified model for zinc oxide surge arresters", *IEEE Transactions on Power Delivery*, Vol. 14, No. 2, April 1999.

[19] M. C. Magro, M. Giannettoni, P. Pinceti, "Validation of ZnO Surge Arresters Model for Overvoltage Studies", *IEEE Transactions on Power Delivery*, Vol. 19, No. 4, October 2004.

[20] *Insulation Co-ordination, Part 1: Definitions, Principles and Rules*, IEC 60071-1, 2006.

[21] *IEEE Guide for Improving the Lightning Performance of Transmission Lines*, Transmission and Distribution Committee of the IEEE Power Engineering Society 1997.