Lightning Overvoltage Analysis of a 380-kV overhead line with a GIL section

M. Kizilcay, C. Neumann

***Abstract*-- A new underground 380-kV gas-insulated line (GIL) of length 400 m has been built near a 380-kV substation to replace an existing overhead line section in an industrial area to gain space for additional buildings. The last 600 m line section between GIL and substation remains as 380-kV overhead line. The power transmission capacity of the GIL amounts to 2000 MVA per circuit. The lightning overvoltage stress and lightning protection of that 380-kV GIL section has been studied in this paper. The lightning overvoltages caused both by back-flashover over the line insulator and by direct lightning strokes are taken into consideration.**

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

I. Introduction

Underground gas-insulated transmission lines (GIL) are gradually preferred to underground XPLE cables in Germany [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.

A new underground 380-kV GIL of length 400 m has been built near a 380-kV substation to replace an existing overhead line section in an industrial area to gain space for additional buildings. At first stage a double-circuit 380-kV GIL has being built in a concrete tunnel. In future it will be extended to four circuits. The last 600 m line section between GIL and substation remains as 380-kV overhead line. In order to connect the GIL section to the existing transmission line two new towers have been built. The power transmission capacity of the GIL amounts to 2000 MVA per circuit.

The configuration of the 380-kV line section consisting of the incoming overhead line, GIL section, overhead line section and connection to the substation is shown in Fig. 1. The surge arresters are installed at the two new towers and there are existing surge arresters in the substation to protect the transformer.

One circuit of the double circuit line is taken into consideration in the simulation model for the lightning overvoltage analysis. The lightning overvoltage stress and lightning protection of that 380-kV GIL has been studied in this paper. A previous lightning overvoltage study for a different GIL has been published in [2] by the same authors. The lightning overvoltages caused both by back-flashover over the line insulator and by direct lightning strokes are taken into consideration.

In the first part of the paper the simulation model created using ATPDraw [3] is described. The results of various simulations performed by EMTP-ATP [4] are discussed in the second part.

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II. Simulation Model

The configuration of the modelled part of the 380-kV transmission system with a new GIL section is shown in Fig. 1. The incoming overhead line at left is represented up to 6 towers. The following double-circuit GIL section of length 400 m has replaced in that area the overhead line. Between GIL and the substation there are three towers and the gantry. Although they are not indicated in Fig. 1, line conductors between gantry and circuit breaker (31 m), and circuit breaker and transformer (81 m) have been modelled in detail, too. In the following the models of various components including flashover model are briefly described.

A. Tower Models

Including gantry total ten towers are represented in the simulation model. Towers M3 and M4 are new towers equipped with an additional cross arm orthogonal to the conventional two cross arms. As an example the simplified structure of the tension tower M6 is shown in Fig. 2 with dimensions in m. The towers are represented by loss-less Constant-Parameter Distributed Line (CPDL) model [4]. The propagation velocity of a traveling wave along a tower is taken to be equal to the light velocity [5], [6]. The surge impedance of the tower is calculated according to the formula given in [6] for the "waisted" tower shape [8]:

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

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

Since the cross arm lengths are not negligible compared to the tower height, the cross arms are represented by surge impedance calculated in a simplified way like horizontal bundle conductors and by the length [9]. Figures 3 and 4 show the parameters of the "waisted" tower structure and the modelled tower consisting of CPDL sections for the body and cross arms, respectively. The surge impedance values vary between 244 and 333 Ω.

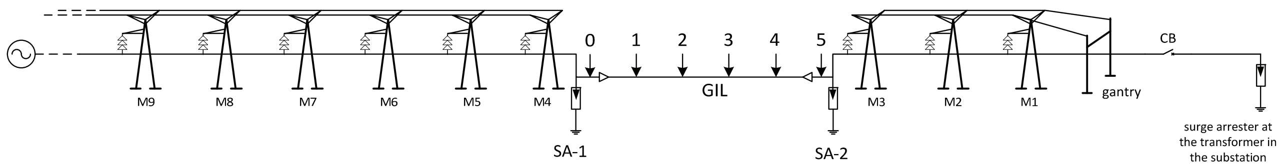

Fig. 1. Configuration of the modelled part of the 380-kV transmission line with a GIL section

As shown in Figures 1, 2 and 3 two shielding ground wires (GW) are installed throughout the route.

The surge impedance of the gantry is calculated according to Eq. (2) referring to Fig. 5 [10].

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

where

$$Z_s = 60\ln\left(h/r\right) + 90\cdot\left(r/h\right) - 60 \tag{2a}$$

$$Z_m = 60\ln\left(h/b\right) + 90\cdot\left(b/h\right) - 60 \tag{2b}$$

The calculated surge impedance of the modeled towers and their heights are given in Table 1.

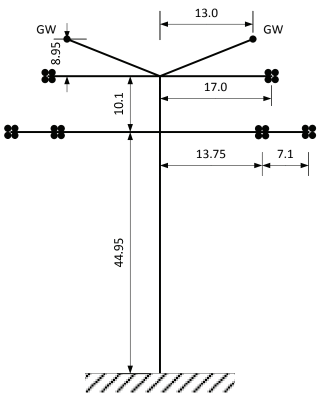

Fig. 2. Layout of tower M6

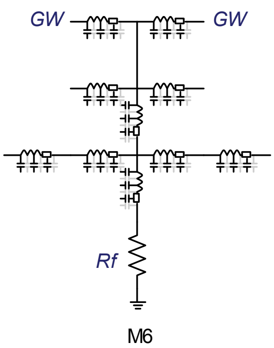

Fig. 3. Surge model of tower M6

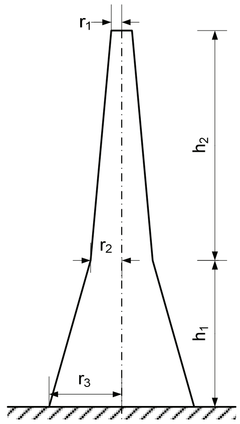

Fig. 4. „Waisted“ tower model

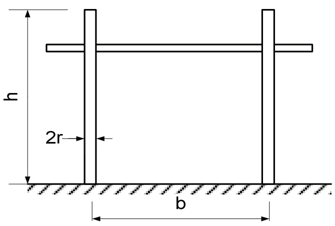

Fig. 5. Simplified model of the gantry

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 [11]. This frequency corresponds to the fundamental resonant frequency $f_{res} = \frac{1}{4\tau}$ of the air mode of travelling waves for an average span length of 200 m, where τ is travel time. Data of the conductors are:

- phase conductors: 4-bundle conductors/phase, ACSR 340/30Al/St
- ground wires: ACSR 120/70 Al/St.

The average ground resistivity is given as $\rho_g = 100\ \Omega\cdot\text{m}$. Span lengths between towers are given in Table 2. The last line section “M9 - source” is selected long enough, so that the reflected waves at the voltage source do not distort the lightning surges around GIL.

TABLE 1
SURGE IMPEDANCE AND HEIGHTS OF THE TOWERS

tower	type	surge impedance (Ω)	tower height (m)
gantry	gantry	103.8	23.00
M1	tension	193.8	50.2
M2	suspension	218.0	62.4
M3	tension	191.5	53.70
M4	tension	191.5	53.70
M5	suspension	212.8	70.65
M6	tension	211.4	64.00
M7	suspension	211.8	78.45
M8	suspension	206.7	52.35
M9	suspension	206.7	52.45

TABLE 2
SPAN LENGTHS

between	span length (m)
transformer surge arrester - CB	81
CB - gantry	31
gantry - M1	106
M1 - M2	153
M2 - M3	345
M3 - M4 (GIL)	404
M4 - M5	193
M5 - M6	266
M6 - M7	501
M7 - M8	411
M8 - M9	392
M9 - source	6000

B. 380-kV GIL

The GIL consists of inner conductor and enclosure both made of Aluminum alloy. The dielectric between conductor and enclosure is a gas mixture of SF6 and nitrogen 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 3. The double-circuit GIL is laid in a rectangular concrete tunnel. Since in the supporting routine CABLE PARAMETERS of [4], a round pipe or tunnel is allowed, the GIL conductors are placed in a round tunnel with the same distance to the wall of rectangular tunnel as an approximation [10]. The GIL is modelled then as a *pipe type cable* as shown in Fig. 6.

TABLE 3
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 line model CPDL (Bergeron model) is created at $f = 200$ kHz, which is approximately the fundamental resonant frequency of the open end GIL. Calculated surge impedance Z_s and propagation velocity v of the coaxial mode at $f = 200$ kHz are:

$$Z_s = 61.3\ \Omega; \quad v = 299.54\ \text{m/µs}.$$

In order to observe voltage surges along the GIL it has been divided into 5 sections of equal length as indicated in Fig. 1.

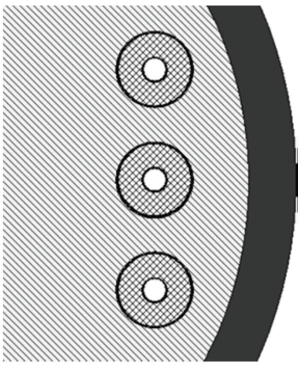

Fig. 6. Cross-section of a 3-phase GIL in tunnel

C. Insulator String and Flashover Model

Double strain insulator strings are used at the towers next to the GIL at both sides, for which a flashover model will be developed. The 50 % sparkover volt-time characteristic of the insulator is calculated according to [11] using the flashover distance of 2.97 m:

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

As flashover model the equal-area criterion by Kind [6], [14] is used as in the past works of the authors [1], [12], [13]. The criterion by Kind requires two parameters, U_0 and F, and it is tested by evaluating the following integral numerically:

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

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 are derived from the 50 % sparkover volt-time characteristic of the insulator. The unknown parameters in (4) are determined according to [14]:

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

Flashover arc channel is represented by a self-inductance of 1 µH/m.

D. Lightning Stroke

The lightning stroke is modeled by an ideal current source and a parallel resistance of 1 kΩ, which represents the lightning-path impedance [5]. According to [7] and [15] the lightning stroke has been represented only by the CIGRE current waveform [6]. Three waveforms with different parameters are selected to represent a stroke to the top of the tower or ground wire:

a) Crest value 200 kA, (8/77.5 µs) with $t_{d30/90} = 8$ µs, $S_m = 72$ kA/µs
b) Crest value 150 kA, (3/77.5 µs) with $t_{d30/90} = 3$ µs, $S_m = 100$ kA/µs
c) Crest value 85 kA, (1/30 µs) with $t_{d30/90} = 1$ µs, $S_m = 237$ kA/µs.

Waveforms a) and b) are representative of the first stroke, whereas c) represents a steep subsequent stroke. According to the IEEE distribution [7] for first strokes the probability to exceed the crest value 200 kA is 0.8 %. Similarly, the probability to exceed the crest value 85 kA of waveform c) as subsequent stroke is very low, 0.5 %. So, both waveforms a) and c) are hard conditions for back-flashover analysis. Waveform b) is selected as lightning surge between characteristics of first and subsequent strokes with a relatively short front time.

For a direct lightning stroke to the upper phase conductor, the crest current is determined using various electrogeometric models (EGM) for the ground and phase conductors. According to the recent CIGRE publication [7] there is no correlation between the crest value and front time. Merely, the correlation between crest value and maximum rate of rise is given for first and subsequent strokes:

- first stroke: $S_m = 3.9 \cdot I^{0.55}$ (5)
- subsequent stroke: $S_m = 3.8 \cdot I^{0.93}$ (6)

For a direct lightning stroke to phase conductor the front time $t_{d30/90} = 3$ µs and the time to half value $T_h = 77.5$ µs are kept constant and the maximum rate of rise is adjusted according to (5).

A. 380-kV Surge Arresters

There are three sets of line-to-ground surge arresters installed in the system, SA-1, SA-2 and at the terminals of the power transformer in the substation. Metal-oxide surge arresters with $U_r = 336$ kV are proposed by the power utility. They are represented using the simplified IEEE model [15] - [17] by two non-linear resistors A_0 and A_1 for the slow and fast surges. The equivalent circuit of the surge arrester is shown in Fig. 7.

The inductances L_0 and L_1 are calculated according to [17], [18].

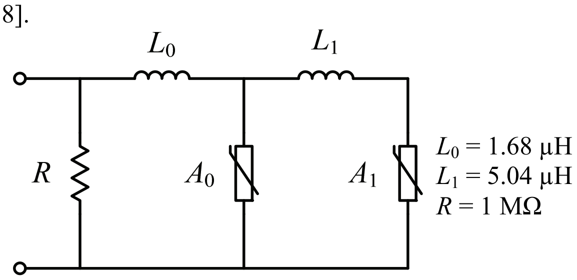

Fig. 7. Surge arrester model [15]

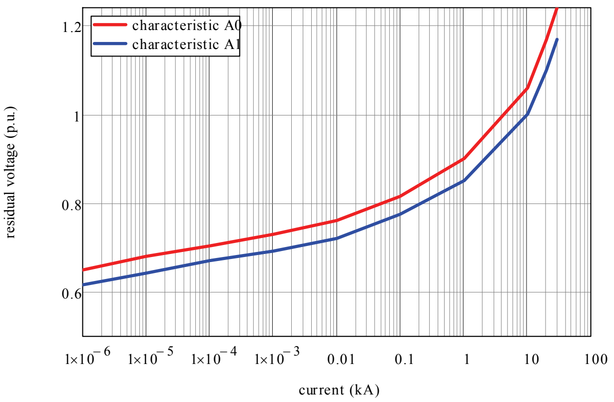

Fig. 8. Voltage-current characteristic of the surge arrester

The voltage-current characteristic of the surge arrester is shown in Fig. 8. Length of the lead wire for each surge arrester is determined individually and modeled by a lumped inductance of 1 µH/m.

III. Computation Results

The overvoltages in GIL caused by following lightning phenomena are computed and analyzed:

- 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 flashover.

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 [19]. Taking the recommended safety factor, $K_s = 1.15$, for internal insulation into consideration, following limiting value for the lightning overvoltages is relevant:

$$u_{\text{lim}} = \frac{1425\text{ kV}}{K_s} = 1239\text{ kV} \tag{7}$$

A. Back-flashover Overvoltages in GIL

As shown in Fig. 9 it is assumed as worst-case the lightning channel strikes to the ground wire on the opposite side of the tower and the power frequency voltage of phase C at the upper cross arm at $t = 0$ is set to

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

where $U_m = 420\text{ kV}$.

The overvoltages and their location in GIL due to back-flashover, the location of the lightning stroke and location of back-flashover are summarized for the lightning current waveform b) in Table 4 because waveform b) causes highest overvoltages in GIL.

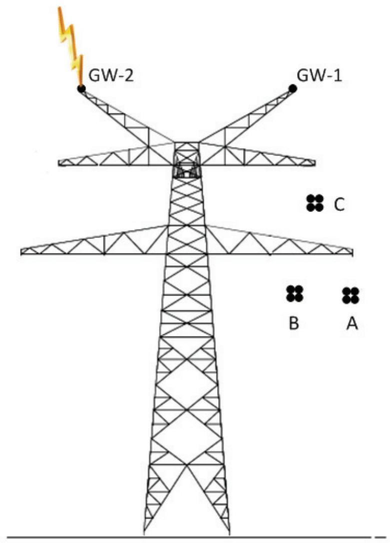

Fig. 9. Lightning stroke to second ground wire and expected back-flashover at phase C

Table 4
Overvoltages in GIL and Locations of Lightning Stroke and Backflash-over

location of lightning stroke	location of back-flashover	u_{peak} (kV)	location of u_{peak}
M2	M2, phase C	982	GIL-IN
between M2 and M3 ¼ distance from M3	M2, phase C	880	GIL-IN
M3	M3, phase C	954	GIL-IN
M4	M4, phase C	821	GIL-5
between M4 and M5 ¼ distance from M4	M4, phase C	535	GIL-5
M5	M5, phase C	804	GIL-4

Locations of occurrence of the overvoltage in GIL are shown in Fig. 1. In addition, connecting points of GIL with the overhead line conductors, where surge arresters are placed, are specified as GIL-IN and GIL-OUT. They are not shown in Fig. 1. Those sections are 36 to 66 m long.

According to Table 4 the highest overvoltage in GIL due to back-flashover occurs at tower M2. The voltage distribution in GIL of that case is shown in Fig. 10. The overvoltages in Table 4 are not critical because they are lower than u_{lim} in (7). Additionally, it has been studied whether or not the state of the CB in Fig. 1 influences the voltage waveforms. The same case has been computed, when the CB is open. The voltage waveforms in the GIL at the location GIL-IN are compared in Fig. 11 for the CB in state open and closed. It is observed that the influence of the state of CB (open/closed) in the substation is insignificant. Peak value of the surge arrester currents remains below 3 kA.

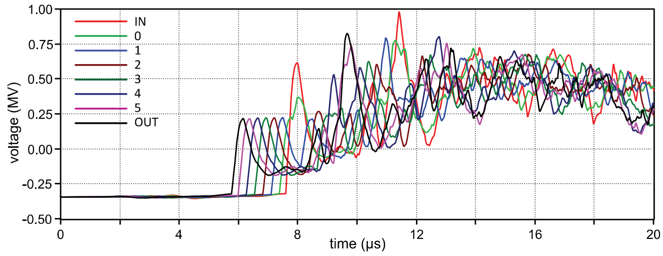

Fig. 10. Voltage waveforms along the GIL between core and enclosure for a lightning stroke at the top of tower M2 with back-flashover in phase C

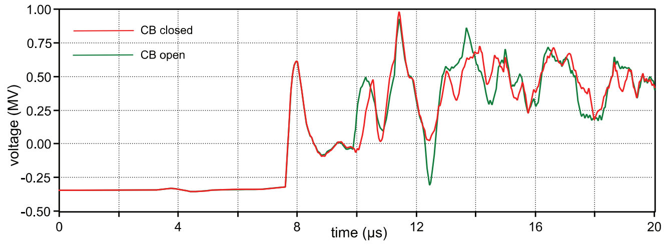

Fig. 11. Voltage waveforms at GIL-IN between core and enclosure for a lightning stroke at the top of tower M2 with back-flashover in phase C. Comparison of waveforms for the CB state open/closed

B. Flashover Overvoltages due to Shielding Failure

In case of a lightning stroke to a phase conductor due to shielding failure 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 [6]. For comparison purpose, following EGM's are applied to different locations along the overhead line for a direct lightning stroke [6]: Love; Young, et al.; Armstrong/Whitehead; Brown/ Whitehead and IEEE WG.

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 parameters A_c, b_c, A_g and b_g for different EGM's are given in [6].

The locations for a direct lightning stroke selected are:

(i) 10 m in front of tower M5 (direction GIL)
(ii) Midway between towers M4 and M5
(iii) 10 m behind tower M4 (direction source)
(iv) 10 m in front of tower M3 (direction substation)
(v) Midway between towers M2 and M3
(vi) 10 m behind tower M2 (direction GIL).

"front" refers to the direction from left to right and "behind" refers to the opposite direction.

Since the calculated maximum values of lightning stroke currents according to Table 4 vary in a wide range depending on EGM, the maximum current value (bold marked) in each column, i.e. for a certain location, is used for the peak current of the lightning stroke that hits the upper outer phase conductor. The results of the simulations are summarized in Table 6.

TABLE 5
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				
	(i)	(ii)	(iii), (iv)	(v)	(vi)
Love	32	23	19	17	21
Young et al.	**64**	31	19	15	24
Armstrong/Whitehead	34	26	22	20	24
Brown/Whitehead	40	30	24	22	27
IEEE [6]	58	**42**	**33**	**29**	**37**

TABLE 6
OVERVOLTAGES IN GIL AND LOCATIONS OF LIGHTNING STROKE AND FLASHOVER

stroke location	location of flash-over	u_{peak} (kV)	location of u_{peak}
(i)	M5, phase C	1108	GIL-1
(ii)	M5, phase C	**1249**	GIL-2
(iii)	no flashover	1188	GIL-3
(iv)	M2, phase C	1179	GIL-1
(v)	M2, phase C	1164	GIL-1
(vi)	M2, phase C	1054	GIL-0

The highest overvoltage 1249 kV in GIL is expected for the stroke location (ii) with a lightning stroke crest value of 42 kA (see Fig. 12). That overvoltage is marginally higher than u_{lim}, but remains far below 1425 kV as given in (7). Maximum current peak of the surge arresters amounts to 19.7 kA. The open/close state of the CB in the substation does not influence the waveforms in the first 10 µs because of the delay of travelling waves which are reflected at the CB and return.

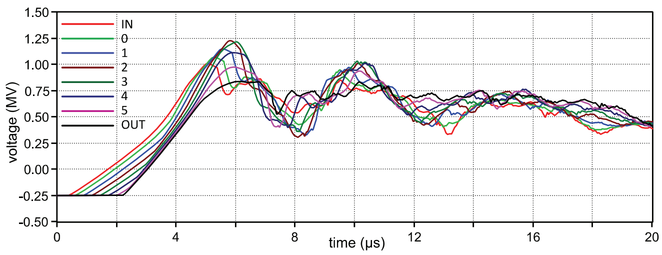

Fig. 12. Voltage waveforms at GIL-IN between core and enclosure for a lightning stroke at (ii) with flashover in phase C on tower M5

IV. CONCLUSIONS

This paper deals with the lightning overvoltage study for a 400 m long 380-kV gas-insulated line (GIL) section that replaces an overhead line in that industrial area to gain space for new works. What is remarkable for the configuration is that the GIL section is followed by another relatively short overhead line that ends in a 380-kV substation. The simulation model has been created using graphical pre-processor ATPDraw and the simulations have been performed using EMTP-ATP.

The lightning overvoltages caused by strokes to the tower or ground wire and subsequent back-flashover of the line insulator and by direct lightning strokes to upper phase conductor due to shielding failure form the basis of this study.

Since the substation is relatively near to the GIL, the relevant components, CB, line conductors between gantry and CB, CB and power transformer, and surge arresters at the terminals of the transformer are taken into consideration in the simulation model. In addition, it is important that the GIL section has been divided in the simulation model into subsections in order to observe the voltage waveforms along the GIL.

The overvoltages caused by lightning strokes to the top of towers or to ground wires in the GIL are not critical, i.e. remain below the limiting value u_{lim} in (7). For the analysis three different waveforms have been used for the lightning stroke based on the concave CIGRE waveform [7], [15]. The influence of the CB with its state open/closed on the overvoltages in GIL has been taken into consideration.

Direct lightning strokes to the phase conductors due to shielding failure and the overvoltages in GIL caused by flashovers over insulators were subject of the second part of this study. For this purpose various EGM's of the ground and phase wires have been set up and the maximum amplitude of the lightning current has been determined that would hit the upper outer phase wire due to shielding failure. The computation results show that in one case the lightning overvoltage is slightly higher than the permissible value u_{lim}. There is a safety margin of 15 % for internal insulation according to [19].

It has been shown that the influence of the state of the CB in the substation (open/closed) is insignificant because of relatively long travel time for the voltage waves which will be reflected at the open CB.

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