Backflashover Simulations of Multi-circuit Transmission Tower with AC/DC systems

A. Mackow, M. Kizilcay, D. Potkrajac

***Abstract*-- ATP-EMTP simulations are performed to estimate backflashover performance of multi-circuit transmission tower. Multi-circuit transmission tower has several systems on the tower and combines DC transmission over long distances with more flexible AC transmission. The outcome of simulations should give the range of backflashover withstand level and backflashover outage level. Moreover subsequent strokes were included to lighting performance evaluations of line. Maximum lightning current amplitude that does not cause backflashover across insulator string is estimated in response to first and subsequent lightning strokes with three different flashover models.**

***Keywords*: backflashover, lightning stroke, multi-circuit transmission tower with AC and DC, modelling.**

I. Introduction

Investigations in this paper have been done for transmission lines that come into consideration related to existing tower configurations, where a DC system has been supplemented. Results are presented for two configurations of tower with different systems (AC/DC). The multi-circuit line with AC and DC systems offers diversified solutions for future transmission lines. HVDC system could be accompanied by AC systems at various transmission voltage levels (e.g. 380 kV, 220 kV in Germany).

This study should determine how new installed HVDC system affects lightning performance of multi-circuit towers. Backflashover withstand current and backflashover outage rate are calculated. A 380-kV system is substituted by a HVDC circuit on a tower. Available conductors and insulators strings of AC lines will be adapted to transfer DC power.

Lightning strike can indirectly cause outages of transmission lines. Lightning surge current generates surge overvoltages over tower. These overvoltages develop across all insulators strings on the tower. As soon as developed overvoltage exceeds the insulation withstand level backflashover occurs [1]. Formerly the lightning performance of transmission lines was evaluated only for first strokes. Investigation of subsequent strokes was not considered in the past, the focus was solely on first lightning strokes. This assumption is based on lower median peak value of subsequent strokes in comparison with first lightning stroke. The overvoltages from subsequent strokes should not be thus hazardous for insulators of transmission lines. Recent measurements and investigations as in [2], [3], [4] make it reasonable to pay more attention to subsequent strokes. The new median values for first and subsequent strokes were registered. In comparison with Berger's data [5] those median values are higher [6]. Further measurements of first and subsequent strokes are required [6]. The number of subsequent strokes for a negative cloud-to-ground was estimated to be 3 to 5. They occur within tens milliseconds successively. Some of those strokes can develop in already existing channels from the first stroke. However they can also terminate on ground nearby original termination point of the first stroke. New termination points can be few kilometers far away from previous termination point of first stroke. In this paper only direct subsequent strokes are investigated, assumed that channel from first stroke has proper condition to slide subsequent strokes.

The transients program EMTP-ATP [7] is well suited to analyze lightning surge phenomenon on overhead lines.

II. Parameters of First and Subsequent Strokes

Lighting parameters are mainly from direct current measurements and differ for various types of lightning strokes. Peak current of the first stroke is expected to be 3 to 5 times higher than peak current of subsequent stroke. Whereas front times of subsequent strokes are usually 5 to 8 times shorter. Waveforms of first and subsequent strokes are represented with the conditional distributions of Berger's data [5], afterwards reexamined by Anderson and Eriksson [8]. This conditional distribution is furthermore recommended in [6] and is considered in this investigation. In Table I median values of relevant parameters for both strokes are summarized. These parameters are required to represent CIGRE lightning waveform [1] that is used in investigation. According to [6] it may be assumed that 90 % of downward lightning flashes are negative. Thus solely downward negative lightning strokes are simulated in EMTP-ATP in this work [7].

TABLE I
Lightning Current Parameters [1]

Parameter	First stroke	Subsequent stroke
$I_{I,\ initial}$	27.7 kA	11.8 kA
S_m	23.3 kA/µs	39.9 kA/µs
$t_{d30/90}$	3.83 µs	0.67 µs
t_h	77.5 µs	30.2 µs

This work was supported by German TSO, Amprion.

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

III. Modelling Method

The modelling method for the backflashover simulations used in this paper is based mainly upon [9]. All simulations were computed for a line section with 9 towers. The lightning stroke is applied to tower 5 that is located in the middle of investigated section. Footing resistance for this tower is chosen as variable and has 5 Ω, 10 Ω, 20 Ω and 30 Ω respectively. Outermost towers 1-4 and 6-9 have grounding resistance of 10 Ω and lightning stroke is not applied to these towers in this investigation. In [10] representation of tower footing resistance was discussed. Resistive model gives conservative results and is adopted in this investigation. Weak correlation between flashover tendency and tower surge impedance was observed in [11]. All towers were assumed to have the same height.

A. Multi-circuit Transmission Tower with AC and DC Systems

The layouts of the modelled towers A and B are shown in Fig. 1. The upper two cross-arms of tower A carry on left and on right side a 420-kV HVDC and 380-kV AC system. The upper two cross-arms of tower B carry at left and right side a 420-kV HVDC and 380-kV HVAC circuit, respectively. A 110-kV double circuit line is suspended from the lowest cross arm. Tower B is 6.5 m higher than tower A.

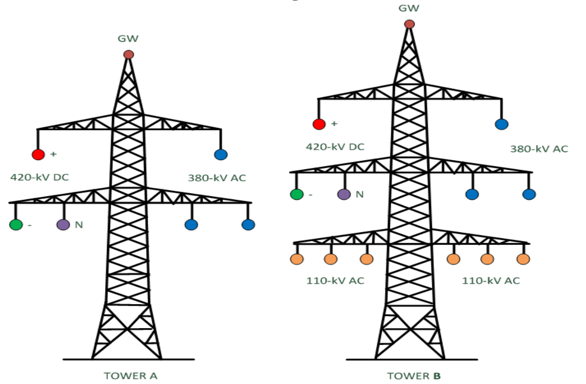

Fig. 1. Layout of multi-circuit suspension towers

B. Tower Model

Multistory model [4] is used to represent transmission towers. In multistory model each vertical tower section between cross arms is represented by lossless line connected in series with *RL* parallel circuit. This parallel circuit represents attenuation of traveling waves.

Model and equations for all impedances are summarized in [9]. In Fig. 2 multistory model is shown. Formula for surge impedance of the tower recommended by [1] is used.

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

where

$$R = \frac{r_1 h_2 + r_2 h + r_3 h_1}{h} \quad (2)$$

$$h = h_1 + h_2 \quad (3)$$

The *RL* values are determined as functions of surge impedance Z_t , traveling time τ_t, distances between cross-arms x_i and attenuation factor α=0.89 by following equations:

$$R_i = \frac{x_i}{h} \cdot 2Z_t \cdot \ln\left(\frac{1}{\alpha}\right) \quad (4)$$

$$L_i = 2Z_t \cdot R_i \quad (5)$$

For the tower A with 50 m and tower B with 56.5 m equation (1) delivers the surge impedance Z_{waist_A} = 204 Ω and Z_{waist_B} = 208 Ω, respectively.

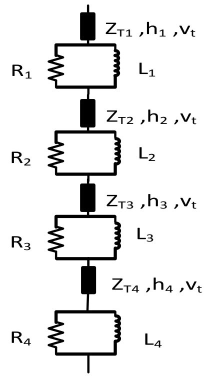

Fig. 2. Tower model with additional RL-circuits.

C. Transmission Lines

Total 9 towers are represented including all line sections. Overhead lines on the same tower are represented by the CPDL (constant-parameter distributed line) model [7] at f = 400 kHz. A line span has length of 330 m. The investigated section with 9 towers is terminated at both ends with 5 km long additional CPDL model that has the same electrical parameters as spans between investigated towers 1-9. These additional sections should prevent impact of reflected waves. The investigated section is connected to voltage sources (via additional line section) in order to take into account the effect of the AC and DC steady-state voltage of the lines on a lightning surge. In simulations a negative lightning strike is considered at the time instant of the positive power-frequency voltage peak of the upper phase of 380-kV circuit. One phase of each 110-kV circuits of tower B is also in positive power-frequency voltage peak. This assumption corresponds to a worst case scenario.

D. Lightning Sources

The lightning stroke is modelled by a current source and a parallel resistance, which represents the lightning path surge impedance. Lightning surge impedance is selected as 1000 Ω according to [9].

Two different lighting current waveforms are used to represent

a) first stroke

b) subsequent stroke

with median parameters given in Table I.

Fig. 3 shows the representation of first and subsequent stroke current waveforms with CIGRE lighting waveform [1] and median parameters from Table I. According to [1] the time $t_{30/90}$ and steepness S_m depend on the peak value of the lightning current for first stroke. For subsequent stroke the front time $t_{30/90}$ is constant, whereas S_m depends on the peak value of the lightning current. In this paper a simplified representation of first stroke was used. Features like: initial concavity, subsequent abrupt rise and several peaks were neglected. Representation of first and subsequent stroke has only one peak and smooth shape.

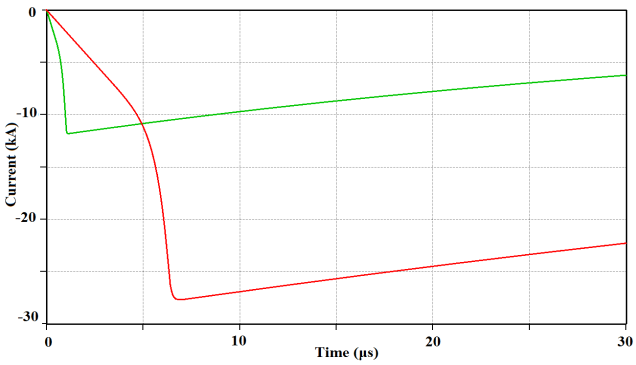

Fig. 3. Lightning current waveform with median values.

TABLE II
PARAMETERS AND FLASHOVER CRITERIA OF FLASHOVER MODELS

KIND [12]		
	110-kV AC	380-kV, HVDC
F	0.304 Vs	0.726 Vs
U_0	475.42 kV	1095 kV
Flashover criterion	$\int_0^t [u(t)-U_0]dt \geq F$ (6)	
PIGINI [13]		
Leader onset condition	$u(t) \geq E_0 \cdot D$ (7)	
Leader velocity	$v_l = 170 \cdot D \cdot \left(\frac{u(t)}{d-l_l} - E_{0p}\right) \cdot e^{(0.0015 u(t)/D)}$ (8)	
Leader length	$l_l = \int v_l(t)dt$ (9)	
E_{0p}	670 kV/m	
MOTOYAMA [14]		
Leader onset condition	$l_l = \int v_l(t)dt$ (10)	
Leader velocity for $0 \leq x_{LAVE} < D/4$	$K_{1A} \cdot \left(\frac{u(t)}{d - 2x_{LAVE}(t)} - E_0\right)$ (11)	
Leader velocity for $D/4 \leq x_{LAVE} < D/2$	$K_{1B} \cdot \left(\frac{u(t)}{D - 2x_{LAVE}(t)} - E_0\right)$ (12)	
Leader length	$x_{LAVE} = \int v_{AVE}(t)dt$ (13)	
E_0	750 kV/m	
K_{1A}	2.5 m^2/Vs	
K_{1B}	0.42 m^2/Vs	

E. Flashover Models

In this study three flashover models are applied for comparison purposes. First model is related to flashover voltage-time characteristic of insulators [12]. Second is based on passive leader development method [13]. Third model is active leader development model [14]. They were implemented using MODELS [15]. In Table II parameters and flashover criteria are listed. Gap length D of composite insulator strings for 110-kV, 380-kV AC and HVDC is ca. 1000 mm and ca. 3000 mm, respectively. Each flashover model connected across insulator strings controls a TACS switch. After fulfillment of breakdown condition, surge current flows into failure conductor. Insulation levels are correspondingly adapted for all systems.

IV. Results

A. Multi-circuit Transmission Tower with HVDC and 380-kV System

Tower A from Fig. 1 is originally for a 380-kV double circuit line. This tower has been chosen for comparison of backflashover behavior of 420-kV HVDC and 380-kV HVAC systems. On both sides of the tower 380-kV insulators are assumed to use with the same length for both systems. Positive pole of 420-kV HVDC has constant voltage. Thus higher surge voltage across the insulator of the positive pole is expected for a negative lightning stroke. The maximum value of phase voltage in the 380-kV system occurs only once in 20 ms period. It may be assumed that backflashover occur firstly across insulator of plus pole. Hence investigation focuses only on the insulator at plus pole of HVDC. This assumption is valid as long as both systems have equal length of insulators strings. Following two lighting current waveforms are injected to the concerning tower:

-CIGRE waveform, I = 27.7 kA; 3.8/77.5 µs

- CIGRE waveform, I = 11.8 kA; 0.67/32 µs.

The model in EMTP-ATP was applied to determine the surge overvoltages across insulators in response to lightning strokes to ground wire at tower top. In Fig. 4 and 5 waveforms of voltages across the upper insulator string of plus pole due to first and subsequent strokes are presented. The peak voltages across the upper insulator string due to first and subsequent strokes are compiled in Table III. Lowering of footing resistance of tower is efficient only for first strokes. The peak voltage across insulator after first stroke was reduced about 24 %. This effect was not observed for subsequent strokes, where reduction of 8 % was achieved. Lightning surge wave travels downward the tower, reflects at the footing resistance and has reverse polarity. Lowering of tower footing resistance increases this reflected reverse wave. This negative wave after time delay reaches upper cross arm of the tower and superposes with incident voltage wave from lightning stroke. Travel time from tower foot to upper cross arm with plus pole of HVDC depends only on tower height and is the same for the first lightning stroke and subsequent stroke. First stroke has longer front time than subsequent stroke. Whereas subsequent stroke reaches about half peak, relative value of first stroke is still low. Meanwhile reflected negative wave has returned from tower foot and begins to superimpose with initial lighting wave. Subsequent stroke has reached higher values than the first stroke. Reduction effect is more efficiently for first stroke with lower voltage at this time instant.

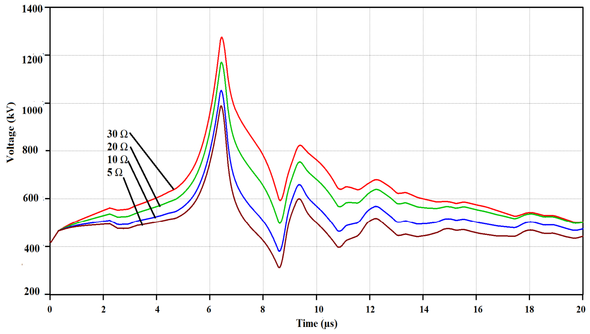

Fig. 4. Overvoltages across the upper insulator string of positive pole for various values of footing resistance in response on first stroke on tower top.

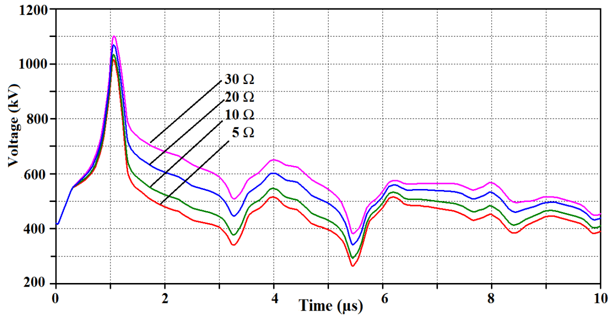

Fig. 5. Overvoltages across the upper insulator string of positive pole for various values of footing resistance in response on subsequent stroke on tower top

TABLE III
OVERVOLTAGES ACROSS THE 420-KV-HVDC-INSULATOR STRING

Footing resistance (Ω)	First stroke u_{peak} (kV)	Subsequent stroke u_{peak} (kV)
30	1274	1101
20	1170	1068
10	1052	1032
5	987	1013

The minimal lightning current that causes backflashover has been determined for plus pole of HVDC system. The time $t_{30/90}$ and steepness S_m dependencies on the peak value of the lightning current are considered [1]. The current amplitude has increased in 5 kA steps from 10 kA up to 200 kA for first stroke and from 5 kA up to 50 kA for subsequent stroke. The current peak values that cause flashovers are summarized and shown for both current waveforms in Fig. 6 for Kind, Pigini and Motoyama flashover models, respectively. In this investigation also insulators on adjacent towers were considered. The performance of flashover models is different in response to different lightning current waveforms. As expected variable footing resistance has influence in particular on backflashover withstand currents for first strokes. Moreover first backflashover across insulator of positive pole can be followed by additional backflashover for higher values of lightning current. Usage of time dependent arc resistance enables investigation of further backflashovers on the tower and adjacent towers up to lighting current of 200 kA. This resistance is installed at each flashover model on tower. Since breakdown condition is satisfied, surge current flows into failure conductor. Depending on flashover model the second backflashover can occur across insulator of 380-kV system in voltage maximum by a lightning current of 75 kA. Thereafter third backflashover on adjacent tower was observed for 90-kA lightning current. Simulations with flashover model by Pigini yielded different result. Backflashover across insulator for 380 kV was not observed. Second backflashover occurred across insulator of plus pole on adjacent tower. Further simulations of backflashover on adjacent tower should be computed.

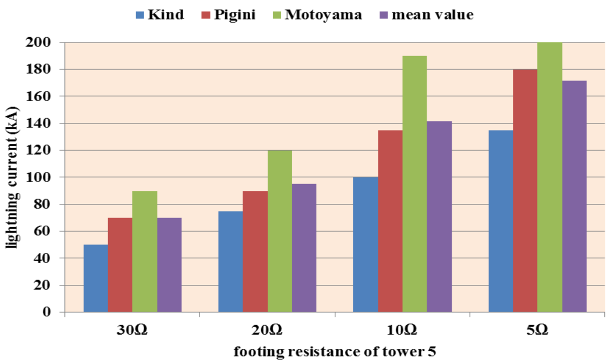

Fig. 6. Minimum lightning current causing backflashover across the upper insulator string of plus pole of HVDC circuit for various values of footing resistance in response on first stroke on tower top

The results of subsequent strokes are presented in Fig. 7, solely for flashover model by Kind. Occurrence of backflashover was detected for high values of footing resistance. Leader-development models do not detect any backflashover across insulator of positive pole up to 50 kA. For multi-circuit tower with HVDC and 380-kV circuit only first stroke can be more hazardous for insulators of positive pole of HVDC. Most vulnerable is tower with 30 Ω footing resistance. Lowest crest value of lightning current for the backflashover at this tower is 70 kA. Taking the probability distribution relation for lightning crest current magnitudes according to [12]

$$p(i > I) = \frac{1}{1+\left(\frac{I}{31\,\mathrm{kA}}\right)^{2.6}} \tag{14}$$

11 % of lightning strokes would exceed 70 kA and cause a backflashover across insulator of positive pole. Procedure to calculate the outage rate of AC circuit was proposed in [16].

This calculation method requires computer use. Simulation in EMTP-ATP allows using that procedure and considers effects like: footing resistance, number of phases and power frequency voltage, coupling from lightning current that flows through shielding wire, dependencies of lightning current parameters from [1]. These effects are considered by calculating the critical current and backflashover rate (BFR) for each of conductors on multi-circuit transmission tower. Conversion of 380-kV AC circuit into 420-kV circuit increases BFR. Considering a flash density of 4.4 flashes/km^2/year [17] lightning incidence for tower A is calculated. 90 flashes can strike the line per 100 km per year. Footing resistance of 10 Ω was assumed by calculating of critical current. Outage rate based on first strokes increases from 0.12 outage/100 km/year for 380-kV AC circuit to 0.65 outage/100 km/year for 420-kV HVDC circuit. Calculation of outage rate for subsequent strokes for tower A is not necessary due to their minor impact on lightning performance of tower A.

Fig. 7. Minimum lightning currents causing backflashover across the upper insulator string of positive pole for various values of footing resistance in response to subsequent stroke on tower top.

B. Multi-circuit Transmission Tower with HVDC, 380-kV System and Double 110-kV System

Tower B from Fig. 1 was designed originally for a 380-kV double circuit with 110-kV double circuit on the lowest cross-arm. This tower has been chosen for the investigation of influence of 110-kV circuits on backflashover performance of 420-kV HVDC systems. Two lightning current waveforms from Fig. 3 were used. The overvoltages across upper insulator of plus pole and one of 110-kV insulators in response to first and subsequent stroke are presented in Fig. 8 to 11. First lightning stroke with median values causes already backflashover for tower with 20 Ω and 30 Ω (s. Fig. 8). The peak voltages across the upper insulator and lowest insulator due to first and subsequent strokes are given in Tables IV and V. The effect of reduction of footing resistance is efficient only for first strokes. The peak voltage across insulator of plus pole after first stroke was reduced about 20 %. The overvoltage across 110-kV insulator was reduced about 41 %. This effect was not observed for subsequent strokes. Reduction was about 7 % and 19 % for insulators of plus pole and 110-kV insulator respectively. The results confirm that reduction of the footing resistance is efficient particularly to first strokes. Moreover reduction is more efficient for insulators of 110-kV circuit. Whereas peak voltage across insulator of plus pole was decreased about 20 %, overvoltage across 110-kV insulator achieved 41 % reduction. On one hand, distance to upper cross-arm from tower bottom is longer and reflected wave at tower foot arrives at upper cross-arm with a larger delay. On the other hand, overvoltage across 110-kV insulator is lower.

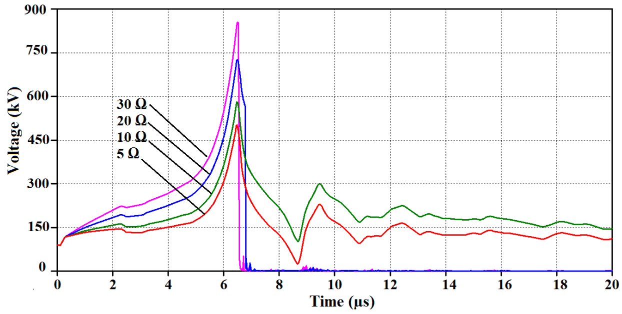

Fig. 8. Overvoltages across the lower insulator string of 110-kV circuit for various values of footing resistance in response to first stroke on tower top.

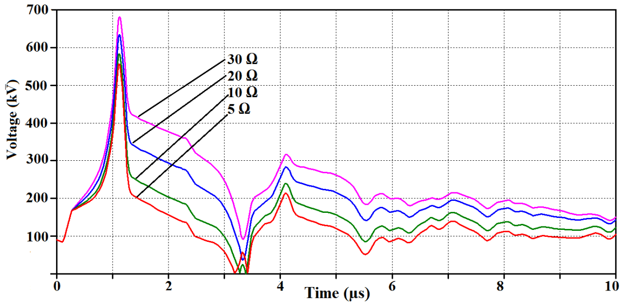

Fig. 9. Overvoltages across the lower insulator string of 110-kV circuit for various values of footing resistance in response to subsequent stroke on tower top.

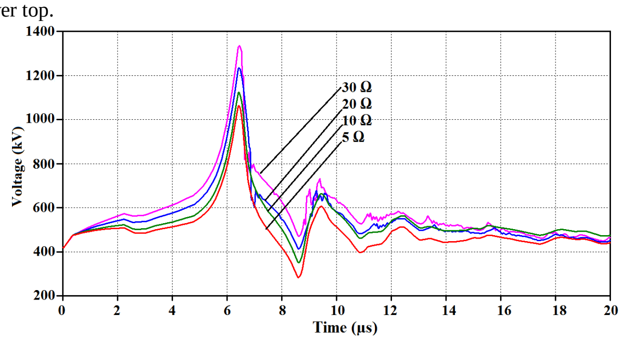

Fig. 10. Overvoltages across the upper insulator string of positive pole for various values of footing resistance in response to first stroke on tower top.

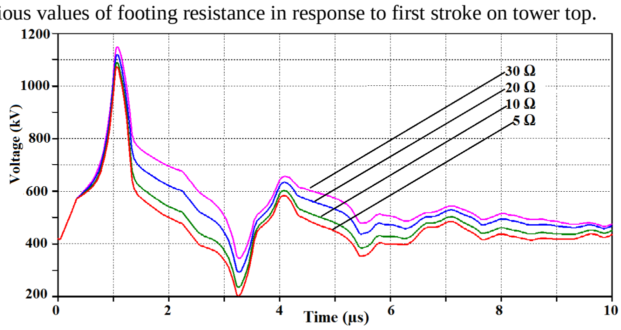

Fig. 11. Overvoltages across the upper insulator string of positive pole for various values of footing resistance in response to subsequent stroke on tower top.

TABLE IV
OVERVOLTAGES ACROSS THE 110-KV -INSULATOR STRING

Footing resistance (Ω)	First stroke u_{peak} (kV)	Subsequent stroke u_{peak} (kV)
30	854	682
20	726	634
10	581	583
5	502	556

TABLE V
OVERVOLTAGES ACROSS THE 420-KV-HVDC-INSULATOR STRING

Footing resistance (Ω)	First stroke u_{peak} (kV)	Subsequent stroke u_{peak} (kV)
30	1334	1149
20	1235	1120
10	1123	1088
5	1061	1072

To estimate which insulators (of HVDC, 380-kV or 110-kV) are prone to backflashover at first, flashover model is connected across each insulator on tower. Backflashover occurs firstly on the lowest cross arm and strikes almost simultaneously across two 110-kV voltage insulators. These insulators belong to the phase conductors with peak value of the power frequency voltage at the instant of stroke. Voltage across insulator of positive pole is the highest among all voltages across insulators. Constant value of voltage- +420 kV and shorter travel time of surge lightning wave between tower top and upper cross-arm cause highest overvoltage at plus pole. Despite of these two aspects first backflashover occurs firstly on the lowest cross arm independently of voltage value in 110-kV circuit (s. Fig. 12). The gap length of 110-kV is about three times shorter than gap length of HVDC and 380-kV insulators and flashover criteria are firstly fulfilled. In Fig. 13 overvoltage waveform across insulator at positive conductor of HVDC for 70 kA first stroke lightning current is presented. The effect of backflashover across 110-kV insulators is visible in the waveform as voltage sags suddenly around 8 µs (compare to Fig. 12).

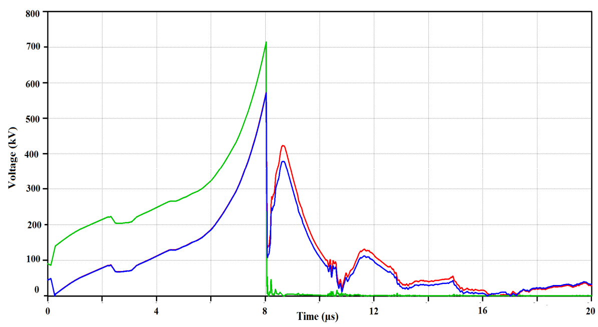

Fig. 12. Overvoltages across the insulator strings of 110-kV conductors for in response to first stroke on tower top.

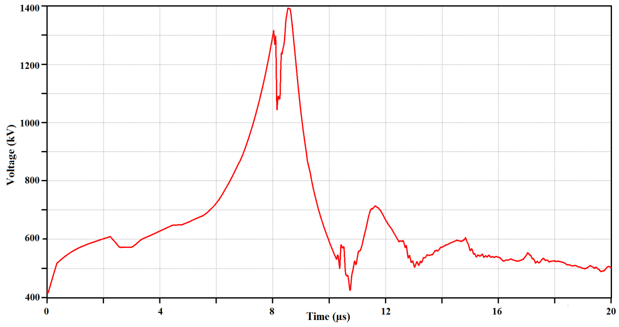

Fig. 13. Overvoltages across the upper insulator string of positive pole for in response to first stroke on tower top.

Backflashover critical currents of first stroke and subsequent stroke that cause backflashover across insulator of 110-kV are presented in Fig. 14 and 15 respectively. For a lighting stroke current higher than 10 kA flashovers occur across next two 110-kV insulators in other phases. Amplitude of the lightning current was further increased up to 200 kA with corresponding front time $t_{d30/90}$ and steepness S_m according to [1]. Whereas flashovers did not occur at the two remaining 110-kV phases (previously four flashovers have already occurred) and at the conductors of 380-kV, a flashover at the positive conductor of HVDC was detected for higher lightning currents. Reduction of footing resistance increases the critical current that causes flashover. This effect is more apparent for first strokes. Lowering of footing resistance from 30 Ω to 5 Ω increases mean value of critical current only from 23 kA to 38 kA for subseqeunt strokes (Fig. 15). In case of first stroke mean value of crictial current increases from 26 kA to 65 kA significantly (Fig. 14). Values of critical currents for the first stroke and subsequent stroke are similar for higher footing resistances 20 Ω and 30 Ω. For lower footing resistances backflashover withstand level is higher for the first stroke.

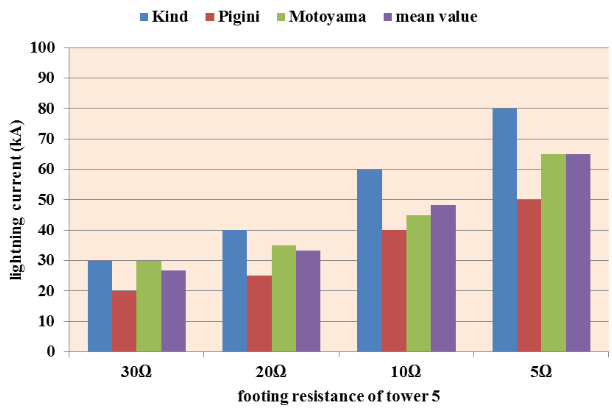

Fig. 14. Minimum lightning peak currents causing backflashover across the insulator string of 110-kV circuit for various values of footing resistance in response to the first stroke on tower top

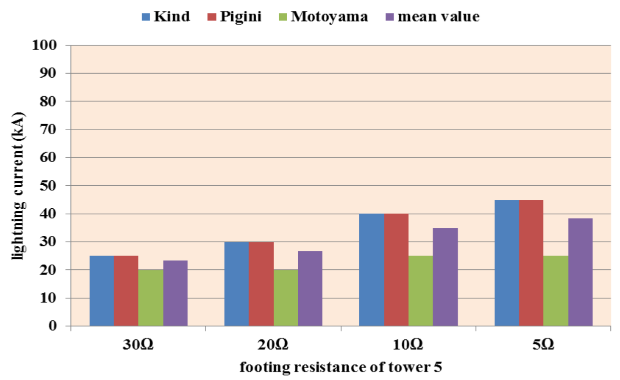

Fig. 15. Minimum lightning peak currents causing backflashover across the insulator string of 110-kV circuit for various values of footing resistance in response to the subsequent stroke on tower top

Replacing of a 380-kV AC circuit by a 420-kV DC circuit can slightly increase BFR of tower B. For a flash density of 4.4 flashes/km^2/year [17] lightning incidence for tower A is calculated. 99 flashes can strike the line per 100 km per year. Assumed that prior backflashovers across 110-kV increase the value of critical backflashover current for plus pole of HVDC, outage rate of HVDC circuit is 0.25 outage/100 km/year.

V. Conclusions

A EMTP-ATP simulations have been performed for two tower configurations coming into consideration for a multi-circuit line with AC/DC circuits. Furthermore subsequent lightning strokes were also considered in this investigation.

Conversion of tower A with 380-kV double circuit into AC/DC multi-circuit line increases the probability of occurrence of backflashover. Constant +420-kV voltage of plus pole makes upper insulator at plus pole more prone to backflashover in comparison with the original 380-kV circuit. Conversion of an AC system into bipolar DC system increases outage rate for the converted circuit. Whereas original 380-kV conductors are unchanged, substitution of AC insulators may be considered. It would be reasonable to increase critical backflashover current in case of a HVDC circuit and decrease this way the BFR. Subsequent strokes are not critical for the operation of HVDC and 380-kV systems.

Conversion of tower B with 380-kV and 110-kV doublecircuits on the same tower into AC/DC multi-circuit line does not increase considerably lightning backflashover performance of the line. Results by three flashover models show that lightning strokes first of all affect 110-kV circuits. First lightning strokes as well as subsequent strokes cause first backflashovers across insulators on the lowest cross arm. Whereas backflashover from subsequent strokes are unlikely to occur across HVDC insulators, they can occur across 110-kV insulators. The backflashover withstand level of the HVDC system is much higher and influenced strongly by the lightning performance of 110-kV systems. Additional investigations of outage rate from first and subsequent strokes are recommended for 110-kV circuits.

The backflashover performance is estimated by means of three different flashover models. They perform differently depending on the lightning waveform and investigated tower. This issue is currently under investigation.

Decreasing the footing resistance of the tower reduces overvoltage across insulators also for higher multi-circuit towers. This method is efficient in particular in response to first strokes. Lower footing resistance decreases also slightly overvoltages from subsequent strokes.

VI. Acknowledgment

The authors like to thank Amprion for their expert advices.

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