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Estimating the Lightning Performance of a Multi-Circuit Transmission Tower

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***Abstract*— Lightning strokes cause mainly outages of transmission lines. A lightning study takes into consideration possible impacts of lightning strokes on transmission systems. The lightning performance of multi-circuit transmission tower with AC and DC circuits is investigated. Till today lightning analysis of HVDC and HVAC systems were done separately. Since both systems will be installed on the same tower, lightning performance analysis of multi-circuit tower that has been converted into a hybrid line has become very challenging. Present paper illustrates how to combine efficiently different methods to support insulation coordination studies. Lightning incidence and range of outages for two configurations of hybrid tower have been estimated using electrogeometric model and simulations in EMTP-ATP.**

***Keywords*—lightning strokes, flashover, lightning attachment model, shielding, modelling**

I. INTRODUCTION

An interest in lightning research has increased in last years. The reasons have different origin. Firstly more field measurements of lightning strokes are available nowadays. Worldwide well-established distributions of lightning current parameters are based on measurements in years 1963-1971 by research group in Switzerland [1]. Since then new measurements of lighting strokes have been conducted in Japan [2], Brazil [3]. Measuring equipment has become more advanced than 30 years ago. Thus quality of measurements of lightning parameters is more reliable. Some of measurements agree coincide with measurements in Switzerland [2], whereas other deviate considerably from them [3]. New design of power transmission towers is another factor that makes lightning studies still necessary. Lightning performance of pylon transmission towers [4] and hybrid HVAC/HVDC [5] lines has to be estimated before they will be erected. Particularly the hybrid line with AC and DC systems offers an interesting alternative that includes two different types of power transmission [6]. The importance of insulation coordination studies of a hybrid line was noted in [5].

Conversion of one 380-kV AC system into new HVDC system along an existing line route on the same tower will be taken into consideration. Available conductors, shield wires and insulators strings of AC lines will be adapted to a HVDC system.

The layout of the modelled towers A is shown in Fig. 1. That tower may have one or two shield wires. Comparison of shielding performance against lightning with one or two shield wires is investigated in this paper. Transmission tower with two shield wires presented in Fig. 1 is named A'. The upper left cross-arm carries a bipolar 420-kV HVDC system.

Evaluation of the risk of lightning stroke outage of transmission lines is very important. The outages that are caused by lightning stroke have two origins. Lightning strokes that are intercepted by shield wires can cause backflashover across insulator strings. Due to shielding failure a lightning stroke may hit a phase conductor and can cause a flashover across an insulator.

Shielding failures that are estimated by electrogeometric models are investigated. This study employs general expression for the estimation of lightning incidence, maximum shielding current and lightning outage rates for the HVDC/HVAC hybrid line. The transients program EMTP-ATP [7] is well suited to analyze lightning surge phenomenon on overhead lines.

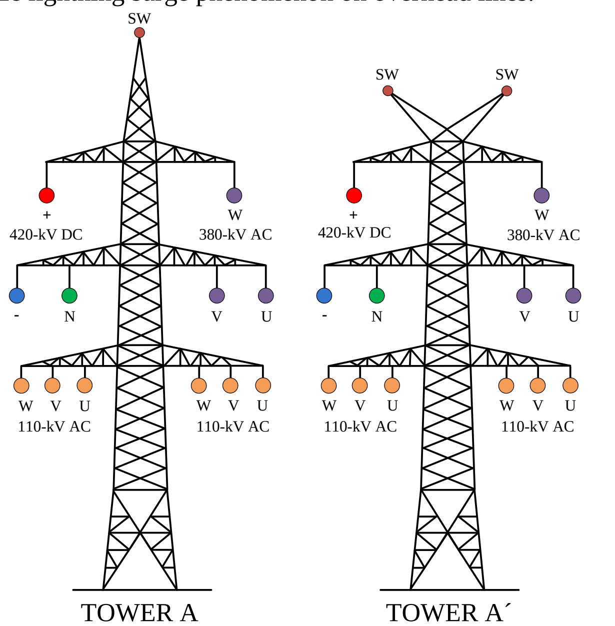

Figure 1. Tower layout of investigated hybrid line A and A'

II. LIGHTNING OCCURENCE

A. Types of Lightning Discharges

About three-quarters of lightning flashes do not hit the ground. These are termed cloud flashes. Lightning discharges between cloud and earth are termed cloud-to-ground discharges. Four types of lightning discharges between cloud to earth and earth to cloud are shown in Fig. 2. Only the initial leader is shown for each type. About 90 % of global cloud-to-ground lightning are downward negative lightning flashes and remaining 10 % of global cloud-to-ground lightning are downward positive lightning flashes according to [13]. Downward flashes exhibit downward branching, while upward flashes are branched upward. Thus only negative downward lightning is considered in this study.

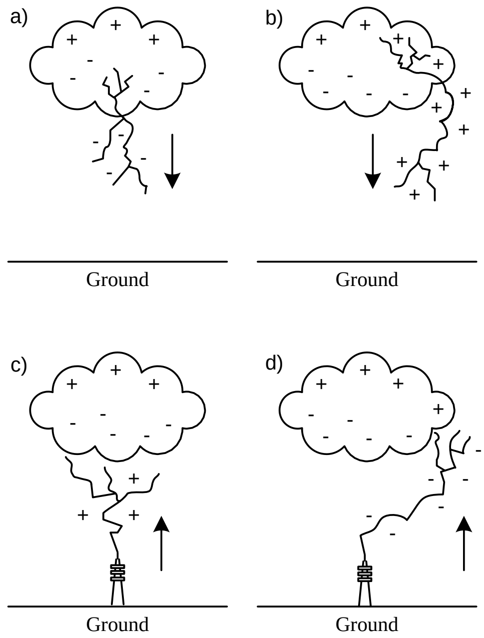

Figure 2. Types of lightning discharges a) Downward negative lightning; b) Downward positive lightning; c) Upward positive lightning; d) Upward negative lightning

B. Ground Flash Density

In the present study the ground flash density N_g (strikes/km^2/year) has been estimated from records of lightning locating system BLIDS [12] in Germany. This lightning locating system is based on the time-of-arrival method (TOA). TOA uses the measurements of the time-of-arrival of electromagnetic field at several stations. A lightning stroke generates an electromagnetic field which propagates with the speed of light. Comparisons of the differences in the arrival time of two or more stations define the source location. Therefore stations must be precisely synchronized. Other lightning locating systems work with magnetic direction-finders (MDF) or with the combination of TOA and MDF [22]. If no measurements of the ground flash density N_g are available, this parameter can be roughly estimated from the annual number of thunderstorm days, also called the keraunic level.

C. Lightning Analysis

The functionality of shield wire can be estimated with Shielding Failure Rate (SFR). SFR is number of lightning strokes (strikes/100 km/year) that can directly terminate on the phase conductor. In other words it indicates malfunctions of shield wire.

$$SFR = 2N_g L \int_{3kA}^{I_{max}} D_C(I) f(I) dI \qquad (1)$$

where: N_g is ground flash density (strikes/km^2/year) according to [12], L is line length (km), I_{max} is the maximum current, that can be estimated with electrogeometric model, $D_C(I)$ is shielding failure width, $f(I)$ is the probability density function of the lightning crest distribution.

Not all of these lightning strikes to phase conductor would result in flashover across insulators on a cross-arm. The number of lightning strokes to phase conductor that cause flashover across insulator is called Shielding Failure Flashover Rate (flashovers/100 km/year) and can be calculated with (2).

$$SFFOR = 2N_g L \int_{I_C}^{I_{max}} D_C(I) f(I) dI \qquad (2)$$

where: N_g is ground flash density (strikes/km^2/year) according to [12], L is line length (km), I_{max} is the maximum current, that can be estimated with electrogeometric model, I_C is shielding critical current (kA), $D_C(I)$ is shielding failure width, $f(I)$ is the probability density function of the lightning crest distribution.

Lightning current parameters and probability density function of the lightning crest distribution are based on the lightning current distribution according to [11]. In Table I different probability density functions for negative first strokes according to [13] are presented.

TABLE I DIFFERENT PROBABILITY DENSITY FUNCTIONS

Probability density function *f(I)* [13]			
Autor	**Location**	**Median (kA)**	**σ_{lg}I**
Berger	Switzerland	30	0.265
Takami	Japan	29	0.28
Visacro	Brazil	45	0.2
Global	7 countries	31	0.21

where: σ_{lg}I is standard deviation of probability density function

The choice of the probability density function *f(I)* has significant influence to SFR and SFFOR. The global distribution of first negative strokes is furthermore recommended in [13] and is considered in this investigation.

III. LIGHTNING ATTACHMENT MODEL

The maximum shielding current I_{max} can be estimated with different lightning attachment models like electrogeometric, Eriksson´s, generic and statistical model according to [23]. In this work maximum shielding current I_{max} was estimated on the basis of the electrogeometric model (EGM) for different transmission line tower geometry. The effect of the struck object height on striking distance is neglected in the electrogeometric model. General concept of electrogeometric model was presented in [14]. In Fig. 3 radii r_c are drawn from shield wire and phase conductor for increasing lightning currents. Additionally a horizontal line a distance r_g is drawn from earth surface. Those radii are striking distances for a vertically moving lightning stroke and are dependent on the stroke current crest value. The intersections are marked A, B and C. The distances D_C and D_G are the exposure distance for the phase conductors and shield wires. For increasing lightning

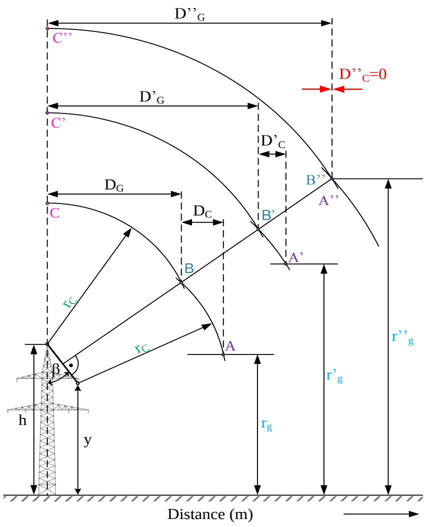

Figure 3. Sketch of striking distances

currents the distance D_C decreases until a point is reached at which D_C becomes zero. This point is defined by the current I_{max}. In Fig. 4 a downward leader in the shaded area will terminate in the phase conductors. According to the lightning attachment models only one phase can be hit directly by the lightning stroke. Consequently only at that phase a flashover may occur.

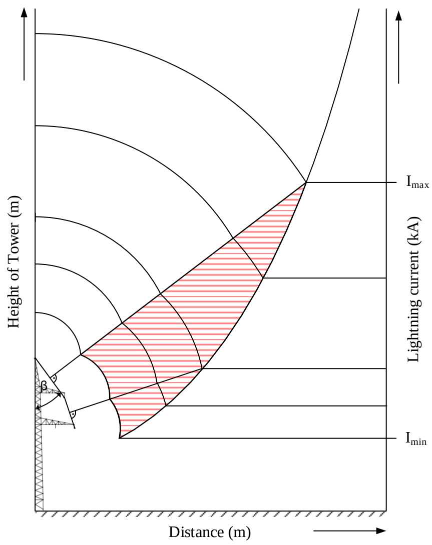

Figure 4. Interception zones of the electrogeometric model

The lowest value of current I_{min} in (1) is 3 kA according to CIGRE data [11]. Various values of coefficients A and b have been proposed by researches over years to calculate r_c and r_g. The basic formulas for striking distances are [8]:

$$r_c = A_C \cdot I^{b_C} \quad (3)$$

$$r_g = A_g \cdot I^{b_g} \quad (4)$$

Lightning incidence is the next quantity to determine for the lightning performance of a transmission line. The annual number of lightning strikes to shield wires per 100 km of a transmission line can be given as a simplified expression

$$N_s = 0.1 \cdot N_g(2 \cdot R_{eq} + b) \quad (5)$$

where: N_g (strikes/km^2/year) is the ground flash density according to [12], b (m) is the separation distance between shield wires and R_{eq} (m) is the equivalent interception radius of the shield wire. The equivalent interception radius of a conductor can be defined as

$$R_{eq} = r \cdot h^E \quad (6)$$

where: h (m) is the height of the conductor with the coefficients r and E. The basic formulas for calculating the factors r and E are given in [14]. In this paper coefficients for EGM and R_{eq} in Table II are used [15].

TABLE II. COEFFICIENTS FOR EGM

Autor	**EGM**		**R_{eq} (m)**
	r_c (m)	**r_g (m)**	
Young	$29 \cdot I^{0.32}$	$27 \cdot I^{0.32}$	$14.3 \cdot h^{0.44}$
Love	$10 \cdot I^{0.65}$	$10 \cdot I^{0.65}$	$13.9 \cdot h^{0.46}$
Armstrong, Whitehead	$6.72 \cdot I^{0.8}$	$6.05 \cdot I^{0.8}$	$33.7 \cdot h^{0.29}$
Brown, Whitehead	$7.1 \cdot I^{0.75}$	$6.4 \cdot I^{0.75}$	$30.1 \cdot h^{0.29}$
Wagner, Hileman	$14.2 \cdot I^{0.42}$	$14.2 \cdot I^{0.42}$	$11.0 \cdot h^{0.43}$
Whitehead	$9.4 \cdot I^{0.67}$	$9.4 \cdot I^{0.67}$	$14.2 \cdot h^{0.46}$

IV. SIMULATION MODEL

The simulation model for the lightning analysis is based mainly on a proposed model in [16]. That model was developed based on several field measurements and tests. Moreover it allows considering most relevant factors that influence propagation of lightning surge on overhead line and transmission tower. The simulation model shown in Fig. 5 enables estimation of shielding critical current. All overhead lines on the same tower are represented by the Constant-Parameter Distributed Line (CPDL) model at f = 400 kHz. This frequency is in the range of main resonant frequency of travelling waves in a line span of length 330 m.

To investigate lightning performance of the hybrid line for two different tower layouts (Fig. 1), a line section with 9 towers is selected in order to take into consideration of reflected/refracted waves from adjacent towers realistically.

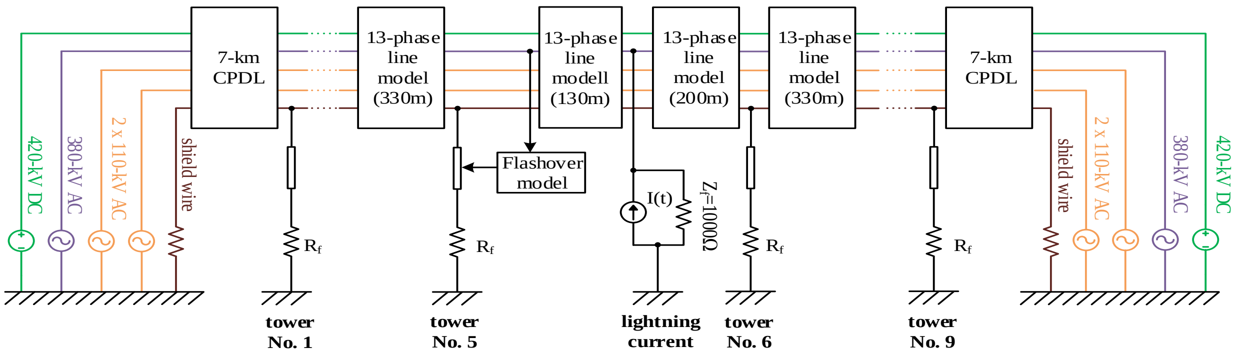

Figure 5. Simulation model for determination of the critical current due to direct lightning stroke

It is assumed that a lightning stroke hits this line section between tower 5 and 6. At both ends of this modelled line section a section of 7 km with the same electric parameters has been added to delay additionally traveling waves reflected at the voltage sources (Fig. 5). So that they do not influence the results in the time window of analysis.

The lightning stroke is modelled by a current source and a parallel resistance of 1000 Ω, which represents the lightning path surge impedance according to [16]. Stroke to a span is more likely to occur than a stroke to a tower according to lightning observation in [18]. Procedure to estimate the critical current was proposed in [14]. Simulation in EMTP-ATP allows using that procedure to obtain the critical current for outermost conductors of 380-kV circuit. Moreover that method considers effects like footing resistance, coupling from lightning current that flows through struck shield wire, dependencies of front time and maximal steepness related to crest current value. The footing impedance R_f was assumed to 10 Ω according to [16]. The power frequency voltage is considered by calculating the critical current for struck phase for instantaneous power frequency voltages estimated for each of twelve 30° steps of phase angle. Thus sinusoidal waveform of 380-kV AC voltage is considered. Mean value of twelve estimated critical currents is inserted in (2) as lower integration limit.

Leader progression model (LPM) is appropriate way to represent flashover across insulator. LPM considers different phases of flashover phenomenon (streamer and leader phases). After streamer has bridged a gap leader progression starts. That transition period can be estimated with leader onset condition (s. TABLE III). Moreover equations to calculate leader velocity and leader length are provided in TABLE III.

TABLE III. LEADER PROGRESSION CONDITIONS

Leader Progression Model [19]	
Leader onset condition	$u(t) \geq E_0 \cdot D$
Leader velocity	$v_l = 170 \cdot D \cdot \left(\frac{u(t)}{D - l_l} - E_{0p}\right) \cdot e^{(0.0015 \cdot u(t)/D)}$
Leader length	$l_l = \int v_l(t)dt$
E_{0p}	670 kV/m

Gap length D of insulator strings for 110-kV, 380-kV AC and 420-kV HVDC is about 1000 mm and 3000 mm, respectively.

The layouts of the modeled towers A and A' are shown in Fig. 1. The tower sections were represented by loss-less Constant-Parameter Distributed Line (CPDL) model [9]. In Fig. 6 the used Multistory model [21] is shown to represent transmission towers.

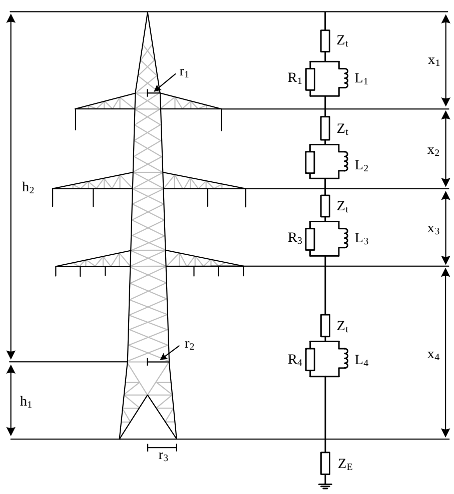

Figure 6. Multistory model

In multistory model each vertical tower section between cross arms is represented by a lossless line connected in series with *RL* parallel circuit. This parallel circuit represents attenuation of traveling waves. Calculation of surge impedance of the tower Z_{T1}-Z_{T4} with formula

$$Z_{Ti} = 60 \cdot ln\left[cot\left\{0.5 \cdot tan^{-1}\left(\frac{R}{h}\right)\right\}\right] \tag{7}$$

The *RL* values are determined as functions of surge impedance [21]. CIGRE waveform of concave shape has variable front time T_{d30}, constant time to half value T_h = 77.5 µs and variable steepness S_m [13]. According to [11] the maximum steepness (8) and the front time (9) depend on the peak value of the lightning current.

$$S_m = 3.9 \cdot I^{0.55} \tag{8}$$

$$T_{d30} = 0.906 \cdot I^{0.411} \tag{9}$$

In Fig. 7 three different lightning current waveforms with variable steepness and front time are shown.

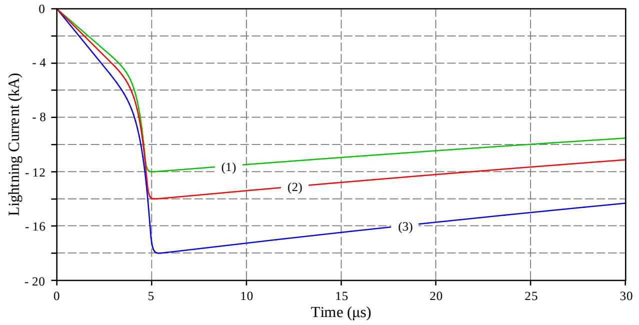

Figure 7. Lightning Current (1) 12 kA; (2) 14 kA ; (3) 18 kA

V. RESULTS

Lightning incidence N_S to shield wire(s) is calculated for various EGM given in Table II. The results are shown in Table IV. N_g is based on [12] and amounts to 4 strikes/km^2/year. Results are similar among all interception models and are higher for tower A' with double shield wires due to higher interception capability.

TABLE IV. LIGHTNING INCIDENCE RESULTS

Autor	R_{eq} (m)	N_s (strikes/100 km/year)	
		Tower A	Tower A'
Young	$14.3 \cdot h^{0.44}$	63.3	65.9
Love	$13.9 \cdot h^{0.46}$	66.5	68.8
Armstrong, Whitehead	$33.7 \cdot h^{0.29}$	83.2	86.2
Brown, Whitehead	$30.1 \cdot h^{0.29}$	74.3	77.6
Wagner, Hileman	$11.0 \cdot h^{0.43}$	46.8	50.3
Whitehead	$14.2 \cdot h^{0.46}$	67.9	70.2

The maximal current as crest value that can directly strike phase conductor is determined by means of electrogeometric models. In Fig. 8 maximum shielding currents among various EGM are summarized. The variation of maximum shielding currents among lightning attachment models is considerably large. Tower A' is equipped with double shield wire and intercepts efficiently lightning strokes. Thus maximal lightning current for tower A' is considerably lower among all EGMs. Since EGM considerably influences SFR and SFFOR performance of the line based on parameter I_{max}, several EGM have been taken into account to show a range of SFR and SFFOR values depending on EGM.

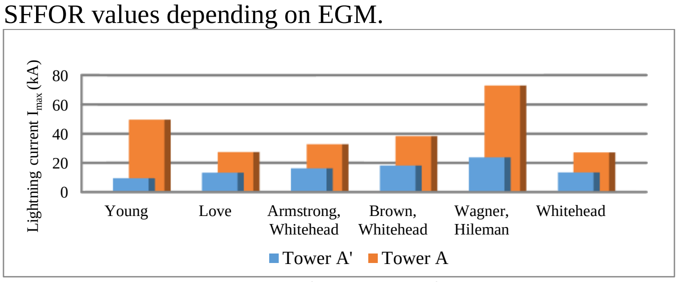

Figure 8. Maximum crest value of the current of a direct lightning stroke to uppermost phase conductor.

The calculation of the critical current for AC circuits is more complex, since power frequency voltage is time-varying. The power frequency voltage is considered by calculating the critical current for struck phase for instantaneous power frequency voltages estimated for each of twelve 30° steps of phase angle (s. Fig. 9). The critical current of each phase depends mainly on the phase angle of power frequency voltage at the stroke instant. In Fig. 9 the value of twelve estimated critical currents is shown. The mean value is inserted in (2) as lower integration limit. In case of HVDC circuit pole-to-ground crest voltage is considered.

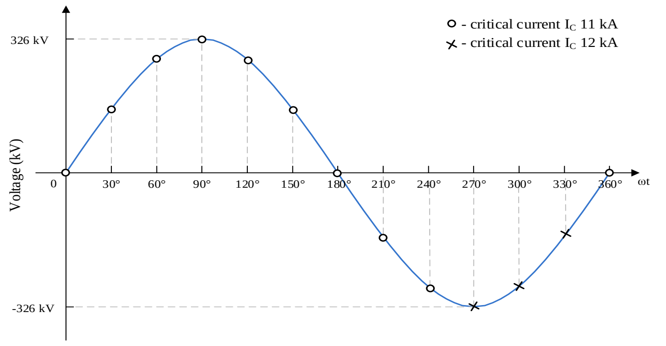

Figure 9. Critical current (380 kV AC System) for each of twelve 30° steps of phase angle

Calculation of critical current for HVDC systems requires only one computation, since voltage of positive pole is constant and equal to +420-kV. Critical current was obtained by a simulation and amounts to 11.25 kA for 380-kV and is about 14 kA for HVDC. In Fig. 10 (1) voltage difference across the insulator string of plus pole of HVDC causing flashover after shielding failure is presented.

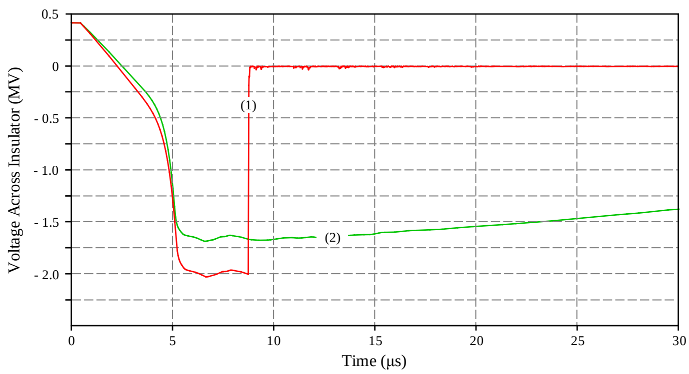

Figure 10. Voltage difference across the insulator string of plus pole causing (1) flashover and (2) no flashover due to shielding failure

Maximum shielding currents that were estimated with EGM are employed for shielding performance calculation. SFR and SFFOR are presented in Table V and Table VI. SFR is the same for both sides of tower despite different systems. Converting of a HVAC system into a HVDC system does not change the location of conductor or length of insulators. The length of highest cross-arms for each tower is the same and this is valid for both sides of the tower. Various values of maximal shielding current I_{max} and shielding width $D_C(I)$ influence shielding performance of the investigated towers.

SFR values estimated with different EGM vary from each other significantly. Two shield wires in tower A' reduce efficiently number of strokes that may directly terminate in outermost phase conductors. SFFOR is different for two sides of the investigated towers. Following a direct stroke in upper outmost conductor flashover across insulator to cross-arm at AC system is more likely. SFFOR for tower A exceeds recommended SFFOR for lines serving critical loads [14]. It is recommended SFFOR of 0.05 flashover/100 km/year. In particular, tower A with one shield wire does not fulfil this requirement.

TABLE V. SFR *(STRIKES/100 KM/YEAR)* AND SFFOR *(FLASHOVER/100 KM/YEAR)* FOR TOWER A

Autor	Tower A		
	SFR	***SFFOR$_{HVDC}$***	***SFFOR$_{380kV}$***
Young	3.13	1.04	1.16
Love	1.88	0.4	0.53
Armstrong, Whitehead	2.8	0.82	0.98
Brown, Whitehead	3.49	1.16	1.32
Wagner, Hileman	5.54	2.2	2.35
Whitehead	1.88	0.4	0.53

TABLE VI. SFR *(STRIKES/100 KM/YEAR)* AND SFFOR *(FLASHOVER/100 KM/YEAR)* FOR TOWER A'

Autor	Tower A'		
	SFR	***SFFOR$_{HVDC}$***	***SFFOR$_{380kV}$***
Young	0.1	0	0
Love	0.25	0	0
Armstrong, Whitehead	0.36	0	0.04
Brown, Whitehead	0.41	0.03	0.07
Wagner, Hileman	0.5	0.07	0.11
Whitehead	0.26	0	0

VI. CONCLUSION

Shielding performance calculations have been performed for two towers coming into consideration for a multi-circuit line with HVAC/HVDC circuits. Several lightning interception and attachment models were implemented to evaluate SFR and SFFOR. The maximum shielding current depends strongly on tower geometry and lightning attachment model used. Results differ considerably depending on the electrogeometric model used. Shielding performance of a tower can be efficiently increased by additional shield wire. Tower A' with two shield wires offers substantially low values of SFR and SFFOR.

Conversion of an existing tower with only HVAC systems into HVAC/HVDC multi-circuit line decreases probability of occurrence of flashover due to direct lightning stroke to outermost conductor. Whereas SFR after conversion into HVDC remains unchanged, SFFOR is slightly reduced for the HVDC system. Constant +420 kV voltage of plus pole makes upper insulator at plus pole less prone to flashover by a direct stroke to phase conductor in comparison with phase conductor of original 380 kV system.

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