Comparison of Backflashover Performance between a Novel Composite Pylon and Metallic Towers

H. Zhang, M. Ghomi, Q. Wang, F. Faria da Silva, C. L. Bak, K. Yin, H. Skouboe

***Abstract*-- A design of a fully composite pylon with external grounding down-leads has been proposed for new-generation 400 kV transmission towers, able to save lines corridors and to reduce visual impact. This paper investigates and compares the backflashover performance of a composite pylon and two conventional metallic towers, which have been widely installed in Denmark. The transient models of overhead lines and all three towers were established respectively and the transient analysis was carried out in PSCAD. Monte Carlo method was used to estimate backflashover rate. The backflashover rate of composite pylon is 0.4526 cases per 100 km per year, which is in the same range, but slightly higher than that of metallic towers. The separated grounding down-leads of double circuits on composite pylon eliminates the danger of simultaneous backflashover of double circuits, which exists in transmission lines supported by metallic towers. After comparing the overvoltages to three phases of the three towers from backflashover, it is worthy considering that the installation of surge arresters at all three phases of composite pylon has a strong impact on the backflashover rather, but for the two metallic towers only the surge arresters at the upper phase has an impact.**

***Keywords*: backflashover rate, fully composite pylon, lightning overvoltages, Monte Carlo method, PSCAD, frequency-dependent footing model.**

I. Introduction

In recent years, usage of overhead lines (OHLs) in transmission system has been faced with great challenges, because of the increasing requirement for transmission capacity along with the public opposing to erect more conventional metallic towers, which have negative visual impact. A proposal for a fully composite pylon has been designed to meet the requirements of compact structure and elegant appearance for new-generation transmission towers[1]. The fully composite pylon is in shape of a 'Y' geometric configuration, shown in Fig. 1. (a). Conductors are fixed by clamps on the surface of the cross-arm, which has an inclined angle of 30° from the horizontal ground plane. Two shield wires are installed at the tips of the two cross-arms respectively. The cross-arms and the pylon body are made of fiber reinforced plastic (FRP). Therefore, the pylon itself cannot conduct lightning current if struck by lightning flashes. Correspondingly, as one choice of grounding schemes, two bare-metal conductors are installed outside the pylon to conduct the lightning current to ground when shield wires are terminated by lightning flashes, which are shown in Fig. 1. (a).

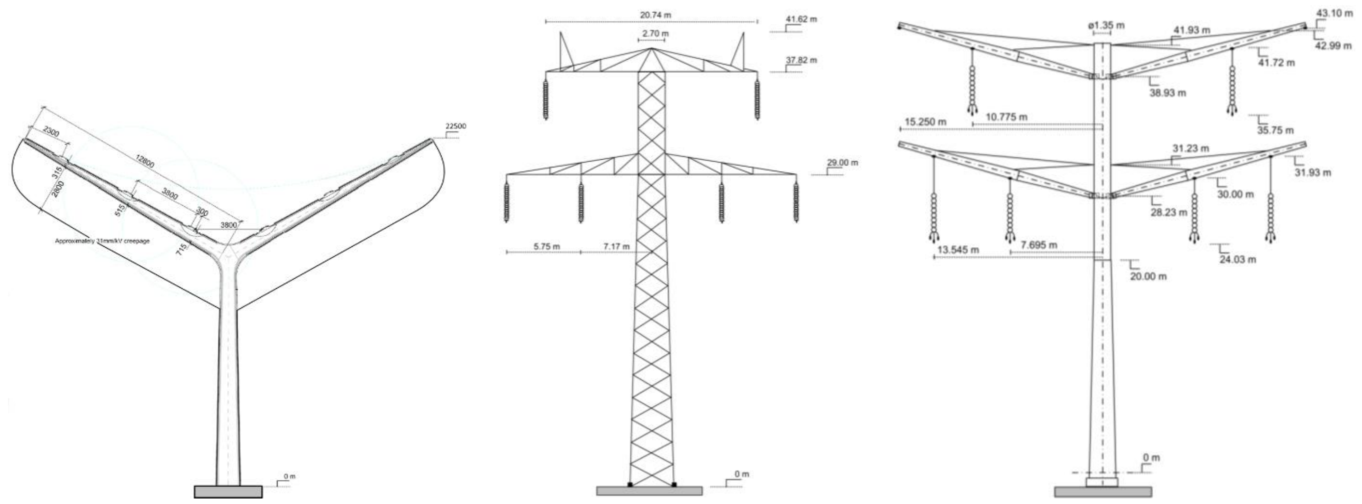
By contrast, variant metallic towers are still the mainstream in transmission power grid at present. Two types of conventional metallic towers, which have been widely installed in Denmark, namely Donau tower and Eagle tower, are selected as comparison to assess the backflashover performance of the novel composite pylon[2]. The configuration and dimension of two metallic towers are shown in Fig. 1. (b) and (c).

The novel pylon has a more compact configuration and reduced height due to elimination of insulator strings. However, there is little experience and research on the lightning performance evaluation of a pylon with such an unusual electric design. In [3], the backflashover evaluation based on constant footing resistance, critical flashover determination and single-variable lightning waveform is performed, but the simulation procedure can be improved. Considering differences between the novel fully composite pylon and conventional metallic towers, several features need to be emphasized when evaluating backflashover performance. Firstly, compared to the OHLs supported by conventional metallic towers, the OHLs supported by composite pylons have more compact configuration with shorter spans, which reduces the tail time of transient overvoltage at insulation[4]. Secondly, compared to the metallic tower body as lightning current grounding path, the grounding down-leads of composite pylons have larger inductance. Thirdly, mainstream, both theoretical and experimental research on insulation flashover for OHLs is based on ceramic insulators. The polymeric cross-arms of novel pylons, which are more similar to polymeric insulators, tend to have shorter dry-arc distance than ceramic ones[5].

This paper deals with the PSCAD implementation of Monte Carlo Method (MCM) for the backflashover rate (BFR) evaluation of the novel fully composite pylon and its backflashover performance is compared with two widely-installed metallic towers in Demark. Chapter II describes the modelling details for the backflashover analysis of composite pylons and proposes a procedure to evaluate BFR using MCM. Results in Chapter III shows that although BFR of composite pylon is higher than metallic towers, composite pylon will not suffer simultaneous backflashover of double circuits, but the backflashover on three phases are the same severe.

H. Zhang, M. Ghomi, Q. Wang, F. F. da Silva, C. L. Bak, and K. Yin are with the Department of Energy Technology, Aalborg University, Aalborg 9100, Denmark (e-mail: hazh@et.aau.dk; qiw@et.aau.dk; ffs@et.aau.dk; clb@et.aau.dk; kyi@et.aau.dk).
H. Skouboe is with the BYSTRUP Architecture Design Engineering, København Ø 2100, Denmark (e-mail: hs@bystrup.dk).

Paper submitted to the International Conference on Power Systems Transients (IPST2021) in Belo Horizonte, Brazil June 6-10, 2021.



(a) Composite pylon (b) Donau tower (c) Eagle tower

Fig. 1. The sketch and configuration of all three transmission towers (not in real relative scale)

II. Simulation Model and Procedure for Backflashover Analysis

A. Lightning current model

CIGRE lightning current model is used because of its consistency with the waveshape of lightning flashes in the nature. Four variables are used in analytical expressions to shape the lightning current waveshape of the first stroke of the downward flash recommended by CIGRE[6], namely lightning current amplitude I_c, maximum steepness S_m, front time (from 30% to 90%) t_f, and tail time t_h. All the parameters yield to log-normal distribution.

In this paper, I_c and t_f are treated as variables to shape the lightning current waveform. t_h is set as constant equal to its median after concluding that it has little effect on overvoltage level. S_m is set as per unit value determined by I_c and t_f and its base value is equal to the quotient by the medians of I_c and t_f.

B. OHL model

The simulated double-circuit OHL is 100 km long, at the rated voltage of 400 kV and highest system voltage of 420 kV. At one end of the OHL, phase conductors are connected with a three-phase voltage source and shield wires are solidly grounded. At the other end, the OHL is connected to a load. The tested transmission tower under research is set in the middle, 50 km to both ends of the whole line. Six adjacent transmission towers are modelled in details because the tower in longer distance have little impact on the overvoltage at the head of tower struck by lightning. The span is 250 m. Fig. 2 shows a schematic of the model. In the study of the three transmission towers, only the model of different towers is replaced.

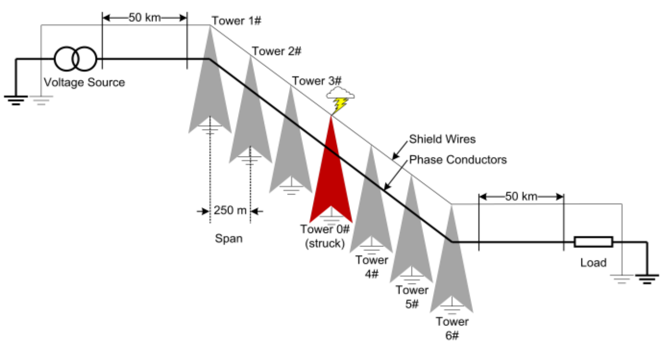


Fig. 2. The demonstration of OHL lines model

C. Down-leads and tower model

The surge impedance of the down-leads varies according to the geometry, as the lightning wave travels from top to ground. To cope with this behavior, the models based on non-uniform transmission lines is considered[7].

The tower model is established by horizontal cylindrical conductors representing cross-arms and vertical cylindrical conductors representing tower bodies. The down-leads model is established as a combination of horizontal and vertical segments. The part along with pylon body is treated as a vertical cylindrical conductors and the part along with the cross-arm is treated as three horizontal cylindrical conductors. The 'Bergeron Model' in PSCAD is used to simulate the transient characteristics of each segment[8]. The surge impedance of vertical segments Z_v can be calculated as equation (1) and surge impedance of horizontal segments Z_h can be calculated as equation (2)[9],

$$Z_v = 60(\ln(h_v/r)-1) \tag{1}$$

$$Z_h = 60\ln(2h_h/r) \tag{2}$$

where r is the radius of each segment and h is the height of different segment. To be noted, the height of the vertical part h_v is from earth bottom to top and the height of each horizontal segments h_h is from earth bottom to the center of each segment.

D. Frequency-dependent Tower footing impedance model

In lightning studies estimating backflashover rate for transmission lines, modelling of grounding systems plays an important role, because the lightning current contains a very high frequency. With this regard, if the high frequency grounding system impedance is not sufficiently low, the resultant overvoltages may reach a level leading to insulation failure. In recent years, the full-wave electromagnetic field methods have been applied for modelling tower grounding system based on both the time and frequency domain numerical solution of Maxwell's equations, for instance, the finite difference time domain (FDTD) method [10], the finite element method (FEM) [11] and the method of moment (MoM) [12].

This paper adopts the same approach presented in [13-16] for frequency dependent modeling of grounding system. Firstly, the grounding system impedance matrix over the frequency range of interest is obtained by applying the full-wave approach MoM solution to Maxwell's equations. In this method, the governing electric field integral equation is formulated for the induced currents along the grounding conductor segments by making use of the MoM, which provides the current distribution along the grounding segments. Then, a rational approximation of the grounding system admittance matrix is obtained by making use of vector fitting techniques in the frequency domain [17]. Finally, the obtained rational approximation is employed to generate a model of the grounding system expressed in the form of state-space equations, which can be simulated and expressed for in the time-domain blocks in electromagnetic transient software.

In this paper, the footing condition is set as a vertical electrode buried in a two-layer soil. The length and the cross section radius of the electrode are L=3 m and r=15 mm respectively. The soil is characterized by resistivity of 100 Ω·m and 1000 Ω·m for upper and lower layer respectively. The relative electric permittivity is set as 10.

E. Leader progression model for flashover

Leader progression method (LPM) considers the physical process of air gap discharge to describe insulation surface flashover, which mainly consists of two stages: the streamer progression stage T_s and the leader progression stage T_l. T_s can be calculated as follow[18],

$$T_s = \frac{1}{k_1(E/E_{50\%}) - k_2} \tag{6}$$

where E is the maximum electric field before insulation flashover while $E_{50\%}$ is the electric field under CFO. k_1 and k_2 are the factors of streamer progression time, which are recommended to be 1.25 and 0.95 respectively.

T_l can be calculated based on its velocity recommended by CIGRE as follow,

$$\frac{dx}{dt} = ku(t)\left(\frac{u(t)}{D-x} - E_l\right) \tag{7}$$

where x is the length of the leader, $u(t)$ is the voltage between the air gap, D is the length of insulation, E_l is the threshold electric field of leader progression and k is the factor of leader progression speed. E_l and k are related to the type of the insulators and the polarity of the lightning impulse voltage, which are obtained from experiments[19].

F. BFR estimation procedure

The BFR evaluation procedure based on MCM uses the statistical result of quantities of single random lightning protection case to evaluate backflashover (BF) probability. The procedure consists of three steps: pre-processing step, numerical simulation step and post-processing step.

In pre-processing step, a large number, N_{total}, of lightning currents are generated to simulate the randomness and statistics of lightning flashes in the nature. Because the front time of lightning current follows log normal distribution, a group of front times are generated using inverse transform sampling. The median of log-normal distribution of I_c can be obtained according to the value of t_f in equation (8)[20],

$$M_I = 19.5 \cdot t_f^{\,0.39} \tag{8}$$

With every front time, a group of lightning current amplitudes can be generated. The number of different front times is 100 and the number of different lightning current amplitudes corresponding to every front time is also 100, thus, the number of lightning currents N_{total} is 10000.

In numerical simulation step, all lightning currents derived from last step were input in OHLs model in PSCAD as lightning impulse current source.

The BF probability for every lightning current was estimated considering the operating voltage on phase conductors. When using LPM to determine the occurrence of backflashover, $u(t)$ in equation (7) is the voltage at the air gap, which is the difference between the overvoltages and the operating voltage V on phase conductors. The operating voltage can be regarded as a constant during lightning transients, because of the relatively extremely short duration of overvoltage. The result after determination of LPM to a certain $u(t)$ is only 1 (flashover) or 0 (not flashover). Thus, there is a critical operating voltage V_i. The voltage difference between overvoltage and the operating voltage larger than V_i can definitely cause flashover, and the voltage difference between overvoltage and the operating voltage smaller than V_i cannot cause flashover. The BF probability can be estimated as the ratio of the duration in one cycle when the operating voltage is above V_i for the whole AC period.

In post-processing step, BFR is calculated after processing the results of BF probability of all lightning currents.

The BFR can be expressed in equation (9)[20],

$$BFR = 0.6 \cdot N_d \cdot \frac{\sum P(I_c)}{N_{total}} \tag{9}$$

where $\Sigma\ P(I_c)$ is the sum of the backflashover probability of every lightning current and N_{total} is the total number of lightning currents. N_d is the estimated number of lightning strikes that terminate on the 100-km line, which can be calculated by equation (10),

$$N_d = N_g \cdot (D + 28H^{0.6}) \cdot 10^{-1} \tag{10}$$

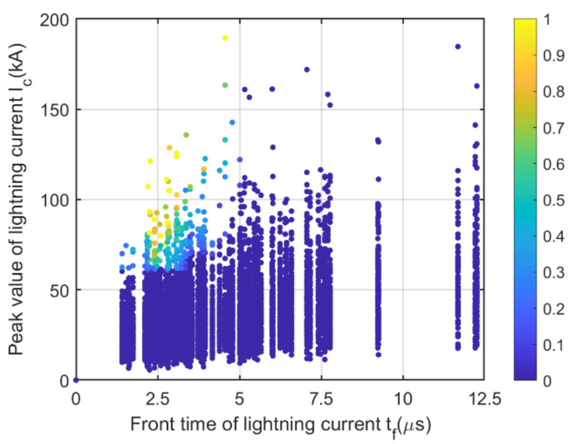
where N_g is the ground flash density describing the number of flashes that terminate on the ground per year per square kilometers. H is the tower height and D is the horizontal distance between shield wires. The numerical multiplicative coefficient 0.6 considers that overvoltage at the shield wire caused by lightning flashes striking within the span is lower than those striking at the pylon head. Consequently, BFR is reduced by 40% if mid-span striking is considered.

III. Results

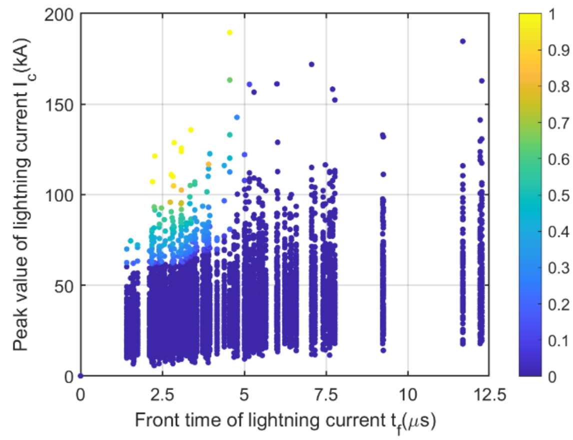
A. Comparison of BF probability and BFR between composite pylon and metallic towers

The evaluation of total BF probability is based on MCM collecting every BF probability of quantities of lightning flashes with different front times and currents. The BF probabilities of the three transmission towers of all the lightning flashes with different front times and currents are shown as spectrums in Fig. 3.

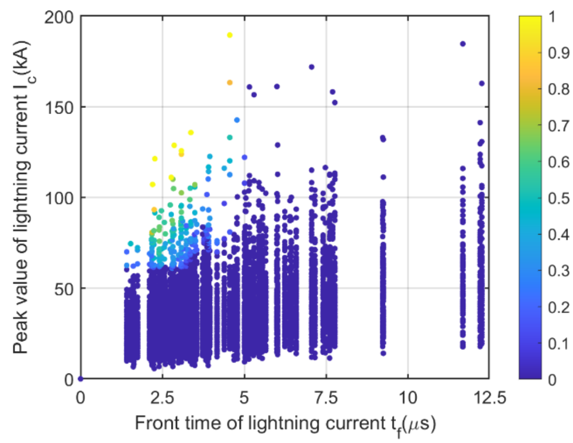
A single spot in spectrum represents BF probability of a single lightning flash. The x-ordinate and y-ordinate of the spot are the front time and lightning current respectively. The color of spot represents the BF probability. Because the parameters of all lightning flashes are sampled following to their statistical probability distribution, lightning BF probability P_{BF} can be obtained by the sum of BF probabilities of all lighting flashes $\Sigma P(I_c)$ divided by the amount of lightning flashes N_{total}. It can be found that both metallic towers provide similar results and under lightning currents with front time shorter than around 3 μs composite pylon also has similar backflashover performance. However, under lightning currents with longer front time, compared with the results from metallic towers, the minimum lightning current to cause backflashover on composite pylon is lower, and BF probability caused by same lightning current is higher. As a result, lightning BF probability P_{BF} provided by composite pylon is higher than metallic towers.



(a) Composite pylon



(b) Donau tower



(c) Eagle tower

Fig. 3. BF probability spectrum after MCM

After calculating the total lightning BF probability P_{BF}, the factors influencing BFR of the three towers are summarized in the Table I. Compared with Donau tower and Eagle tower at the same lightning conditions, the composite pylon has lower height, which will attract fewer flashes, higher surge impedance, which will cause higher overvoltage, and shorter insulation distance, which means flashover is easier to occur at the same overvoltage. As a result, the BFR of composite pylon is 0.4526 cases per 100 km per year, which is a little higher than that of Donau tower and Eagle tower.

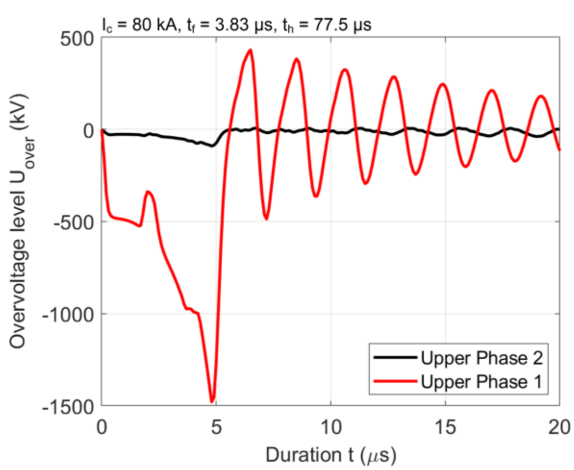
TABLE I
Factors Influencing BFR of Three Transmission Towers

Tower type	Composite pylon	Donau tower	Eagle tower
Ground flash density N_g [cases/km^2·year]		1.39	
Tower height H [m]	22.50	41.62	43.10
Shielding distance D [m]	21.28	20.74	27.09
Line flash density N_d [cases/100 km·year]	20.26	28.3	29.60
DC footing resistance R_0 [Ω]		50	
Insulation length L [m]	2.8	3.2	3.72
CFO [kV]	1960	2240	2604
Total BF probability P_{BF}	0.0267	0.0134	0.0121
BFR [cases/100km·year]	0.4526	0.3176	0.2992

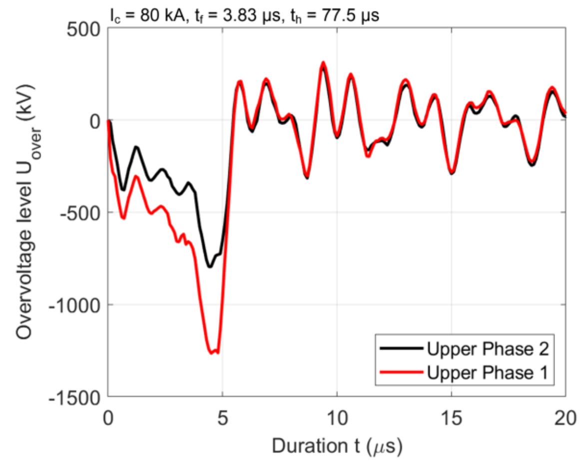
B. Comparison of overvoltage of double circuit between composite pylon and metallic towers

All three transmission towers are designed to support double-circuit OHLs at 400 kV. For metallic towers, no matter which shield wires is struck, lightning current travels through the tower body to ground. High overvoltage rises across insulators, which may cause backflashover of both circuits. A review from Queensland Transmission Company shows that 4.7 % of the outage faults of a 275 kV transmission line were double circuit outages[21]. Multi-circuit outages account for 33.7 % of total lightning caused faults in Korea[22]. Although the probability of double circuit outage is lower than single circuit outage, double circuit outages often lead to especially severe power interruption problems. For composite pylons, two down-leads are separated from shield wires to ground individually. When one of shield wires is struck by lightning, high overvoltage only rises on one of the down-leads, which solely faces with the danger of backflashover.

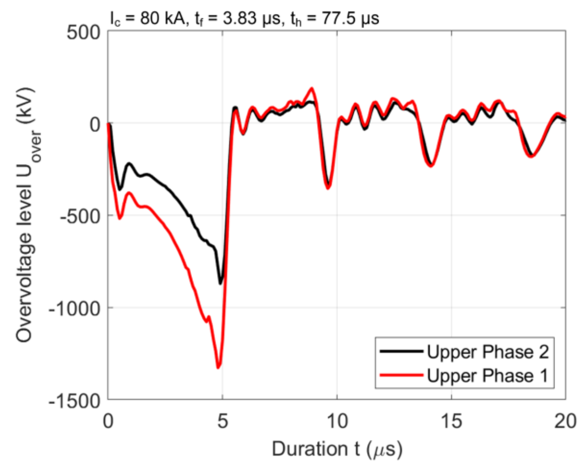
Fig. 4 shows the overvoltage across cross-arm of composite pylon and insulators on metallic towers to the upper phase conductors of double circuits when lightning strikes at shield wires of one circuit. For composite pylons, the overvoltage is measured from tip of down-lead across cross-arm to upper phase conductors. For metallic towers, the overvoltage is from suspending points across insulators to upper phase conductors. The lightning parameters are the same for all three cases (80 kA, 3.83/77.5 μs) and the shield wires of circuit 1 is struck. Red lines show the overvoltage waveforms across insulation to the upper phase conductors in circuit 1, which is in the same side with shield wires struck by lightning. Black lines show the overvoltage waveforms across insulation to the upper phase conductors in the other circuit. It can be observed that, for Donau tower and Eagle tower, the overvoltages of both circuits are closely high. However, for composite pylon, the overvoltage in circuit 1 is of a quite high amplitude while the overvoltage in circuit 2 is of lower amplitude. The opposite phase between the overvoltage oscillations of double circuits shows the overvoltage in circuit 2 of composite pylon is caused by induction of the overvoltage in circuit 1 instead of direct lightning current, which results in lower amplitude.



(a) Composite pylon



(b) Donau tower



(c) Eagle tower

(d)

Fig. 4. Overvoltage across cross-arm (composite pylon) and insulators (metallic towers) to the upper phase conductors of double circuits when lightning strikes at shield wire of one circuit

The BF probability of all six cases are calculated according to MCM procedure introduced above and summarized in following Table II. For Donau tower and Eagle tower, although lightning flash strikes only one of shield wires, both circuits are probable to occur backflashover at the same time. For composite pylon, the phase conductor in the same circuit with the struck shield wire is faced with higher BF probability, but the other circuit has little probability to occur backflashover.

TABLE II
MAXIMUM AND BF PROBABILITY OF THE OVERVOLTAGES THREATENING BOTH DOUBLE CIRCUITS OF THREE TRANSMISSION TOWERS UNDER THE LIGHTNING (80 KA, 3.83/77.5 μS)

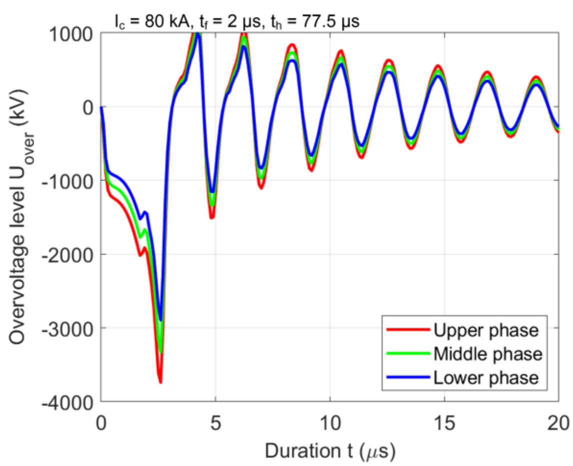
Tower type	Circuit No.	Max. Overvoltage [kV]	BF probability
Composite pylon	1	-1479.20	0.4027
	2	-90.21	0
Donau tower	1	-1264.62	0.3251
	2	-795.18	0.0735
Eagle tower	1	-1326.80	0.3541
	2	-871.25	0.0950

In order to prevent the backflashover of both circuits under the strike of a single lightning flash, differential insulation may be adopted in conventional OHLs supported by metallic towers, to sacrifice one circuit with weaker insulation to protect the other circuit with stronger insulation[23]. By contrast, backflashover cases may occur at both circuits randomly in composite pylons and solely occur at the circuit with weaker insulation in metallic towers, which overloads insulation strength and shortens lifetime of insulators in metallic towers.

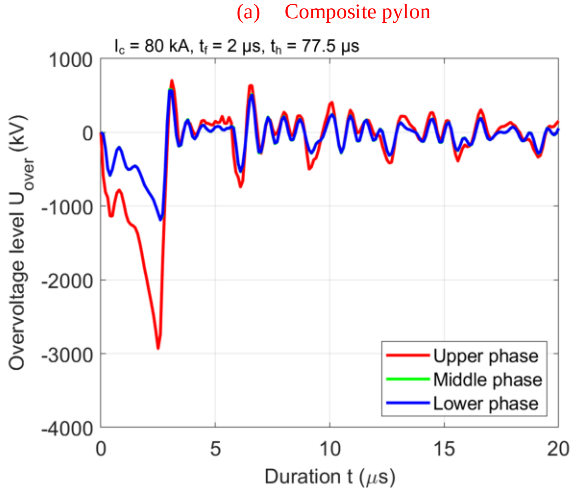
In summary, compared with conventional metallic towers, OHLs supported by composite pylons are not faced with simultaneous backflashover of double circuits. Compared with conventional metallic towers with differential insulation, OHLs supported by composite pylons have longer lifetime.

C. Comparison of overvoltage of three phases between composite pylon and metallic towers

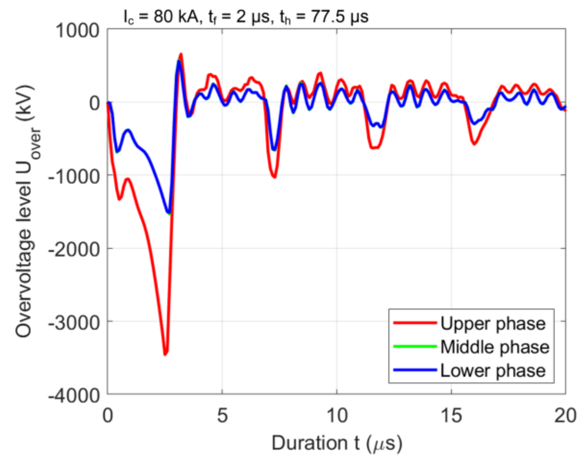
The overvoltages of three phases in the same circuit of the three towers are shown in Fig. 4. The lightning parameters are the same for all three cases (80 kA, 2/77.5 μs). As for the composite pylon, the overvoltages are measured at the locations on the down-lead nearest to the phase conductors. As for the two metallic towers, the overvoltages are measured at the locations suspending the insulators and phase conductors. From the results, it can be found that the overvoltages on the down-lead of the composite pylon are of closely amplitudes and all three phase conductors are faced with backflashover of close probability. However, for metallic towers, the overvoltages at the suspending points of upper phase are far higher than the other two phases. In other words, the tower configuration has an important impact on the overvoltage of different phases according to their locations on the tower.



(a) Composite pylon



(b) Donau tower



(c) Eagle tower

Fig. 4. Overvoltage across cross-arm (composite pylon) and insulators (metallic towers) to the conductors of three phases when lightning strikes at shield wire

The application of surge arresters is a widely used method to protect transmission lines. If the surge arresters are installed at all three phases, this countermeasure will certainly have a best backflashover protection performance than if no surge arresters are installed. Considering the cost of surge arresters, it is economic to minimize the number of surge arresters if possible. The default surge arrester model in PSCAD is selected and Table. III summarizes the BFR of the three towers using three different strategies of surge arrester installation. The first strategy is without surge arresters (No MOV). The second is to install surge arresters only on the upper phases (MOV-Upper). The third is to install surge arresters on all three phases (MOV-3-phase).

From the BFR results of the three towers, installing surge arresters on three phases leads to the best performance and installing upper-phase surge arresters is still better than no surge arresters, both results in accordance with the expectations. However, for the two metallic towers, the BFR of installing 3-phase surge arresters is only slightly lower than that of installing a surge arrester only on the upper phase. For composite pylons, installing 3-phase surge arresters has obviously lower BFR than installing only upper-phase surge arresters. Compared with the BFR without surge arresters, the BFR after installing surge arrester on upper phase decreases 32.90 %, while the BFR after installing surge arresters on three phases decreases 86.01%. Thus, for metallic towers, it is not recommended to install surge arresters on all three phases out of economy, but it is worthy to consider installing surge arresters on all three phases of composite pylon for good backflashover performance.

TABLE III

MAXIMUM AND BF PROBABILITY OF THE OVERVOLTAGES THREATENING BOTH DOUBLE CIRCUITS OF THREE TRANSMISSION TOWERS

Tower type	Method	BFR [cases/100km·year]
Composite pylon	No MOV	0.4526
	MOV-Upper	0.3037(-32.90%)
	MOV-3-phase	0.0633(-86.01%)
Donau tower	No MOV	0.3176
	MOV-Upper	0.0825(-74.02%)
	MOV-3-phase	0.0622(-80.41%)
Eagle tower	No MOV	0.2992
	MOV-Upper	0.0794(-73.46%)
	MOV-3-phase	0.0591(-80.24%)

To be noted, the above conclusions are only investigated from the aspect of backflashover performance. The installation of surge arresters is also need to be examined from the aspect of shielding failure in case that lightning directly strikes at the phase conductors.

IV. Conclusions

This paper investigated and compared the backflashover performance of a novel fully composite pylon of 400 kV with external grounding down-leads with two conventional metallic towers widely installed in Denmark. The transient models of OHLs and all three towers were established and the transient analysis was carried out in PSCAD. Monte Carlo method was used to simulate the randomness of lightning current waveforms in the nature in order to estimate the backflashover rate. Methods to improve the backflashover performance of composite pylons were proposed and analyzed. The following conclusions can be drawn:

(1) Compared with conventional metallic towers at the same lightning conditions, the compact configuration of composite pylons and larger surge impedance may attract fewer lightning flashes, but it presents higher overvoltage, resulting in higher BFR. The BFR of composite pylon is 0.4526 cases per 100 km per year, which is higher than Donau tower and Eagle tower.

(2) All three towers are designed to support double circuits. Compared with conventional metallic towers, OHLs supported by composite pylons are not faced with simultaneous backflashover of double circuits attributed to separated grounding down-leads.

(3) In the same circuit, where the shield wire is struck by lightning, the overvoltages on the down-lead of composite pylon are of closely amplitude, whereas the overvoltages across the upper phase insulators on the metallic towers are far higher than those of the other two phases. Thus, from backflashover, it might be worthy considering that all three phases of composite pylon are installed with surge arresters.

V. References

[1] BYSTRUP. "THE COMPOSITE PYLON." https://www.powerpylons.com/composite-pylon (accessed.

[2] T. Ebdrup, D. Olason, K. Pederson, C. L. Bak, and F. F. Silva, "Comparison of overhead line lightning performance based on two different tower geometries," presented at the Cigré International colloquium on lightning and power systems, Lyon, 2014.

[3] K. Velitsikakis, F. M. F. da Silva, Q. Wang, C. L. Bak, and H. Skouboe, "Performance Analysis for the Innovative 400 kV Double-Circuit'Y'Composite Tower Under Backflashover Conditions," in *CIGRE International Colloquium on Lightning and Power Systems 2019*, 2019: CIGRE (International Council on Large Electric Systems).

[4] W. A. Chisholm, "New challenges in lightning impulse flashover modeling of air gaps and insulators," *IEEE Electrical Insulation Magazine*, vol. 26, no. 2, pp. 14-25, 2010, doi: 10.1109/MEI.2010.5482551.

[5] S. Venkataraman and R. S. Gorur, "Prediction of flashover voltage of non-ceramic insulators under contaminated conditions," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 13, no. 4, pp. 862-869, 2006, doi: 10.1109/TDEI.2006.1667747.

[6] W. S. 33, "Guide to procedures for estimating the lightning performance of transmission lines," CIGRE 1991, vol. 63.

[7] J. R. Martí and A. Tavighi, "Frequency-Dependent Multiconductor Transmission Line Model With Collocated Voltage and Current Propagation," *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 71-81, 2018, doi: 10.1109/TPWRD.2017.2691343.

[8] J. A. Martinez and F. Castro-Aranda, "Tower modeling for lightning analysis of overhead transmission lines," in *IEEE Power Engineering Society General Meeting, 2005*, 16-16 June 2005 2005, pp. 1212-1217 Vol. 2, doi: 10.1109/PES.2005.1489355.

[9] T. Hara and O. Yamamoto, "Modelling of a transmission tower for lightning-surge analysis," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 143, no. 3, pp. 283-289, 1996, doi: 10.1049/ip-gtd:19960289.

[10] M. Tsumura, Y. Baba, N. Nagaoka, and A. Ametani, "FDTD Simulation of a Horizontal Grounding Electrode and Modeling of its Equivalent Circuit," *IEEE Transactions on Electromagnetic Compatibility*, vol. 48, no. 4, pp. 817-825, 2006, doi: 10.1109/TEMC.2006.884448.

[11] L. Qi, X. Cui, Z. Zhao, and H. Li, "Grounding Performance Analysis of the Substation Grounding Grids by Finite Element Method in Frequency Domain," *IEEE Transactions on Magnetics*, vol. 43, no. 4, pp. 1181-1184, 2007, doi: 10.1109/TMAG.2007.892283.

[12] V. A. Toseva, L. Grcev, and K. E. K. Drissi, "High frequency performance of ground rod in two-layer soil," in *IEEE EUROCON 2017 -17th International Conference on Smart Technologies*, 6-8 July 2017 2017, pp. 914-918, doi: 10.1109/EUROCON.2017.8011244. [Online]. Available: https://ieeexplore.ieee.org/document/8011244/

[13] L. Grcev, "Modeling of Grounding Electrodes Under Lightning Currents," *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, no. 3, pp. 559-571, 2009, doi: 10.1109/TEMC.2009.2025771.

[14] L. Grcev, "Impulse Efficiency of Ground Electrodes," *IEEE Transactions on Power Delivery*, vol. 24, no. 1, pp. 441-451, 2009, doi: 10.1109/TPWRD.2008.923396.

[15] M. Ghomi, C. L. Bak, and F. M. F. da Silva, "Frequency Dependence of Multilayer Soil Electrical Parameters: Effects on Ground Potential Rise," in *International conference on Lightning protection: ICLP2020*, 2020.

[16] M. Ghomi, C. L. Bak, and F. M. F. da Silva, "Frequency Dependence of Multilayer Soil Electrical Parameters: Effects on the Input Impedance of Grounding Systems," in *16th International conference on AC and DC power transmission.: IET event*, 2020.

[17] B. Gustavsen, "Computer code for rational approximation of frequency dependent admittance matrices," *IEEE Transactions on Power Delivery*, vol. 17, no. 4, pp. 1093-1098, 2002.

[18] A. Pigini, G. Rizzi, E. Garbagnati, A. Porrino, G. Baldo, and G. Pesavento, "Performance of large air gaps under lightning overvoltages: experimental study and analysis of accuracy predetermination methods," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1379-1392, 1989, doi: 10.1109/61.25625.

[19] X. Chen, X. Wen, and L. Lan, "Application of the Leader Progression Model in the Insulation Flashover Criterion for Lightning Performance Calculation," in *Proceedings of the Second International Conference on Mechatronics and Automatic Control*, Cham, W. Wang, Ed., 2015// 2015: Springer International Publishing, pp. 459-466.

[20] A. R. Hileman, *Insulation Coordination for Power Systems* (POWER ENGINEERING). Taylor & Francis Group, 1999.

[21] J. Gillespie and G. Stapleton, "Improving double circuit transmission line reliability through lightning design," *Cigré*, pp. B2-301, 2004.

[22] J. Kwak, J. Woo, E. Shim, H. Kim, and J. Moon, "Application of arrester to double circuit transmission line to enhance lightning performance and introduction about the obtained lightning waveforms by monitering systems," in *19th International Lightning Detection Conference, Tucson, Arizona, USA*, 2006, pp. 24-25.

[23] W. C4.301, "Use of Surge Arresters for Lightning Protection of Transmission Lines," *CIGRE Techinical Brochures*, 2010.