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TRANSIENT MODELLING AND BACKFLASHOVER RATE ANALYSIS OF A FULLY COMPOSITE PYLON

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Keywords: FULLY COMPOSITE PYLON, BACKFLASHOVER RATE, PSCAD, MONTE CARLO METHOD

Abstract

A proposal for a fully composite pylon has been designed to meet the requirements of compact structure and elegant appearance for new-generation 400 kV transmission towers, able to save lines corridors and reduce visual impact. Correspondingly, a method of external down-lead has been proposed to bring grounding potential to the shield wires. Based on this design, in this paper, lightning overvoltage level of the fully composite pylon is investigated by using transient simulation tools and backflashover performance is evaluated through Monte Carlo method. An equivalent distributed parameter model of the pylon is established, with the stray capacitances of phase conductors calculated in advance. Monte Carlo method is used to simulate the randomness of lightning current waveform in the nature. The overvoltage levels are simulated in PSCAD to determine the occurrence of backflashover. The backflashover rate (BFOR) is estimated by accumulate the probability of backflashover after repeated random sampling of lightning current. Simulating results show that the BFOR is 0.074 flashes/100 km-year and the overvoltage level calculated becomes lower in the modified model considering stray capacitances. Effects of both the lightning peak current and the tail time on the probability of backflashover occurrence is also summarized.

1. Introduction

In recent years, usage of overhead lines 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 metal lattice 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, which has the advantages of saving lines corridors and reducing visual impact[1]. The fully composite pylon is in the shape of a 'Y' geometric configuration, shown in Fig. 1. Conductors are fixed by clamps on the surface of the cross-arm which has an inclined angle of 30° from the horizontal ground plane, thus the conductors are in a diagonal form. Two shield wires are installed at the tips of the two cross-arms respectively. The cross-arms and the body are made of fibre reinforced plastic (FRP) so the pylon itself can not conduct lightning current anymore. Correspondingly, two bare-metal down conductors downwards outside the pylon are used to conduct the lightning current to ground when shield wires are terminated by lightning flashes, which are shown as red lines in Fig. 1.

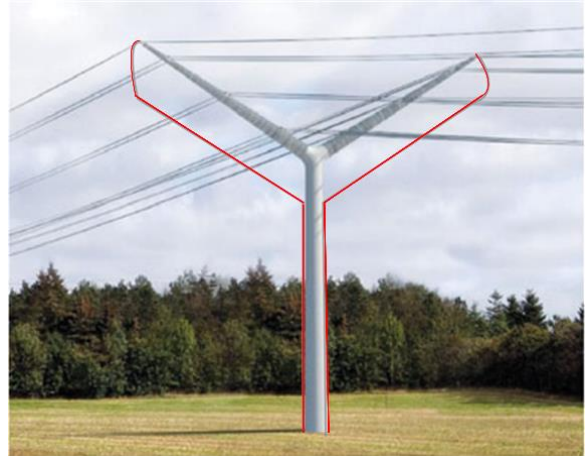


Fig. 1 The picture of the novel 400 kV fully composite pylon

The novel pylon has a more compact size and reduced height due to the elimination of insulator strings. However, there is little experience and research on the lightning performance evaluation about a pylon with such an unusual configuration and electric design. High voltage overhead lines are exposed to lightning strikes, which may cause flashover threatening the safe and steady operation of power grid[2]. If the flashover occurs when the lightning flash strikes directly on the phase conductors bypassing the shield wires, the rate of this condition per 100 km-years of the transmission line is termed the shield failure flashover rate (SFFOR). Direct lightning strikes to shield wires can increase the electric potential of the shield wires in a short time, which may also provoke a flashover between shield wires and conductors. The rate of this condition per 100 km-years of the transmission line is termed the backflashover rate (BFOR)[3].

The SFFOR of this pylon has been studied comprehensively in previous studies. The lightning shield performance of the pylon was investigated based on the electro-geometric model (EGM) and found that there existed an unprotected zone in the middle span of the pylon[4]. The lightning shield performance of the pylon was investigated furthermore based on the method of scale model test, it was proved that shield failure happened in the middle of pylon[5]. To optimize the lightning shield performance, two different shield angles, -60° and -70°, were investigated via both the electro-geometric model (EGM) and scale model tests. And -60° can provide better shield performance[6]. According to the above experience, the possibility of lightning shield failure was deeply investigated via both the revised electro-geometric model (EGM) and scale

model tests[7], and it was proved to be practically negligible. Operating experience showed that for the overhead lines over 500 kV, lightning strike accidents were majorly caused by the shield failure of lightning striking towers and shield wires. However, for the overhead lines below 500 kV, lightning strike accidents were majorly caused by the backflashover when lightning striking towers and shield wires [8]. Therefore, the research on BFOR of this 400 kV fully composite pylon is as significant as SFFOR.

The present paper uses the mathematical calculation function of Matlab and the electromagnetic transient analysis function of PSCAD to deal with the BFOR evaluation procedure based on Monte Carlo method. The Monte Carlo method is used to simulate the randomness of lightning current waveform in the nature in order to approach the probability of backflashover[9]. The procedure consists of three steps: pre-processing, numerical simulation and post-processing. In the first step, inverse transform sampling is used in Matlab to create a set of different lightning current waveshapes, with peak current and wave tail time as variables following log-normal distribution, to simulate the statistics of lightning flashes in the nature. In the second step, the OHL transmission system with the novel pylons is established in PSCAD and after inserting the lightning current set from Matlab, the overvoltage level of the certain points on the down-lead is calculated. In the third step, the backflashover is determined in Matlab according to the comparison of the overvoltage level and critical flashover voltage and the BFOR is estimated by the numerical results from the repeated random sampling[10].

2. Methodology

2.1. Transmission line modelling

2.1.1 Configuration of the pylon and wires coordination

The configuration of the fully composite pylon and coordinates of the phase conductors and shield wires are shown in Fig. 2, by setting the horizon as the x-axis and the symmetry axis of the pylon as the y-axis.

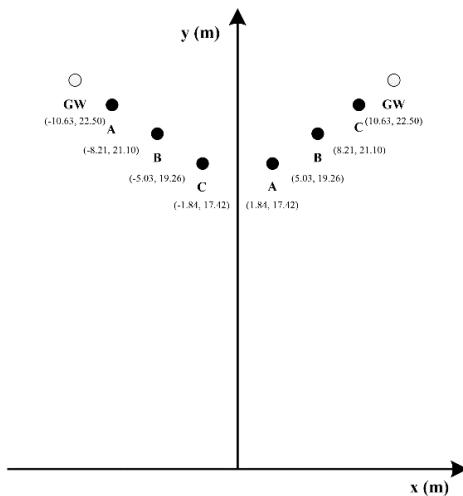


Fig. 2 The configuration of the fully composite pylon and coordinates of the phase conductors and shield wires

2.1.2 OHL Model

The simulated 400 kV/50 Hz double-circuit OHL is 100 km long. The pylon stroke by lightning flash is in the middle of the whole line and the neighbouring two pylons are modelled, the span between which is 250 m. The OHL is simulated in PSCAD by the means of 'Bergeron Model'. 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. Corona effect that influence the effective radius of OHL is not simulated for simplification reason.

2.1.3 Down-lead Model

Because the novel pylon body is made of composite materials, the external down-lead is the only path to conduct lightning current to ground. The down-leads can be and regarded as cylindrical bare conductors.

The down-leads can be modelled by a 'Bergeron Model' in PSCAD. The Bergeron Model is represented by a distributed inductance, capacitance and lumped resistance property to approximate system losses[11]. In this paper, one down-lead is divided into two parts, one is the vertical part along with the pylon body and the other is the approximately horizontal part along with the cross-arm, where the overvoltages need to be simulated. The former is modelled in PSCAD by the means of 'Bergeron Model'. Because the length of the latter is relatively short, it is modelled by several RLC-Pi-equivalent circuits so as to the distributed capacitance can be modelled more precisely by considering stray capacitances together[12]. The stray capacitances are calculated by the finite element analysis software COMSOL, the simplified model and results calculated are shown in Fig. 3. The physical model is simply one cross-arm with three phase conductors, one shield wire and an external down-lead surrounded by air. The colorbar shows the electric potential on the cross-arm

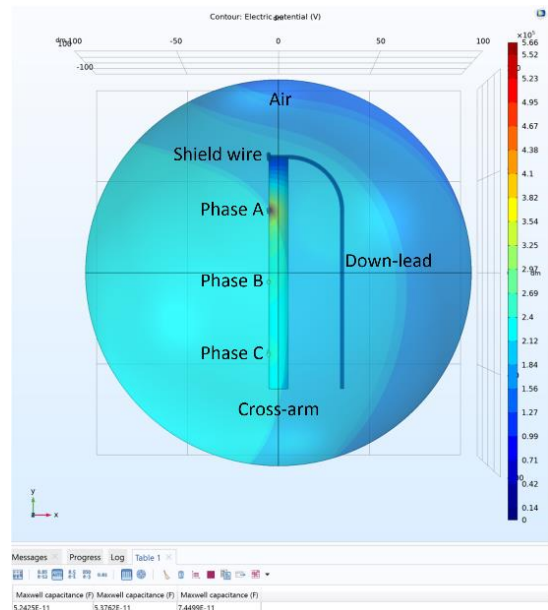


Fig. 3 The model and simulating results of stray capacitances in COMSOL

Given that the radius of the down-lead r is 8 mm, the resistivity ρ is $3.78 \times 10^{-8} \Omega \cdot m$ and the permeability is equal to μ_0 the permeability of vacuum, the resistance R and inductance L per unit can be calculated at power frequency. R is equal to $0.19 \Omega/km$ and L is equal to $0.047 mH/km$. A generic value of 50Ω is used to represent grounding resistance. The sketch of the down-lead model established in PSCAD is shown in Fig. 4.

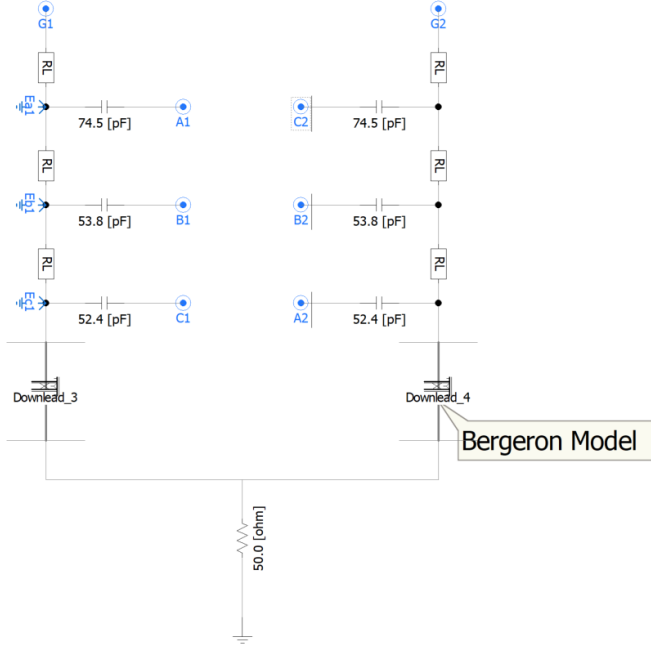


Fig. 4 The sketch of the down-lead model established in PSCAD

2.1.4 Lightning Model

A direct lightning that strikes to one of the shield wires connected to the grounding down-lead is modelled as an ideal current source in parallel with a resistance, which represents the lightning-channel surge impedance[13]. This value ranges from 400Ω to 1000Ω and here is set as 400Ω [14]. The waveform is selected as CIGRE type, which is a piecewise function shaped by four variables, namely the peak of the lightning current I_F , the maximum steepness S_m , the front time (from 30% to 90%) t_f , and the time to half t_h .

2.2. Procedure to estimate BFOR

A simple but approximate deterministic formulation is used to estimate the BFOR (the amount of backflashovers per 100 km lines per year), as shown in equation (1)[3],

$$BFOR = 0.6 \times N_d \times P(I_c) \quad [\text{flashes}/100 \text{ km} \cdot \text{year}] \quad (1)$$

where N_d is the estimated number of lightning strikes which terminate on the 100 km line, and $P(I_c)$ is the cumulative probability that a overvoltage caused by lightning current I equals or exceeds the critical flashover voltage level, which is defined as the voltage level where the probability of flashover occurrence is 50%. The numerical multiplicative coefficient 0.6 takes it into consideration that backflashovers within the span can be neglected whereas the voltages caused by the

strokes to shield wires along the span practically are lower than those to pylons[15].

2.2.1 Lightning incidences

Ground flash density N_g is used to describe the number of flashes which terminate on the ground per year per square kilometers. The estimated number of lightning strikes which terminate on the lines N_d can be calculated by N_g and shadow area using equation (2),

$$N_d = N_g \times A \quad [\text{flashes}/\text{km} \cdot \text{year}] \quad (2)$$

The red area shielded by the grounding wires shown in Fig. 5 is called shadow area, where if the lightning terminates within, it will be attracted to the lines. D is the horizontal distance between the grounding wires, H is the height of the pylon, and R is the protective radii which is related to H , as shown in equation (3)[16],

$$R = 14 \times H^{0.6} \quad [m] \quad (3)$$

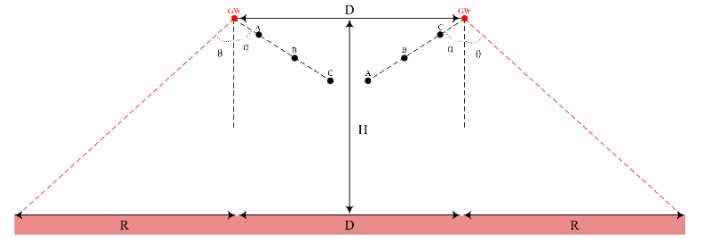


Fig. 5 The demonstration of shielding shadow area

Therefore, the estimated number of lightning strikes which terminate on a 100 km line can be changed into equation (4)[2],

$$N_d = N_g \times (D + 28 \times H^{0.6}) \times 10^{-1} [\text{flashes}/100 \text{ km} \cdot \text{year}] \quad (4)$$

2.2.2 Lightning current variables

Analytical expressions to simulate the lightning current waveshape of the first stroke of the downward flash are proposed and recommended CIGRE. Four variables are used to shape the lightning current wave, namely the peak of the lightning current I_F , the maximum steepness S_m , the front time (from 30% to 90%) t_f , and the time to half t_h . All the parameters yield to log-normal distribution. The statistical parameters median M and log standard deviation β of the variables are shown in Table 1[3].

Table 1 The median M and log standard deviation β of the lightning current parameters

Variable	M , median	β , log std. deviation
I_F (>20 kA, kA)	33.3	0.605
S_m (kA/ μs)	24.3	0.599
t_f (μs)	3.83	0.553
t_h (μs)	77.5	0.577

In this paper, the peak of the lightning current I_F and the time to half , or in another term, wave tail time t_h are treated as the

variables to shape the lightning current waveform. The front time t_f is equal to the median and the steepness can be determined by I_F and t_f .

2.2.3 Generating the lightning set

Because the probability distributions of the variables follow a log-normal distribution, several mathematical methods can be used to create a set of lightning flashes.

The function in Matlab 'lognrnd' can generate a group of random numbers when the median and log standard deviation of the log-normal distribution are known.

Inverse transform sampling (ITS) can be used when the cumulative distribution function $F(x)$ is known or can be derived by integrating the probability distribution function $f(x)$. Then the inverse function of $F(x)$, $F^{-1}(x)$ can be obtained. According, the random sampling of uniform distribution can be done easily by computer, if u is an element generated by uniform distribution, $x=F^{-1}(u)$ is a sampling element of $f(x)$. As a result, the sampling set of $f(x)$ can be generated from the sampling set of uniform distribution.

In this paper, ITS is adopted to generate the set of random numbers because the cumulative distribution function of log-normal distribution is known. Besides, acceptance-rejection sampling (ARS) and Markov chain-Monte Carlo sampling (MCMCS) can also be used, however they are of lower computational efficiency compared to ITS.

2.2.4 Lightning polarity and CFO

Given that 90% of the lightning flashes to ground are negative while other 10% are positive, the lightning current set is divided into two parts proportionally. For instance, the set size created in this study is 100000, thus 90000 of them are negative lightning flashes and 10000 are positive lightning flashes.

The critical flashover (CFO) is defined as the voltage level where there is 50% probability for flashover to occur, which is determined by the distance of a specific air gap and the environmental factors. Given the environmental condition is wet due to rain, the equations of the CFO under different lightning polarity are selected as follows[15],

$$CFO_{neg,wet} = 605 \times D_{flash} \quad [kV](5)$$

$$CFO_{pos,wet} = 560 \times D_{flash} \quad [kV](6)$$

where D_{flash} is the gap distance when flashover happens. The overvoltages simulated from positive and negative lightning currents need to be compared with corresponding CFO respectively.

2.2.5 Phase angle of the operating voltage

The phase angle of the three-phase system is assumed as a uniformly distributed variable between 0° and 360° . Compared with the period of operating voltage, the duration of overvoltage is very short. When calculating the difference

between overvoltage and operating voltage, the phase angle must be taken into consideration.

For a certain lightning current input, the occurrence of the backflashover depends on whether the difference of the overvoltage on the down-lead and the operating voltage exceed CFO. It can be transferred that the occurrence of the backflashover depends on whether the overvoltage exceed the sum of operating voltage and CFO. As shown in Fig. 6 to be specific, if the overvoltage is below the sum of CFO and minimum value of operating voltage, the backflashover won't occur, thus the probability of the backflashover equals to 0. If the overvoltage is below the sum of CFO and maximum value of operating voltage, the backflashover will definitely occur, thus the probability of the backflashover equals to 1. When the overvoltage is between the above two conditions, the occurrence of backflashover depends on the operating voltage at certain phase angle, thus the probability of backflashover can be estimated by the relation between the operating voltage amplitude and the phase angle, as shown in equation (7),

$$P(V_{over} - V_{phase} \geq CFO) = 1 - \frac{t}{T} \quad (7)$$

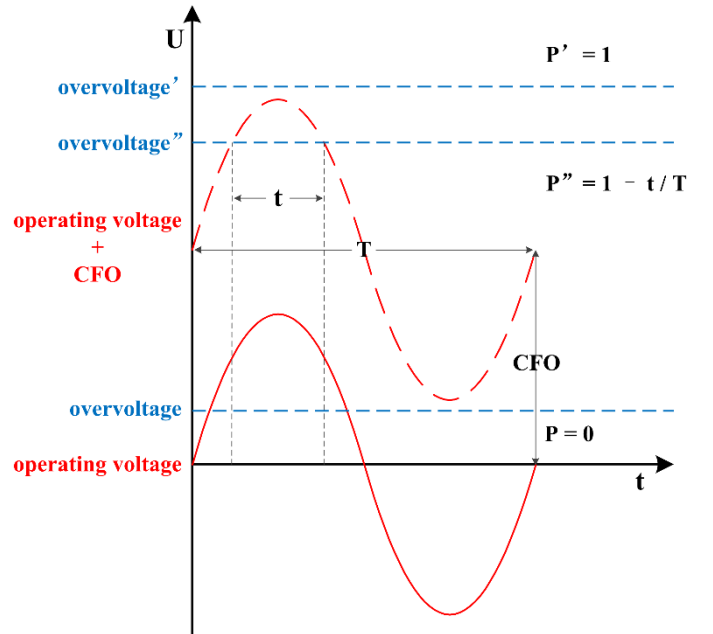


Fig. 6 The demonstration of calculating the backflashover probability under a certain overvoltage

For all the lightning currents input, given that the sample set size of lightning currents is large enough, the probability of backflashover can be estimated by the discrete statistical method. The probability of backflashover $P(I_c)$ is equal to the ratio of the cumulative probabilities of backflashover under every negative and positive lightning flash, which are calculated above among the total number of the lightning flashes input. Thus $P(I_c)$ can be equated as follows in equation (8),

$$P(I_c) = 0.5 \times \frac{0.9 \times \sum P(|V_o - V_{ph}| \geq CFO_n) + 0.1 \times \sum P(|V_o - V_{ph}| \geq CFO_p)}{N_{total}} \quad (8)$$

where V_o is overvoltage on the down-leads, V_{ph} is the operating voltage of the phase conductors, CFO_n and CFO_p are negative critical flashover voltage and positive critical flashover voltage respectively, and N_{total} is the total number of the lightning flashes input. The numerical multiplicative coefficient 0.5 represents the 50% probability for flashover to occur based on the definition of CFO.

3. Results

3.1. Outcome of the procedure

For the case under study, the parameters of the BFOR estimation can be specified or calculated.

The worst case of ground flash density N_g in Denmark was during 2001-2005, which was equal to 1.39 flashes/km²[2]. According to the configuration of the pylon, the height of the pylon H is 22.5 m and the horizontal distance between the grounding wires D is 21.28 m. Therefore, the estimated number of lightning strikes which terminate on the 100 km line N_d is equal to 27.5 flashes/100 km-year.

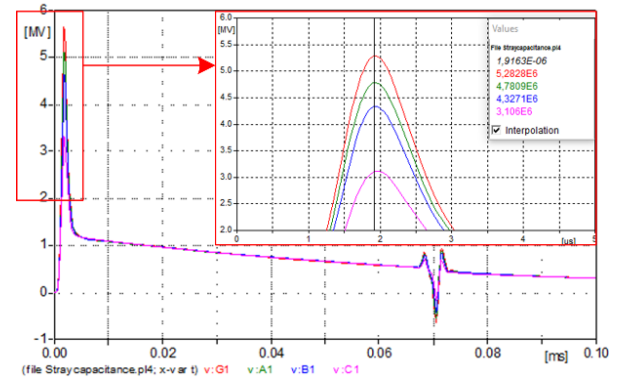
The set size of lightning peak current is 1000 and the set size of lightning wave tail time is 100, thus the total number N_{total} of the input lightning flashes is 100000. According to the simulating results, the number of negative lightning flashes that cause backflashover is 876.43 while the number of positive lightning flashes that cause backflashover is 1127.14 among 100000 flashes. Therefore, the cumulative probability that the overvoltage caused by lightning current equals or exceeds CFO, $P(I_c)$, is equal to 0.0045.

In summary, the BFOR of this case is 0.074 flashes/100 km-year. Referred to the '110 (66) kV-500 kV Overhead Transmission Line Operation Specifications' published by China State Grid in 2005[17], which regulated that the criterion of the BFOR of 220 kV OHL is 0.221 flashes/100 km-year, the BFOR of this case is rather lower than the criterion value.

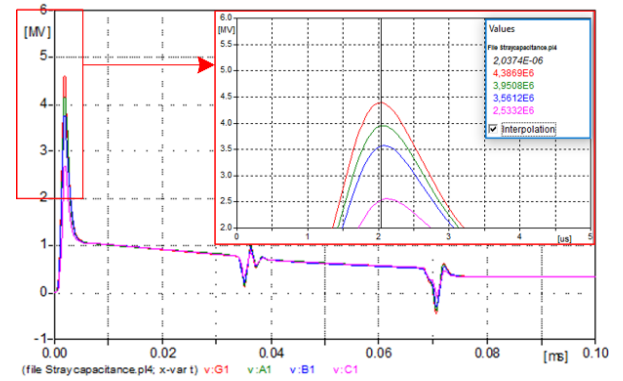
3.2. Effect of stray capacitances on overvoltage

Capacitors can provide the high-pass path for high frequency wave. Therefore, when the stray capacitances are taken into consideration and modelled in the transient analysis for the down-lead after lightning striking, the transient steep lightning current would be dispersed partially. Fig. 7 (a) shows the overvoltages on the down-lead without considering stray capacitances, whereas Fig. 7 (b) shows the overvoltages considering stray capacitances. It can be found that the

maximum magnitude of the overvoltage is by 24.28% lower when modelling stray capacitances.



(a)



(b)

Fig. 7 (a) The overvoltages on the down-lead modelled without stray capacitances (b) The overvoltages on the down-lead modelled with stray capacitances

3.3. Effect of lightning current parameters on backflashover

The random values of peak value and tail time of lightning current are sampled independently. In Fig. 8, the graph (a) shows the probability distribution function (PDF) in histogram of tail time of lightning current t_h and the graph (b) shows the PDF in histogram of peak value of lightning current I_f . The graph (c) in Fig. 8 shows the probability of backflashover under the lightning flashes with different peak values and tail times. Every point on the graph (c) in Fig. 8 represent one lightning waveform shaped by one combination of a peak current and a tail time and its colour represents the probability of backflashover occurrence when the shield wire is terminated by this lightning flash.

It can be seen that along with the increase of the peak value of the lightning current or the increase of the tail time, the probability of the backflashover increases because the overvoltage levels rises up. The curves of the critical probability of 0 and 1 can be plotted and shown as the long-dash red curve and short-dash red curve in graph (c) respectively. The relation between I_f and t_h to result in

backflashover can be fitted and described in rectangular hyperbolic functions as follows equation (9) and (10),

$$I_f = \frac{7229}{t_h} + 139.6 \quad [\text{kA}](9)$$

$$I_f = \frac{5141}{t_h} + 52.78 \quad [\text{kA}](10)$$

When the peak current and tail time of a lightning flash can be located beyond the short-dash curve, it can be determined that this lightning will result in backflashover. Conversely, if the peak current and tail time of a lightning flash can be located below the long-dash curve, it can be determined that this lightning will not result in backflashover. If the peak current and tail time of a lightning flash can be located between the two curves, the occurrence of backflashover depends on the phase angle of operating voltage at that time.

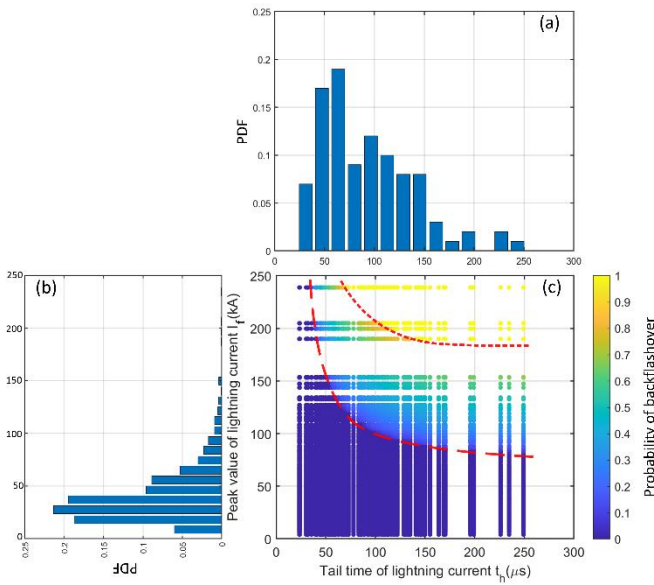


Fig. 8 (a) PDF of tail time of lightning current t_h (b) PDF of peak value of lightning current I_f (c) The probability of backflashover under the lightning flashes with different peak values and tail times

4. Conclusion

This paper investigates the backflashover performance of a novel fully composite pylon of 400 kV with external grounding down-leads. The transmission system model was established and the transient analysis was carried out in PSCAD. Monte Carlo method was used to simulate the randomness of lightning current waveform in the nature in order to estimate the backflashover rate. The following conclusions can be drawn:

- After Monte Carlo procedure, the BFOR of this case is estimated to 0.074 flashes/100 km-year, which is rather lower than the criterion in industrial standards.
- The stray capacitances were considered and calculated in the study, which will decrease the maximum magnitude of overvoltage when lightning striking compared with the case ignoring stray capacitances. Thus the modelling of

stray capacitances is recommended and necessary to accord with practical conditions.

- The relationship of both peak current and tail time to the probability of backflashover occurrence is summarized and described in equations. The threshold of the lightning waveform to result in backflashover is fitted which can be referred in the following research on lightning protection performance.

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