FAILURE RISK CALCULATION OF LIGHTNING OVER-VOLTAGES ON HIGH VOLTAGE OVERHEAD LINES USING EMTP AND MATLAB

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Abstract: In order to have a proper insulation-coordination, it is necessary to investigate lightning over-voltages and their damage risk for installed equipments. An algorithm to simulate stroke effects of all possible lightning with different parameters and to drive the stroke probability of a critical lightning is presented in this work. In one hand, the destruction ability of a lightning depends on its power, crest value, and shape which have to be taken into account to improve the accuracy of investigations. On the other hand, the different points of strokes (to the tower, earth wire, or phase wire) produce different overvoltage shapes. The total failure risk of an overhead line is divided here to the failure risk of strokes to the phase wire and the failure risk of strokes to the earth wire (and the probability of back-flashovers). As an important part of this work, a back-flash over model is implemented in the simulations. EMTP is used for simulations of direct strokes against the overhead phase and earth (for back-flashovers) wires. The parameter calculations of different lightning impulses are done in MATLAB. A useful tool to link EMTP und MATLAB is designed and presented as well. Based on the calculated probability, the position and type of protecting measures (e.g. earth wires and arresters) can be chosen.

1 INTRODUCTION

Lightning strokes are one of the most critical stresses for power systems and can produce usually very high over-voltages. Because the insulation cannot usually withstand them, all the power system elements have to be protected against lightning over-voltages. The protection includes the design of primary (e.g. earth wires) and secondary (e.g. surge arresters and protective spark gaps) protection systems and there are already a lot of methods to design and exploit such protection systems [1-3].

In order to calculate and design the protection system, the IEEE Std 1313.2-1999 [2] suggests using the critical flash over, BIL, which is a reference voltage for insulation breakdown voltage. The critical current crest value, I_c, can be approximately calculated as follows:

$$I_c = \frac{2\,BIL}{Z_w}, \qquad (1)$$

where Z_w is the OHL surge impedance.

In the design phase, the shape and the steepness of the current impulse has to be ignored because the design phase necessitates simplification. After specifying the position and property of protection devices, it still have to be calculated, whether the designed system is able to protect the system against all possible lightning with the different shapes and crest values. The reason is, that *BIL*, as also mentioned in IEEE Std 1313.2-1999 [2], is dependent of the shape of current impulse.

The failure possibilities are all lightning strokes with the specific parameters, against which the designed protection devices are not able to protect the system. The parameters of these lightning strokes can include the shape, crest value, and energy of the current impulse as well as the corresponding attractive area and probability of a stroke on the relative attractive area.

Finally, the failure risk or the stroke probability of all critical impulse forms has to be calculated. It is the sum of probabilities of each lightning stroke, whose current can produce an over-voltage greater than BIL. By comparing the desired level of failure risk with the calculated failure risk of currently designed system, an approval or a better suggestion has to be made.

In the present work, a MATLAB-EMTP link tool is presented. At the first step, the electrical system including the over-voltage protection devices has to be modelled in EMTP. The possible stroke points as well as the parameters of possible lightning strokes must be defined. At the second step, with the aid of the designed MATLAB-EMTP link tool, several simulation will be carried out, whose source parameters are automatically selected from the group of possible lightning strokes. At the last step, the simulation results must be analyzed and regarding the probability function of lightning strokes, the total failure risk has to be calculated.

This work is organized as follows: after this brief introduction, the designed tool is presented in the second section. An algorithm to simulate several lightning strokes in EMTP and to calculate the failure risk is described here. In the third section, as an example, a 220/110 kV transformer substation is chosen and modelled. A model of back-flashover is implemented as well. The failure risk is calculated for this substation and the simulation results are analyzed. The last chapter as a conclusion summarizes the research results.

2 BORDERLINE CALCULATION IN THE CURRENT-STEEPNESS

EMTP is one of the most powerful programs worldwide for the transient investigation in power systems. The MATLAB is also well-known for its several mathematical calculation abilities. In order to use both of them, a link tool is designed, which makes it possible to calculate the necessary parameters in MATLAB and then simulate the model with the calculated parameters in EMTP. It can also be automatized in order to simulate a series of scenarios and to summarize all simulation results.

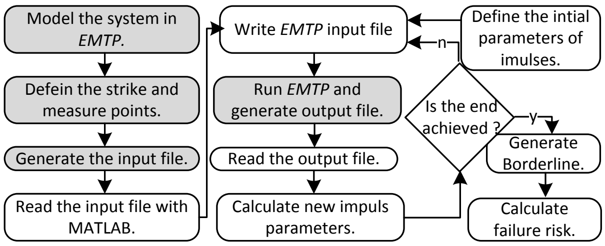

Figure 1: MATLAB-EMTP Link.

Figure 1 presents an overview of the necessary steps. The steps with the gray background will be done with EMTP and the rest with MATLAB.

With the aid of MATLAB-EMTP-link tool, it is now possible to simulate the over-voltages of all possible lightning strokes in an automated way. In each simulation, it must be recognized, whether the over-voltages exceed the station BIL. In other words, this lightning parameters plane can be divided into critical and uncritical zones. Figure 4 shows the borderline of these zones. It is interpolated from a series of EMTP simulations whose pathway are shown in the same figure (This figure will be discussed in more details later.). A lightning with the current crest value and maximum steepness properties from the upper zone produces an over-voltage greater than the BIL of substation and vice versa.

In order to carry out this borderline, the following steps are necessary to be done:

2.1 Definition of the Possible Lightning Strokes and Probability

In order to calculate the total failure probability, the lightning parameters and their probability functions must be known. There are a lot of studies which deal with the calculation of the probability function of lightning parameters. As Anderson and Eriksson [5], as well as Berger et al. [6] have already shown, the lightning stroke parameters for downward strokes are considered to be approximated by a log-normal distribution.

The joint probability density function of two stroke parameters x and y (e.g. crest value and maximum steepness), can be expressed as follows [7]:

$$p(x,y) = \frac{1}{2\pi\, x\, y\, \sigma_{\ln x}\, \sigma_{\ln y} \sqrt{1-\rho^2}}\, e^{-\frac{1}{2}\left[\frac{f_1 - f_2 + f_3}{1-\rho^2}\right]^2}, \qquad (2)$$

where, from now, the variable x and y are used for the current crest value, I_{max}, and the maximum steepness, S_{max}, of a stroke, respectively, p(x,y) is the probability density function, ρ is the correlation coefficient, $\sigma_{\ln x}$ is the logarithmic standard deviation of variable x, and:

$$f_1 = \left(\frac{\ln \frac{x}{x_m}}{\sigma_{\ln x}}\right)^2,\quad f_2 = 2\rho\left(\frac{\ln \frac{x}{x_m}}{\sigma_{\ln x}}\right)\left(\frac{\ln \frac{y}{y_m}}{\sigma_{\ln y}}\right)^2,\quad f_3 = \left(\frac{\ln \frac{y}{y_m}}{\sigma_{\ln y}}\right)^2.$$

It must be noticed here that the probability function given in (2) considers a stroke on a unit of area and in order to calculate the effective probability function (e.g. for an OHL), the attractive area (see Figure 2) of a stroke must be multiplied to the probability functions:

$$q(x,y) = p(x,y) \cdot \ell \cdot w(x) \qquad (3)$$

where l and w(x) are the length and width of a stroke attractive area above the OHL for earth or phase wires and q(x,y) is the effective probability.

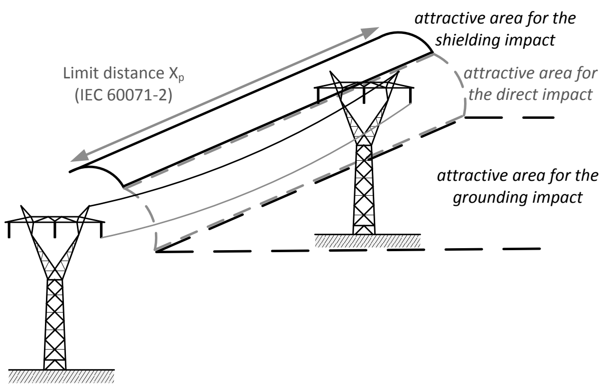

Figure 2: Attractive area for direct and shielding strokes.

Because of damping effects of OHLs, l is extremely dependent on the OHL structure, current crest value, and maximum steepness, whereas IEC 60071-2:1996 [1] defines it as a constant value, X_d (see Fig. 3). To solve this problem, several stroke points and an accurate model of OHL are used in the present work.

The IEEE Std 1243-1997 [8] defines w(x) as the exposure distance for a shielding failure (a direct stroke), D_C. It will decrease if the current crest value increases. The higher current crest values will be absorbed from earth wires and will be no longer critical (usually above 20 kA). In the contrary, the low lightning currents cannot lead to back-flashovers. Whereas, the width of attractive area for earth wire(s) becomes more important if the current crest value increases.

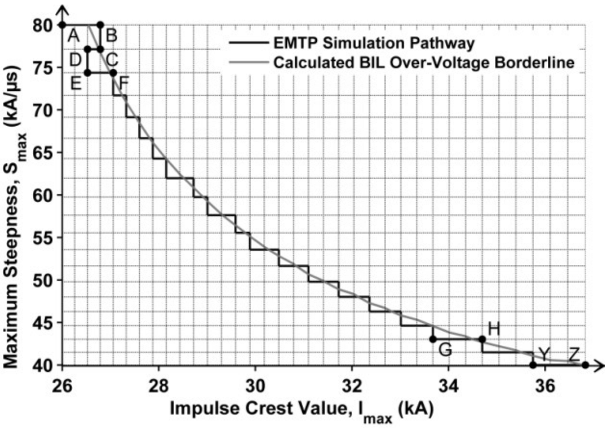

Figure 3: Borderline of critical and uncritical zones in plane of lightning parameters.

Figure 3 shows an example of the plane in the range of 40 to 80 (kA/µs) and 26 to 37 (kA). All the cross sections between the horizontal and vertical dashed lines present a member of the discretized lightning parameters.

2.2 Initial Definition of the Source Parameters

The simulation can begin with a lightning which has the maximal possible steepness and the minimum possible crest value (the left-upper corner in the current-steepness plane of lightning parameters, defined as point A in Figure 3).

From the position of this point, the I_{max}, T_f , and S_{max} of Cigre impulse can be derivated. But T_h is more dependent of the lightning charge. Theoretically, it has the same probability function as maximum steepness and crest value. Based on the experience, it is decided in the present work to take only the greatest possible charge in calculations, instead of simulating all possible values.

A considerable difference cannot be seen in final results if all possible charges are simulated.

2.3 Parameter Calculation for the Next Simulation

The iteration begins with the simulation from point A in Figure 3. In each step MATLAB increases the lightning crest value to the value of next point in the discretized plane until the resulted over-voltage exceeds the reference BIL. This point has been reached at the third iteration and shown as point B in Figure 3. The same is occurred from point E to F. In the contrary, if the earlier point locates in the left side of the borderline, which means that the resulted over-voltages is greater than the reference BIL, MATLAB decreases the lightning crest value in the next step and finally reaches the right side of the borderline. An example can be seen from point C to D. In other words, MATLAB tries to find the cross-over point of the simulated over-voltages with the reference BIL in each level of maximum steepness shown by the horizontal dashed lines. After finding this point, MATLAB decreases the maximum steepness. Such a steepness change can be seen from point B to C or from D to E.

2.4 Borderline Interpolation

The iteration described in previous section takes place until reaching the lowest possible S_{max} or the greatest possible I_{max} which are shown by point Y and Z. EMTP simulations can be now stopped and the borderline can be interpolated from all edges of the simulation pathway A to Z.

2.5 Failure Risk Calculation

The probability integral of all lightning in the upper zone of the borderline is the failure risk and can be calculated by (3).

$$Failure\,Risk = N_g \iint_D q(x,y)\; dx\, dy = N_g \sum_{(x,y)\in D} q(x,y) \qquad (4)$$

where D is the critical zone above the borderline in Figure 3 and N_g is the ground flash density (GFD).

3 SIMULATION RESULTS

A 220/110 kV transformer substation is chosen as a case study. A general view of the substation model used to calculate direct stroke as well as back-flashover over-voltages is shown in Figure 4. An over-voltage measuring point at the transformer high voltage terminal is demonstrated as well. The transformer BIL of the transformer primary side is assumed to be 650 kV.

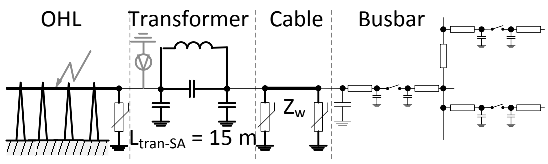

Figure 4: Transformer substation.

The OHL wave parameters are calculated based on the geometrical data shown in Figure 5. The OHL-model used in simulations is shown in Figure 6. Jmarti-Model [9] is used to represent the behaviour of OHL segments. The OHL length is 4 km, and for each tower, a unit of back-flashover is applied between the earth wire and phases. The method suggested in the Cigre-Guide [10] and [11] is used to estimate the velocity of the streamer after each lightning stroke in time.

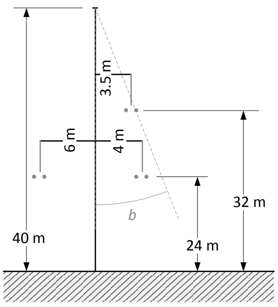

Figure 5: Tower schema.

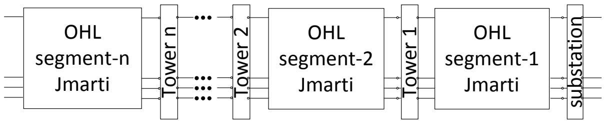

Figure 6: OHL Model.

Figure 7 shows the tower and phase voltages as well as the streamer development of a 330 kV-OHL. As shown in this figure, the spark gap breakdown has been happened after approx. 6µs. At this moment, the streamer length has achieved the insulator length 4.5 m.

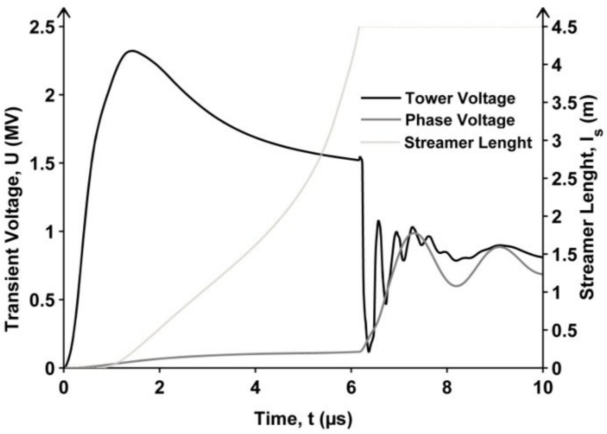

Figure 7: Back-flashover simulation results.

The suggested method has been applied to the substation and the over-voltages of different strokes have been simulated. The resulted borderlines of 650 kV for direct strokes against a phase wire in the distances of 0, 1, 2, and 3 km from transformer are shown in Figure 8. As expected, the over-voltages after direct strokes in front of the transformer have the greater risky zone than those from the strokes which are far from the transformer. Because of damping effects of OHLs, the over-voltages become smaller till arriving to the transformer terminals. The impulses with lower steepness than approx. 10 kA/µs will be damped from arrester regardless of their current crest value. For each point of impact, there is a minimum current crest value which leads to over-voltages greater than 650 kV. As it can been seen in Figure 8, the minimum current crest value is approx. 6 kA for the impacts in front of the transformer and 7 kA for those in 3 km away in OHL. As, these two facts make the probability calculation possible without the necessity of the calculation of over-voltages below these margins.

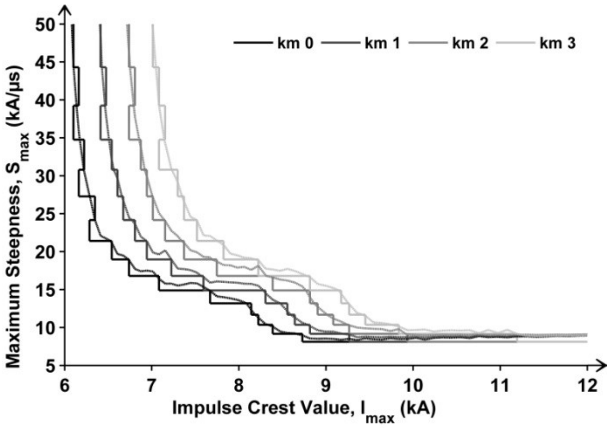

Figure 8: Simulation results of direct strokes.

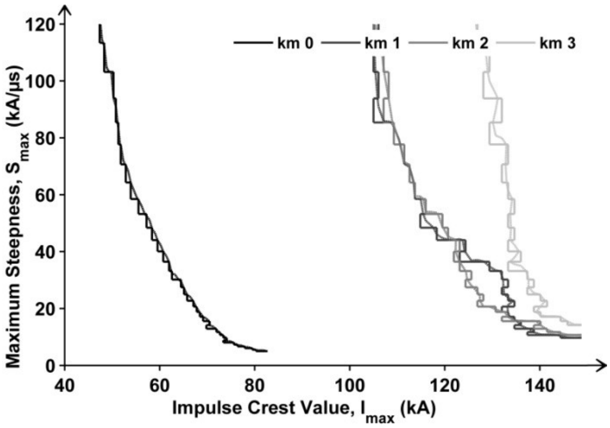

Figure 9: Simulation results of Back-flashovers.

In the current study, the corona effects are not taken into account because they are not the main purpose of this study. They can be considered with the steepness damping effects per unit length. Figure 9 shows the simulation results of back-flashovers after lightning strokes at the same distances of OHL. In comparison with the direct flashovers, back-flashovers have smaller risky zone. The lower margin of current crest value is here about 45 kA (very greater than 6 kA for direct impact to the phases).

Figures 11 and 12 show the risky zones of Flashover and Back-flashover as well as the relative width of stroke attractive area (see Figure 2). Considering that the lightning impulses greater than 19 kA will be absorbed by the OHL earth wire (calculated from the tower structure shown in Figure 5), the failure risk can be calculated as described in (3) and (4). The results are summarized in Table 1.

Based on the calculated failure risks, the position and type of protecting measures (e.g. earth wires and arresters) can be determined. Usually, the value of one failure per three hundred years can be accepted. If the calculated failure risk is not below the acceptable margin, the protection system must be improved.

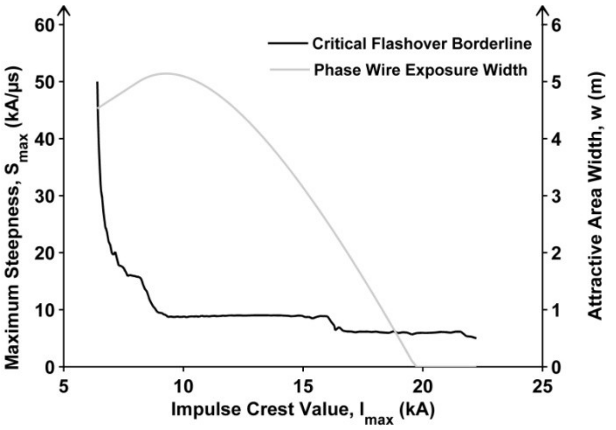

Figure 10: Risky zone and attractive area of direct strokes.

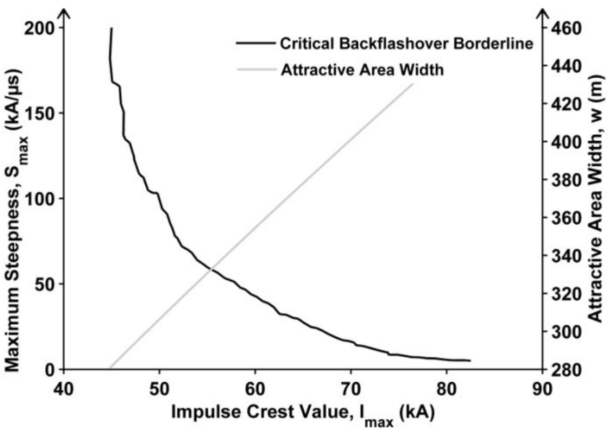

Figure 11: Risky zone and attractive area of Back-flashovers.

Table 1: Summary of Failure Risk Calculations

	Minimum I_{max}	*Minimum S_{max}*	*Failure Risk*
Direct strokes	6.0kA	8.9kA/µs	$\frac{1}{1095}\frac{\text{Failures}}{\text{year}}$
Back-flashovers	45kA	5.3kA/µs	$\frac{1}{210}\frac{\text{Failures}}{\text{year}}$

4 CONCLUSIONS

In this paper, a MATLAB-EMTP tool has been used for a series of network simulations and calculations of over-voltages in power systems after lightning strokes. The lightning properties have been changed in each simulation in order to define the critical lightning properties. Based on the probabilistic data of lightning parameters, the occurrence probability of the critical lightning strokes has been calculated. The protection system, which was designed only upon standard over-voltage shapes, can be finally tested against a variety of lightning shapes.

5 ACKNOWLEDGMENTS

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