Implementation of ATP/EMTP for statistical calculations of lightning processes in cable lines

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Abstract *– The majority of cable lines of voltage classes 6-500 kV are laid underground and for this reason are not subject to direct lightning discharges and their consequences. Perhaps this explains the traditionally weak interest in lightning processes in cable networks, both on the part of experts on overvoltage and on the part of specialists on cables. However, the situation is changing as more and more so-called mixed lines appear, having both cable (underground) and overhead sections (on towers). It is obvious that lightning processes in cable sections with direct connection to overhead ones require mandatory study, but it cannot be said that convenient calculation tools are available for this.*

The article offers a solution to the problem of analyzing lightning processes in cable lines (in any types of lines and switchgear) using ATP/EMTP, which has been supplemented with a number of modules that allow statistical calculations of processes and their processing. The proposed approaches are demonstrated using examples of calculating several 110 kV cable lines, where the probability of damage to the cable termination is calculated (depending on the length of the cable section), as well as the probability of damage to the cable joint at the screen cross-bonding node (depending on the type and length of the bonding cables).

Keywords: cable line, lightning processes, statistical calculation, surge protection, surge arrester, screens' cross-bonding, bonding cable, sheath voltage limiter.

1. Introduction

Lightning discharges to overhead power lines are the main source of lightning processes in high-voltage 6-500 kV networks. Therefore, lightning processes in a cable line are possible, first of all, when it is connected to an overhead line – by a transition point (Figure 1), or through busbars of the switchgear of the electric station or substation. The most dangerous processes are possible mainly in cases of direct connection of a cable line to an overhead line – and there are more and more such cases all over the world. For example, it is necessary to talk about the direct connection of cable lines to overhead lines when a cable line (cable section) is used:

- to connect an overhead line to a switchgear, in particular, to a gas-insulated switchgear (so-called cable inputs);
- for crossing obstacles, such as water barriers or populated areas (so-called cable inserts);
- for powering consumers located along the overhead line (so-called cable branches).

In all these cases, it is necessary to analyze lightning processes in cable lines and draw conclusions about the degree of their danger to cables and couplings, as well as suggest ways to protect cables from lightning surges. For example, the following questions require analysis:

- is it always necessary to install surge arresters at transition points (these surge arresters are missing on the left photo of Figure 1, and installed on the right photo);
- is it necessary to install surge arresters at the end of the cable line, which is opposite to the transition point;
- what is the permissible grounding impedance of the towers of transition points;
- what are the consequences of abandoning the lightning shield wire in the sections of the overhead line adjacent to the transition point and underground cable;
- how many spans of the overhead line should be protected by a shield wire (wires) in order to better protect the connected cables from lightning processes.

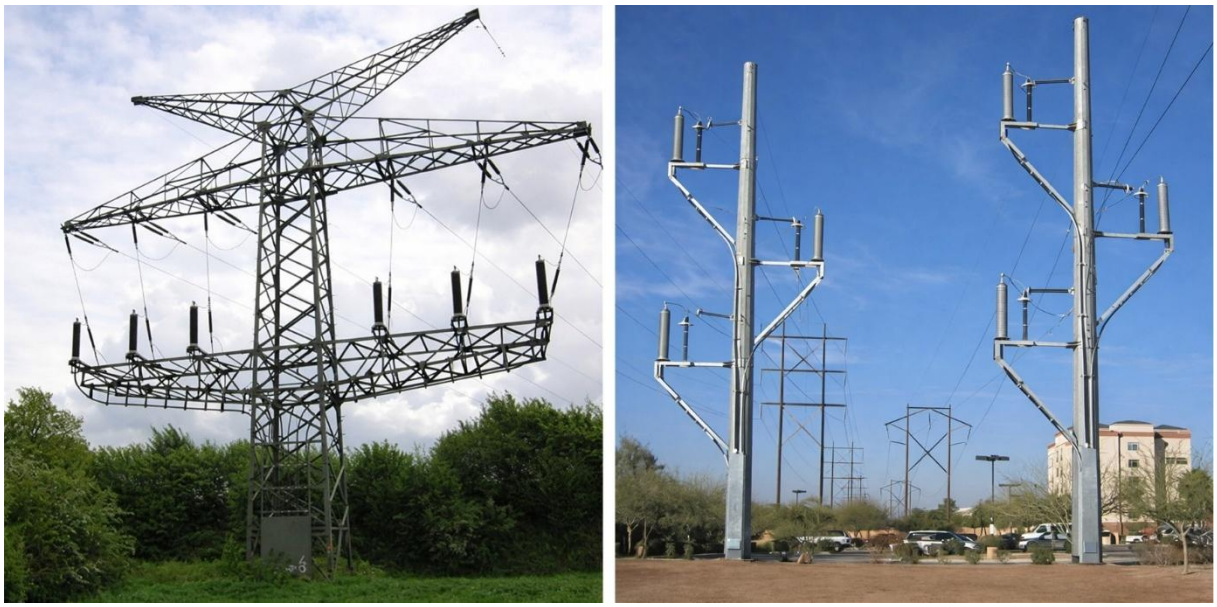


Figure 1 – Transition point between overhead line and cable line:
left – on lattice tower; right – on multifaceted pole.

It is important to note that modern cables with solid insulation (XLPE, EPR, PP), as a rule, have not only an insulated conductor (core), but also metallic (Cu or Al) screens [1-3] (with one or another bonding/grounding type [4]) coated with a dielectric sheath, which leads to the need to study the effects of lightning surges not only on the main insulation, but also on the dielectric outer sheath. Therefore, the following additional problems have to be solved [4]:

- selection of sufficient energy absorption capability of the sheath voltage limiters (SVL) installed between the screen and the ground to protect the cable sheath (SVLs are needed if the screens have single-point bonding/grounding or cross-bonding);
- if single-point bonding/grounding is used, select the end of the line at which it is more advantageous to ground the screens in order to reduce overvoltage levels on the sheath;
- selection of the permissible length of bonding cables laid between the cable joint and the SVL, as well as between the SVL and the grounding contour;
- selection of the type of bonding cables in the screen cross-bonding nodes (one coaxial for each cable joint or a pair of two single-core cables per joint, as shown in Figure 2);
- justification of the optimal grounding impedance at the cross-bonding nodes.



Figure 2 – Node of screen cross-bonding of singe-core cables:
left – cable joints with bonding cables; right – link-boxes with bonding cables.

The above list of problems related to main insulation and sheath is by no means complete, but it is already impressive in its size and the seriousness of the tasks that need to be solved. Unfortunately, it is not possible to give correct answers to the questions posed (even to the simplest of them) using some formula or, in computer models, by setting lightning currents with specific parameters. These processes cannot be correctly considered within the framework of the "deterministic method", but require statistical calculations, because the main parameters of lightning (magnitude of the impulse, its front and duration, number of components and the charge carried by them) are occasional and described by certain distribution laws.

Realizing the necessity and importance of statistical calculations of lightning processes in cables, we have to admit that there are practically no proven recognized tools in the world for carrying out such calculations and processing their results. Moreover, it cannot be said that they are in sufficient quantity even for overhead lines, where the analysis of lightning processes is a primary task. In particular, some of the programs available on the market for calculating the number of overhead line outages and selecting protective surge arresters (with or without a spark gap), let us be honest, do not inspire much confidence – it is so due to their closed algorithm, small number of developers and limited number of users, which increases the risks of developer errors and the fact that these errors haven't been detected by users.

If we develop tools for calculating lightning processes, it seems reasonable to try to do this on the basis of the ATP/EMTP software, because it has a long history, known algorithms, user communities, and conferences. From the point of view of calculating lightning processes, the problem of ATP/EMTP lies mainly in the fact that its developers did not provide for the possibility of such calculations for lightning processes, but focused only on switching (with the help of so-called "Statistical Switch"). Therefore, for example, almost all published studies of lightning processes in ATP/EMTP come down to the fact that their authors set lightning strike by certain specific parameters. However, such a deterministic approach does not always allow us to see the true picture that would be visible as a result of calculations that take into account statistical nature. We will show how ATP/EMTP can be used to calculate statistical lightning processes, and, in particular, such processes in cable lines connected to overhead lines [5].

2. ATP/EMTP model

If we talk about a mixed cable-overhead line having both cable and overhead sections, then the general model for calculating lightning processes (of any kind, not only statistical) should usually include at least the following separate sub-models described in [5]:

- overhead line with phase wires and shield wire/wires (if provided), divided into separate spans (usually 200-400 m long);
- towers (supports, pylons, poles) included between these spans;
- grounding contours of the towers;
- strings of line insulators connecting the phase wires to the towers;
- surge arresters (if any);
- cable line, taking into account the bonding/grounding of the screens and the presence of SVLs in the screens connected by bonding cables;
- lightning with the possibility of varying the point of a strike to the overhead line (tower, shield wire, phase wire) and lightning current main parameters (setting manually by the user or automatically in the case of statistical calculations).

There are dozens of publications around the world on how to model certain elements from the above list, but within the framework of this article we would not like to enter into discussions about the advantages/disadvantages of known models, because the main purpose of this article is to show the possibility of adapting ATP/EMTP software for statistical calculations of lightning processes. Although in ATP/EMTP we could use any models of circuit elements, however, for specifics we will list those that were used as part of the calculation examples and which, in our opinion, are quite simple and convenient to repeat:

- the lines were modeled taking into account the frequency dependencies of the main parameters, as well as taking into account the impulse corona on the wires [6] (the corona was taken into account by connecting additional "dynamic" capacitances that depend on the applied voltage and were created by the "Model's language");
- towers (poles and crossarms) were modeled by lumped inductances determined on the basis of linear inductance (for example, for a concrete tower of the type Figure 3, linear inductance was assumed at the rate of 1 μH/m);
- insulation strings were modeled by the volt-second characteristic [7] (the dependence of the breakdown voltage on the time of voltage application, by "Model's language");
- the grounding circuits of the towers were modeled by one or another active impedance, without taking into account the inductance;
- surge arresters were modeled by a nonlinear voltage characteristic (for 110 kV examples, the residual voltage on the 8/20 μs current impulse form with a magnitude of 10 kA was assumed to be 250 kV for the surge arrester, and 23 kV for the SVL);
- lightning was modeled by a current impulse with zero initial derivative [8], with varying magnitude, front duration, and conditional impulse duration; the surge impedance of the lightning channel was also taken into account.

Figure 3 shows an example of a single-circuit intermediate reinforced concrete tower with its dimensions. Figure 4 shows a model of an overhead line on such towers, at the end of which a 500 m cable input section is connected (the line circuit breaker is disconnected and replaced with a capacitance of 500 pF), and lightning strikes the top of Tower 2. Note that in order to be able to vary the location of the lightning strike to the shield wire, as well as to evenly account for the influence of the impulse corona on the waves moving along the phase wires of the line, each span of the line (300 m) is divided into two sections of equal length (2x150 m).

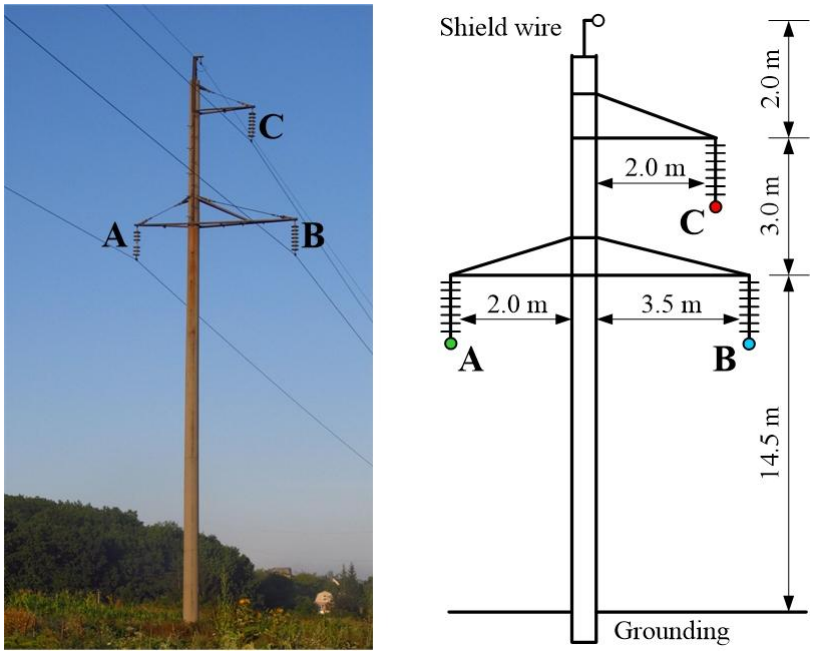


Figure 3 – Concrete tower of 110 kV single-circuit overhead line with a single shield wire.

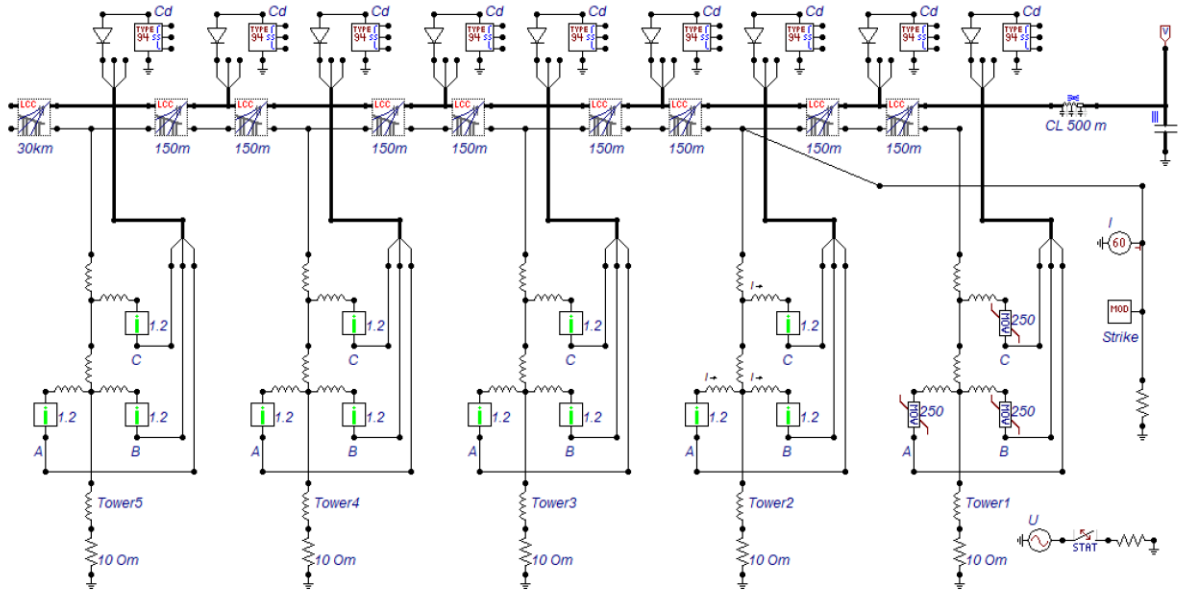


Figure 4 – Example of ATP/EMTP circuit for statistical calculations of lightning processes.

3. ATP/EMTP for statistical calculations

Let us focus on the most interesting thing – how exactly is it possible, by specifying the location of the lightning strike to the line, to configure the possibility of statistical calculations in ATP/EMTP. To do this, we had to take the following steps [5]:

- create a current source, the parameters of which are randomly determined each time the ATP/EMTP is started, using a block written in the "Model's language", based on statistical lightning data embedded there by the user;
- provide the ability to run ATP/EMTP automatically multiple times, for which we had to "cheat" ATP/EMTP and add a Statistical Switch to the model; such a Statistical Switch is shown in Figure 4 at the bottom right and was originally conceived by ATP/EMTP developers as an element for analyzing switching processes, but we use it for lightning, where the properties of this Statistical Switch turned out to be useful to provide automatic start of ATP/EMTP calculation as many times as the user has set;
- create an additional tool (Figure 5) that opens the *.LIS file of the calculation results of ATP/EMTP, finds in its text all peak values (there are as many as the number of times ATP/EMTP was run with the Statistical Switch), sort them from minimum to maximum and then export this data to MS Excel for later their analysis (MS Excel is necessary because it has excellent opportunities to work with data arrays and graphs).

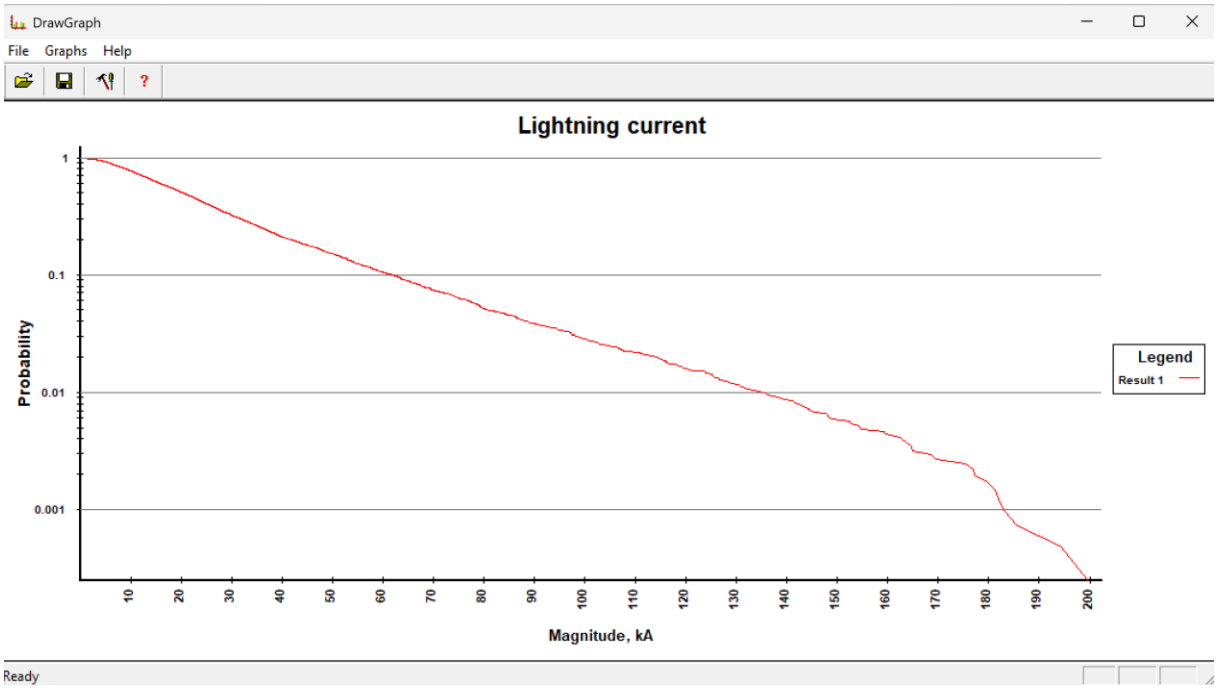


Figure 5 – "DrawGraph" tool developed to read and analyze *.LIS files. As an example, for the case of lightning strike to the shield wire, the distribution of lightning current is shown.

For example, calculation in ATP/EMTP of a sequence of 5 000 strikes (corresponds to a minimum probability of 1/5000=0.0002), depending on the calculation step and the simulation time, may take from 5 to 20 minutes (on a computer with an Intel Core i7 processor). As a result of calculation in ATP/EMTP, subsequent processing of the results in DrawGraph and export to

MS Excel, graphs are obtained that show the dependence of the probability of occurrence of a particular value (voltage, current, energy, charge). Rather, we are talking about graphs that show the probability that the value of interest will exceed the value that is plotted along the axis of the abscissa. Therefore, using such graphs, the probability of exceeding the permissible level is clearly visible (for example, the voltage of the value that is acceptable for insulation).

In addition to a statistical enumeration of possible lightning parameters, if desired, it was also possible to add to ATP/EMTP the ability to automatically select the location of a lightning strike. However, we did not do this, and the place of the lightning strike was set manually – in one or another tower, shield wire, phase wire. That is, user chose a location, made calculations (say 10 000 strikes), then processed the results in MS Excel (obtained the probabilities) and moved on to the next lightning strike location, and did the calculations again.

As an example, Figure 5 shows how the DrawGraph tool found in a *.LIS file all the data on the magnitude of the lightning current, sorted them and plotted them on a single graph, which can then be exported to MS Excel for further processing. Note that the lightning was assumed to have a negative polarity (important for impulse corona issues). Figure 5 shows that the highest current was 200 kA, and the 50% current was about 20 kA – these are the NIIPT's statistics [5] used in the countries of the former USSR. If desired, user can set any other data (with the help of the "Strike" block in Figure 4). For example, it is important to do this in the case of calculating processes for lightning breaks to phase wires, where the values of the current are usually several times lower than when striking towers and shields (later in the article, when lightning strikes to the upper phase wire, it was assumed that the 50% current amplitude was 5 kA, and the maximum possible value was 50 kA).

Figure 6 shows an MS Excel graph of impulse currents in crossarms A, B, C of Tower 2, which was struck by lightning. It can be seen, for example, that the current in the crossarm of the upper phase C appears with a probability of 0.02 – that is, once out of 50 lightning discharges. This value 0.02 is the probability of a back flashover of the line insulation when lightning strikes the tower. The value 0.02 is obtained when the grounding impedance of the towers is 10 Ω, and with increasing impedance, this probability, of course, will also increase. Knowing the number of lightning strikes to line per year of operation, it is possible to estimate how many line outages the probability of 0.02 will correspond to.

Interestingly, the probability for the upper phase C is higher than for the lower A and B. In addition, it is in the upper phase that lightning breaks through the protective shield are most likely. Therefore, next, providing the tower grounding impedance of 10 Ω, we will focus on the upper phase C as the most problematic, and it is for this phase that Figure 4 shows the "Cd" models that take into account the dynamic change in wire capacitance due to the presence of an impulse corona at the negative voltage polarity (taking into account the corona makes it possible to better take into account the deformation of the wave as it propagates along overhead line).

Next, let us give two examples of ATP/EMTP statistical calculations of cable lines:

1) calculation of the processes at the input section of the overhead line to the switchgear (let us have a circuit breaker of the line in switchgear to be switched off);
2) calculation of the processes in the screen cross-bonding node and selection of a limiting length of the bonding cable, depending on its type.

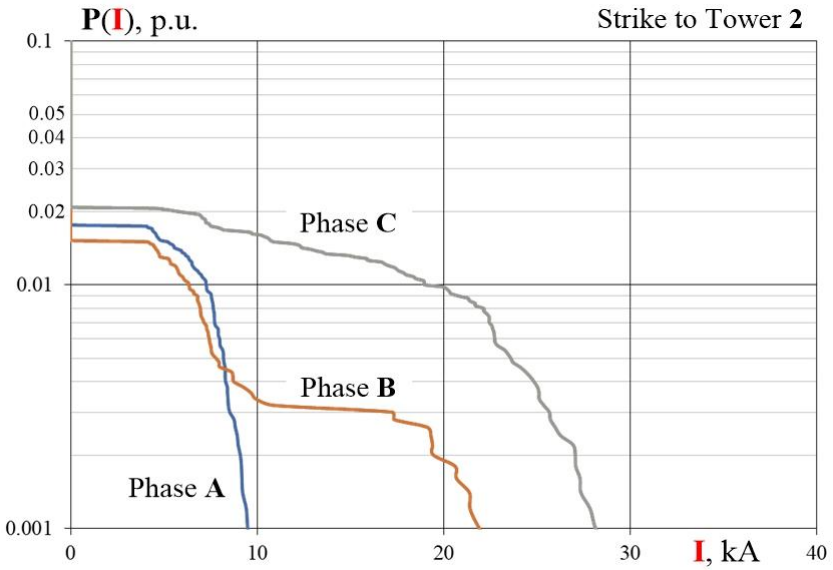


Figure 6 – Peak values of impulse currents in the three cross-arms A, B, C when lightning strikes to the top of the Tower 2 in the circuit of Figure 4.

4. Processes on the cable insulation

Let us calculate the processes at the input section of the overhead line to the switchgear. The circuit diagram is shown in Figure 7, where Tower 1 is the tower of the transition point [9]. This task is interesting, since in the case of an opened circuit breaker of the line, the end of the input section connected to the switchgear turns out to be poorly protected from surges, because with long input sections, the surge arrester installed at the transition point may not be enough.

We will vary the length of the input section, from 50 to 500 m. Also, for comparison, we will consider the option when instead of a cable input (cable line, CL), an overhead input is made (overhead line, OHL). A lightning impulse with a peak of 500 kV (without analyzing the form) will be considered as the maximum permissible for insulation of 110 kV class equipment.

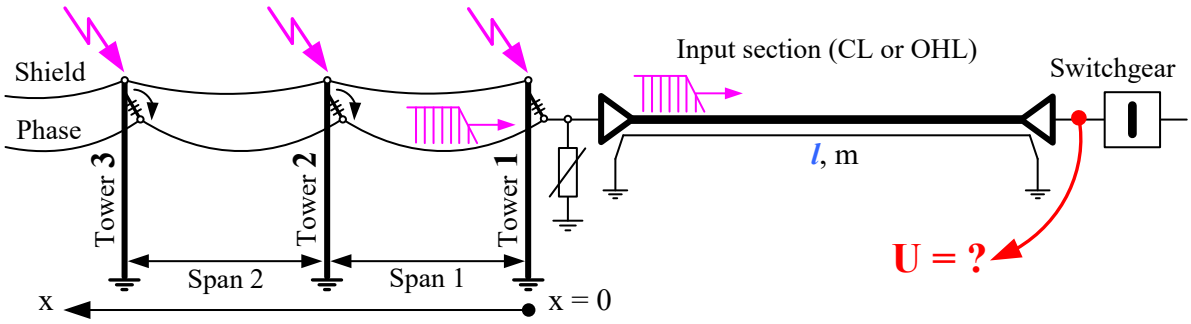


Figure 7 – Circuit for analysis of overvoltage at the free end of the input section of the overhead line to the switchgear.

Figure 8, for the case of an OHL section with a length of 50 m, shows how the probability of peak voltages above 500 kV on the phase-to-ground insulation varies as the strike moves away from the transition point. When lightning hits Tower 4 and further, dangerous voltages no longer occur, including due to the influence of loss in the line and the corona.

Figure 9, for the case of an OHL input with a length of 200 m, shows how the probability of peak voltages above 500 kV on the phase-to-ground insulation varies as the lightning moves away from the transition point. For strikes near Tower 4 and beyond, dangerous overvoltages no longer occur, including due to the influence of losses in the line and the corona.

Calculations similar to Figures 8-9 performed for all types of the input section (CL or OHL) and their lengths (from 50 to 500 m) allow us to get dependences of the probability $P(x)$ of dangerous overvoltages depending on the distance x of the lightning strike from the transition point (transition point corresponds to $x = 0$). These results are shown in Figures 10-11:

- in Figure 10, for lightning strikes to a shield wire;
- in Figure 11, for lightning breaks through the shield wire to the upper phase wire.

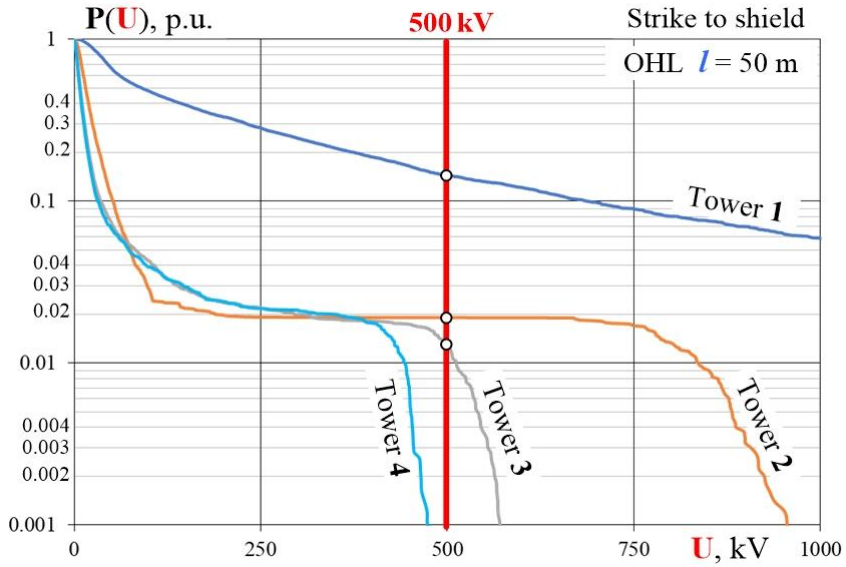


Figure 8 – Peak values of impulse voltages at the free end of the input section when lightning strikes the shield (as an example, the 50 m long input section is considered, of overhead type).

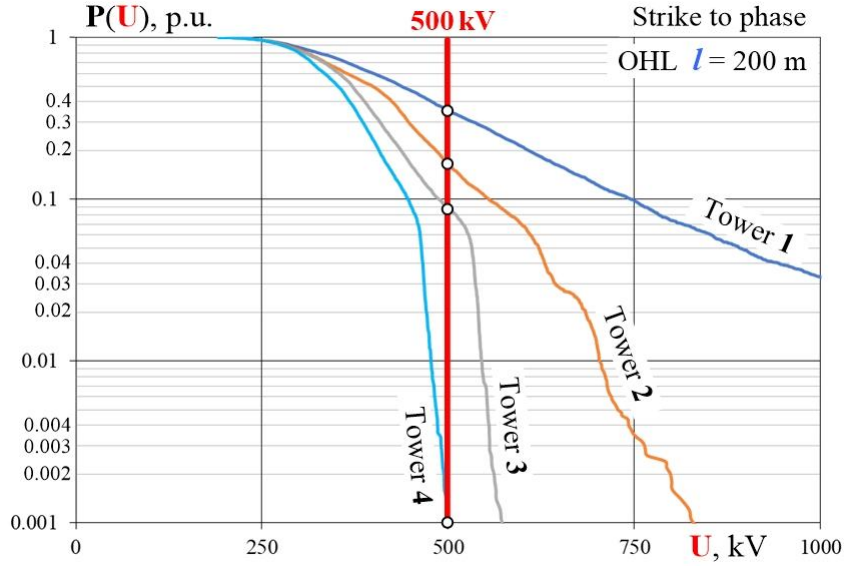


Figure 9 – Peak values of impulse voltages at the free end of the input section when lightning strikes the phase (as an example, the 200 m long input section is considered, of overhead type).

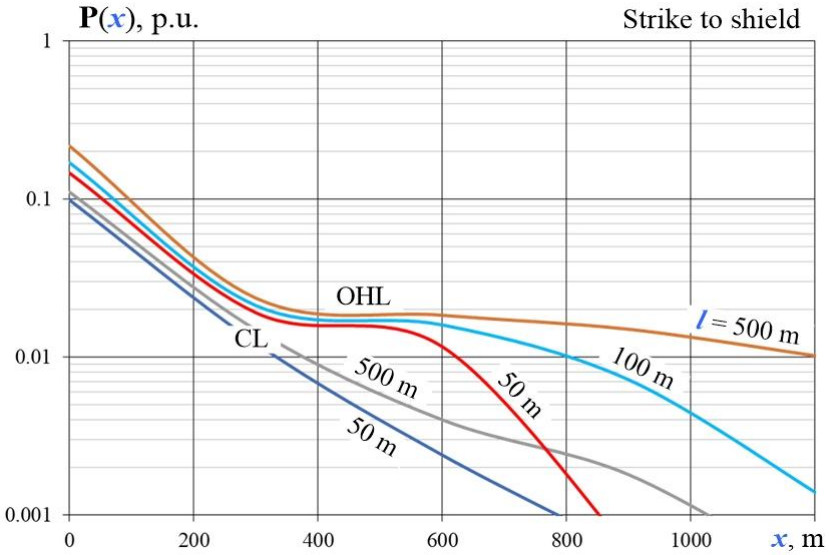


Figure 10 – The probability to get dangerous peak voltages at the free end of the input section (CL or OHL), for the case when lightning strikes to the shield wire.

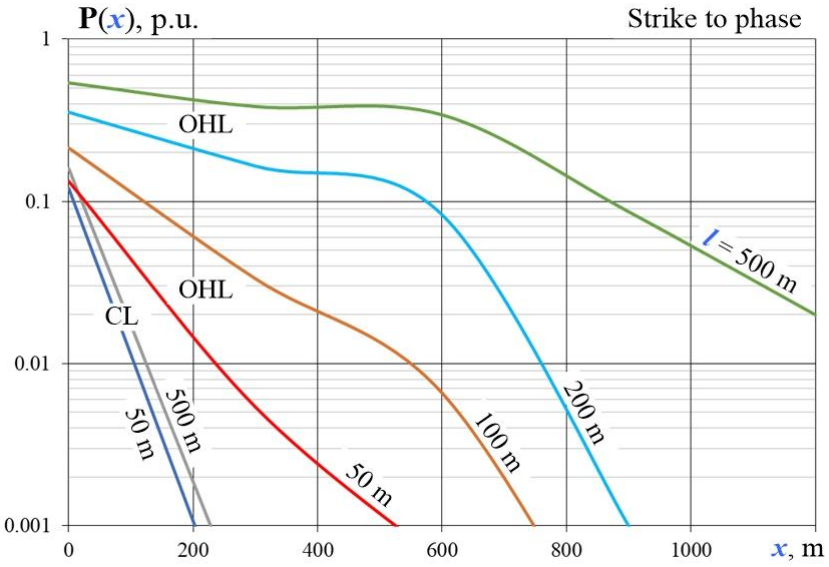


Figure 11 –The probability to get dangerous peak voltages at the free end of the input section (CL or OHL), for the case when lightning strikes to the phase wire.

Based on Figures 10-11, the following conclusions can be drawn:

- lightning strikes to a line at a distance x of more than 1-2 km from the input section can no longer cause dangerous overvoltages on it;
- the probability of dangerous overvoltages in the case of a strike to the phase is higher than to the shield and tower; for this reason, it is important to have a shield wire, but its presence beyond 1-2 km from transition no longer affects the protection of insulation;
- cable input sections, even extended, provides less probability of dangerous overvoltages compared to overhead, i.e. provides better protection due to its small surge impedance;
- the danger increases for longer input section, and this is quite noticeable for input sections of an overhead type, not of a cable type.

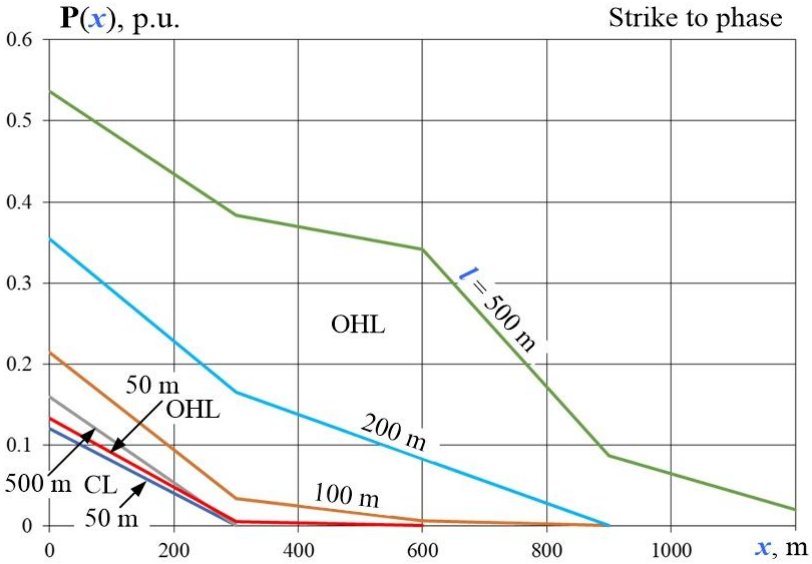


Figure 12 – A repeat of Figure 11, but without the logarithmic scale.

Let us compare the probability for each of the cases shown in Figures 10-11. To do this, we will calculate the area under each of the curves $P(x)$. It is more convenient to calculate this probability if the graphs are built not on a logarithmic scale, but on a regular scale. For example, Figure 12 re-shows the data taken from Figure 11, but presented on a regular linear scale, which simplifies the calculation of areas under the curves. The areas are shown in Table 1.

Table 1 shows how many times the probability of dangerous voltages is higher for cable and overhead input sections with a length of more than minimal (50 m). For example, if the probability is almost the same for all lengths of cable inputs (the cases of CL 50 and CL 500 are almost the same), whereas for overhead inputs, an increase in length, especially in the case of a strike to a phase, leads to a significant increase in the probability (the cases of OHL 50 and OHL 500 differ 18.2/1.2~15 times). If desired, knowing the number of strikes to the line and the number of breakthroughs to the phases, we can recalculate the probabilities to the number of events per year of operation or the expected number of years of trouble-free operation.

Table 1 – The probability to get dangerous peak voltages at the free end of the input section (comparison of areas under $P(x)$ probability distribution curves).

Input type	Cable input (CL)		Overhead input (OHL)			
Input length, m	50	500	50	100	200	500
Strike to the shield wire						
$S = \int P(x)\,dx$	19	23	31	39	-	53
S/S_{min}	**1**	1.2	1.6	2	-	2.7
Strike to the phase wire						
$S = \int P(x)\,dx$	18	24	22	44	128	330
S/S_{min}	**1**	1.3	1.2	2.4	7.1	18.2

5. Processes on the cable sheath

Let us consider another example of the practical application of statistical calculations – the processes in the screen cross-bonding node of a cable line. Let us evaluate how the type and length of the bonding cables shown in Figure 2 affects the probability of damage to the joint.

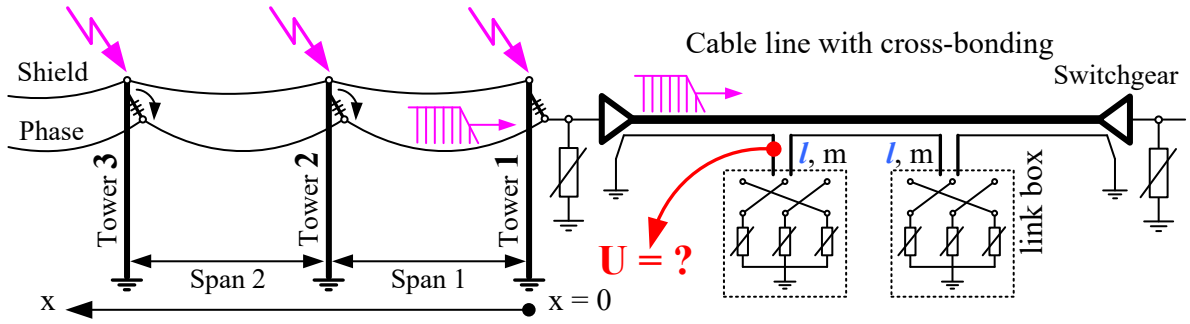


Figure 13 – Circuit for analysis of overvoltage in the node of screen cross-bonding.

The voltage in the cable joint is equal to the sum of the residual voltage on the SVL and voltage drop on the bonding cable. It is considered [10-12] that the length of the bonding cables should not exceed 10 m, and this value was based on the voltage drop that was determined by multiplying the inductance of the bonding cable by the rate of change of the impulse current in it, however, both values are controversial because:

- the inductance of the bonding cable depends on the current flow pattern (are the currents in the bonding cables of the pair pass in one direction or in opposite directions; are these currents equal to each other in magnitude or differ);
- the steepness of the current in the bonding cable is a statistical parameter that depends on the location of the lightning strike (tower, shield wire, phase wire), the distance of the strike from the cross-bonding node, and the lightning parameters.

To take all this into account, we will make statistical calculations. For simplicity, due to the limited space, we will consider only the lightning strikes to the shield (as the most common) and the processes in the first node of the screen cross-bonding of the 110 kV line with a length of 3 km. We will take 75 kV as acceptable peak value of screen-to-ground voltage in the joint, which is based on our experience [4] and exceeds the values given by the standards (for example, according to [10], a peak value of 37.5 kV is recommended for 110 kV cable lines).

In Figure 14, obtained using the example of a bonding cable length of 30 m (pair of two bonding cables laid close to each other, or a single coaxial bonding cable), it can be seen that dangerous overvoltages occur only for strikes to Tower 1. The probability of 0.04 in Figure 14 means that danger occurs 1 time out of 25 lightning strikes this tower of the transition point.

Figure 15 shows how this probability (0.04) varies depending on the length of the bonding cable (from 0 to 30 m) and depending on the distance between the cables. It can be seen that if, for example, instead of 10 m (the norm limit) we have 30 m, then the probability of an accident does not increase by an order of magnitude at all, but only about 2 times. Thus, there are no fatal consequences in the case of an increase in length from 10 m to 20-30 m.

Statistical calculations can be carried out not only to analyze the level of overvoltage, but also, for example, to estimate the energy released in SVL installed in the link-boxes.

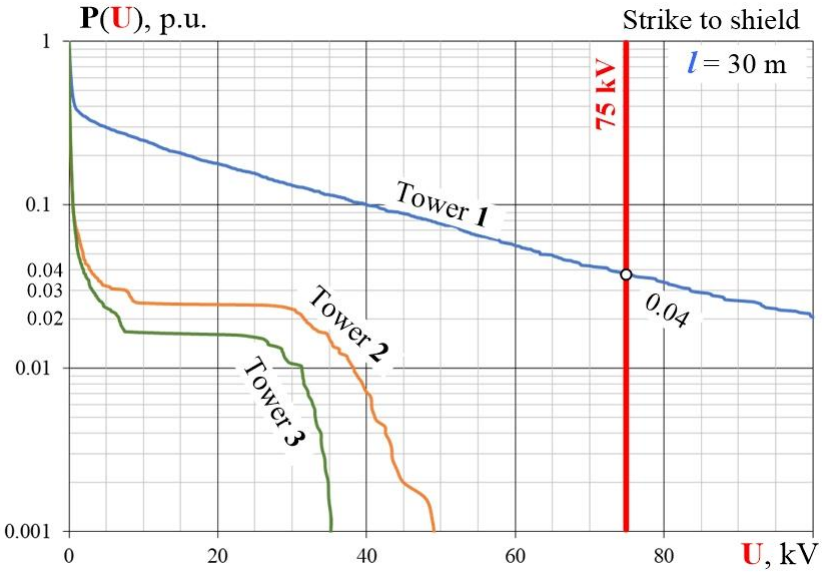


Figure 14 – The probability to get dangerous peak voltages at the cross-bonding joint, for the case when lightning strikes to different towers of overhead line (bonding cables of single-core type have a length of 30 m).

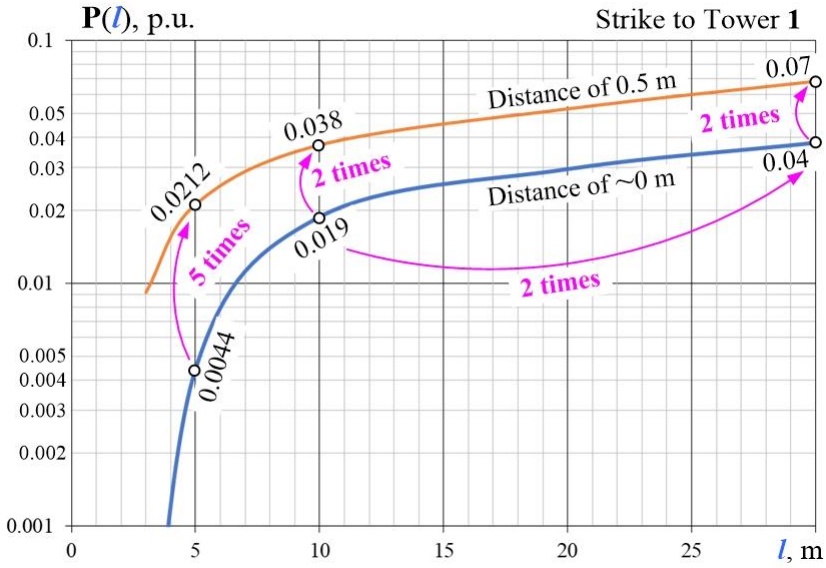


Figure 15 – The probability to get dangerous peak voltages at the cross-bonding joint (the length of the single-core bonding cables and the distance between them in pair are varied).

6. Conclusions

The article provides examples showing the possibility of using ATP/EMTP for statistical calculations of lightning processes. Such approaches can be applied both to the analysis of processes on lines (overhead and cable), and in switchgear of electric stations and substations (it helps selecting there the optimal arrangement of surge arresters).

The statistical calculation methodology described in the article can be combined with any models of lines, towers, insulation, lightning – both the standard ones available in ATP/EMTP and those created by users with the help of "Model's language".

The results obtained by statistics calculations make it possible to estimate the probability of equipment damage, as well as compare different options in terms of their reliability. As an example, the article provides for calculating some transient processes on cable lines connected to overhead lines, which is the most unfavourable case in terms of the magnitude of lightning surges occurring on the insulation and sheath of cables. The example of a 110 kV line shows:

- The probability of dangerous lightning surges at the free end of a cable input of overhead line to switchgear is weakly dependent on the cable length, and therefore the concept of "protection zone of a surge arrester mounted on a transition tower" is partly meaningless for cable inputs, unlike such a concept in the case of overhead inputs. Cable input protects itself with the help of its low surge impedance.
- The probability of dangerous overvoltages in the cross-bonding nodes depends slightly on the length of the bonding cables, and an increase in the length of these cables from 10 m to 20-30 m (provided the bonding cables in a pair are laid close together) will not lead to any fatal consequences for the cross-bonding cable joint. Regulations should accept bonding cable length of more than 10 m since there is no serious danger in it.

Bibliography

[1] IEC 60502-2: *Power cables with extruded insulation and their accessories for rated voltages from 1 kV up to 30 kV – Part 2: Cables for rated voltages from 6 kV to 30 kV*.

[2] IEC 60840: *Power cables with extruded insulation and their accessories for rated voltages above 30 kV up to 150 kV – Test methods and requirements*.

[3] IEC 62067: *Power cables with extruded insulation and their accessories for rated voltages above 150 kV up to 500 kV – Test methods and requirements*.

[4] Dmitriev M.: *High voltage cable lines*. -Porto, 2021. -690 p.

[5] Dmitriev M.: *Lightning overvoltages in high voltage switchgear*. -Porto, 2025. -68 p.

[6] Kostenko M.V., Messerman D.G.: *Deformation of lightning surge waves in transmission lines over and ultra-high voltage at long range* // Proceedings of the USSR Academy of Sciences: Energy and Transport, 1987, No.3, pp.158-164.

[7] Anderson J.G.: *Lightning Performance of Transmission Lines. Transmission Line Reference Book 345 kV and Above: Chapter 12* // EPRI, California, 1992, pp.545-597.

[8] Kadomskaya K.P., Borisov E.A.: *On modelling lightning current waves in the study of lightning protection of electric power facilities* // Collection of scientific papers of NSTU, Novosibirsk, 2003, No.2(32), pp.89-98.

[9] IEEE 1793-2012: *Guide for planning and designing transition facilities between overhead and underground transmission lines*.

[10] IEEE 575-2014: *Guide for bonding shields and sheaths of single-conductor power cables rated 5 kV through 500 kV*.

[11] CIGRE Technical Brochure TB 283: *Special bonding of high voltage power cables*.

[12] Khamlichi A., Denche G,. Garnacho F. and others: *Location of sheath voltage limiters (SVLs) used for accessory protection to assure the insulation coordination of cable outer sheath, sectionalizing joints and terminations of high voltage cable systems* // CIGRE session, Paris 2016, paper B1-108.