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# PROBABILITY OF APPEARANCE OF CERTAIN VALUE OF PHASE TO GROUND OVERVOLTAGE DUE TO DIRECT LIGHTNING STROKE

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**ABSTRACT**
This paper describes analytical method for calculation of probability of appearance of certain values of phase to ground overvoltage which is caused by direct lightning stroke. The computer program for calculation of those probabilities is also explained and applied. Influences of the position of direct lightning stroke as well as influences of some line parameters on probability of appearance of certain value of phase to ground overvoltage are described and analyzed.

**KEY WORDS**
Modeling, Simulation, Power Systems, Probability, Direct Lightning Stroke, Overvoltage

## 1. Introduction

The direct lightning stroke to the distribution lines is the main factor which causes the lightning outages [1, 2]. Estimation of overvoltage due to lightning is crucial for correct protection and insulation coordination of overhead lines. As a consequence, this has been the subject of various studies during the past decades. The problem has been seriously reconsidered in recent years due to the increasing demand by customers for good quality in the power supply, and new models have consequently been developed to obtain a more accurate estimation of lightning voltage [3].
Due to random nature of lightning stroke, the analysis of the lightning performance of transmission lines must be based on a statistical approach [4]. The location of the leader of the lightning discharge is randomly. It can occur near by line or directly in line on: tower, shielding wire or phase conductors.
In the case of direct lightning stroke the greatest influence on voltage phase to ground insulation strain has lightning current. It can have different values and it depends on quantity of charge accumulated in the clouds as well as on other factors (witch have random character [5], [6]). That is the reason why it is usually only possible to calculate probability of appearance of certain value of lightning current, but it isn't possible to calculate exact value. Since phase to ground overvoltage is caused by lightning current, its value is also characterized with some probability of appearance.
Probability of lightning flashover depends on probability of appearance of certain value of lightning overvoltage. Many parameters (characteristic impedance of conductor, tower inductance, coefficient α, height of line, nominal line voltage, and so on) have influence on that probability. Also, the position of direct lighting stroke (transmission tower, shielding wire or phase conductor) has great influence on that probability. So, in order to obtain an accurate probability it is necessary to include all parameters in calculation.
On the basis of these facts in this paper the following subjects such as: - analytical method for calculating probability of appearance of certain values of phase to ground overvoltage; - computer program for calculating probability; - influence of the position of direct lightning stroke on probability and - influence of some line parameters on probability, are described and analyzed.

## 2. Mathematical model for probability calculation of appearance of certain value of phase to ground overvoltage caused by direct lightning stroke

Probability of appearance the values of lightning current *P(I)* greater than value $I_g$ can be calculated by equation [7]:

$$P(I) = e^{-\frac{I_g}{\alpha}}, \quad (1)$$

where α is coefficient obtained empirically by a lot of measurements.
Depending on the position of direct lightning stroke the probability of appearance of certain value of phase to ground overvoltage is different. It can be calculated by following method:

### 2.1. Probability calculation of appearance of certain value of phase to ground overvoltage caused by direct lightning stroke in transmission tower

In the case of direct lightning stroke in transmission tower two analyses can be made. One analyze can be made for the case of existence of shielding wire, when 80 % lightning current flows through tower in the ground, and the rest of current flows over shielding wire and other towers. The second analyze can be made for the case of lightning stroke in tower without shielding wire, when all lightning current flows through tower in the ground.

The amplitude of overvoltage $U_s$ generated on the highest console of tower (HCT) caused by direct lightning in tower can be calculated as [7]:

$$U_s = I_s R_{uz} + l_s h_k \frac{I_s}{T_c} + m_s h_k \frac{I_g}{T_c} \tag{2}$$

where is: $I_g$ – amplitude of the lightning current with constant wave tail; $I_s$ – amplitude of the current which flows through tower; $T_c$ - rise-time of wave front; $h_k$ – the height of the highest console of tower (HCT); $R_{uz}$ - grounding resistance; $l_s$ - tower inductance; $m_s$ - mutual inductance of the lightning channel and tower.

In the case that overhead line has shielding wire the value of lightning current which flows through tower is $I_s=0.8\cdot I_g$, but if shielding wire is not exist that current is $I_s=I_g$.

The value of overvoltage on phase to ground insulation in the case of direct lightning stroke in tower is difference between impulse voltage wave on HCT $U_s$ and currently value of working voltage on phase conductor $U_m \cos\Theta$, and it is equal [7]:

$$U_{iz} = U_s - U_m \cos\Theta\,, \tag{3}$$

where is: $U_m$ - peak value of working voltage on phase conductor; $\Theta$ - a phase angle with range of [0, 2π] which determinate current value of working voltage in the moment of lightning stroke.

From equation (3) can be concluded that the most critical moment of lightning stroke is moment when impulse voltage wave has polarity opposite to working voltage and when working voltage has peak value. In that case strain of phase to ground insulation is maximum $U_{izmax}$ and it is equal to:

$$U_{iz\max} = U_s + U_m\,. \tag{4}$$

The maximum overvoltage value which can appear on HCT due to lightning stroke in tower and which does not generate flashover has to satisfy following relation:

$$U_s < U_{pod} - U_m\,. \tag{5}$$

where is $U_{pod}$ withstand voltage of insulation.

The overvoltage on HCT will have value greater than $U_s$ in the case when lightning current has value greater than $I_g$. The probability when it will happen, based on (1) and (2), is:

- in the case when shielding wire exists:

$$P = e^{-\frac{U_s}{\alpha\left(0.8R_{uz}+l_s h_k \frac{0.8}{T_c}+m_s h_k \frac{1}{T_c}\right)}} \tag{6}$$

- in the case when shielding wire does not exist:

$$P = e^{-\frac{U_s}{\alpha\left(R_{uz}+l_s h_k \frac{1}{T_c}+m_s h_k \frac{1}{T_c}\right)}}\,. \tag{7}$$

### 2.2. Probability calculation of appearance of certain value of phase to ground overvoltage caused by direct lightning stroke in shielding wire

In the case of direct lightning stroke in shielding wire it can be taken that half of lightning current propagate on one side of shielding wire and second half on other side. One part of such divided lightning wave is refracted and other one is reflected when it arrives on transmission tower point. There are two components of refracted wave. One component flows through tower directly in ground and its amount is about 80 % of wave which reaches the tower [7]. The other component continues to propagate over shielding wire in direction of incident wave and it will be refracted and reflected when arrives to some other tower.

Probability of overvoltage appearance on HCT with value greater than $U_s$ due to lightning stroke in shielding wire can be calculated as [7]:

$$P = e^{-\frac{U_s}{\alpha\left(0.2R_{uz}+l_s h_k \frac{0.2}{T_c}\right)}}\,. \tag{8}$$

### 2.3. Probability calculation of appearance of certain value of phase to ground overvoltage caused by direct lightning stroke in phase conductor

At the overhead transmission lines without shielding wire the most common places of lightning strokes are phase conductors, and only a small number of strokes happen in tower [8]. If overhead transmission line has shielding wire the probability of direct stroke is very small (for example, it is 0.2 % for the conductor height of 15 m [7]). If direct stroke happens in phase conductor, generated overvoltage strains phase to ground and phase to phase insulations.

The value of phase to ground overvoltage depends on the value of the working voltage in the moment of stroke in the phase conductor. That influence of working voltage on flashover is important for transmission line with nominal voltage greater that 110 kV, but for other line that influence is negligible because overvoltage due to lightning is highly greater than working voltage. The overvoltage value $U_s$ generated on conductor by lightning is equal [7]:

$$U_s = \frac{I_g}{4\cdot Z_c} + U_m \cos\Theta\,, \tag{9}$$

where $Z_c$ is characteristic impedance of conductor.

From equation (9) can be concluded that the most critical moment of lightning stroke is moment when impulse voltage wave has same polarity as working voltage and when working voltage has peak value. The maximum overvoltage value $U_s$ on conductor due to lightning stroke in phase conductor, which will not generate flashover on phase to ground insulation, has to satisfy following relation:

$$U_s < U_{pod} - U_m \,. \tag{10}$$

where is: $U_{pod}$ withstand voltage of insulation and $U_m$ peak value of working voltage on phase conductor.

Probability of overvoltage appearance on conductor with value greater than $U_s$ due to lightning stroke in conductor can be calculated as:

$$P(I) = e^{-\frac{4 \cdot U_s}{\alpha \cdot Z_C}} \tag{11}$$

## 3. Computer program

Probability of appearance of certain value of overvoltage on line due to direct lightning depends on many parameters. Computer program for calculation of appearance of certain value of phase to ground overvoltage, taking in account all relevant parameters, has been developed by software MATLAB and using GUI (Graphic User Interface).

All calculations are based on the presented mathematical models, explained in part 2. Depending on the position of direct lightning stroke the input parameters are different and they can be: rise-time of wave, the height of HCT, grounding resistance, a value of phase to ground voltage which probability of appearance is aim of calculations, characteristic impedance of conductor, tower inductance, mutual inductance of the lightning channel and tower, coefficient α, nominal line voltage, end so on.

Program provides graphical and tabular output results of probability of appearance of certain value of overvoltage caused by direct lightning stroke. For each particular input parameter its influence on probability of voltage appearance can be calculated and displayed. The program can deal with following probabilities:

(i) Probability of appearance of certain value of phase to ground overvoltage due to lightning stroke in tower;

(ii) Probability of appearance of certain value of phase to ground and phase to phase overvoltage due to lightning stroke in phase conductor;

(iii) Probability of appearance of certain value of phase to ground overvoltage due to lightning stroke in shielding wire.

On the base of such presented results it is easy to create an economical and technical practical solution which will decrease flashover risk.

## 4. Obtained results

As it is mentioned earlier, many parameters have influence on probability of appearance of phase to ground overvoltage due to lightning. Because of limit of paper's size here will be presented only a part of graphical results. Also, for direct lightning stroke in tower and shielding wire here will be presented changes of probability of overvoltage appearance for only two variable parameters: grounding resistance and height of HCT. In the case of lightning stroke in phase conductor here will be presented results which show phase to ground insulation strain.

Curves on figures 1 and 2 represent results obtained by relation (6) for the case of direct lightning stroke in tower with shielding wire. They show probability appearance of phase to ground overvoltages with value greater than U = 550 kV (figure 1) and U = 1050 kV (figure 2) in the case of several values of ground resistance and height of HCT. These values of overvoltage are chosen because they present the values of positive and negative polarity withstand impulse voltages for full degree of insulation of highest nominal value voltage of 123 kV and 245 kV, respectively [8]. Degree of insulation is determined with value of withstand voltage.

Curves on figure 3 represent results obtained by relation (7) for the case of direct lightning stroke in tower without shielding wire. It shows probability appearance of phase to ground overvoltages with value greater than U = 550 kV in the case of changes of values of ground resistance.

Note that figure 1, 2 and 3 are obtained for: $T_c$ = 1.2 μs, α = 26.1, $l_s$ = 0.6 mH, $m_s$ = 0.2 mH.

Curves on figures 4 and 5 represent results obtained by relation (6) for the case of direct lightning stroke in tower with shielding wire. They show probability of certain phase to ground overvoltages appearance depending on ground resistance. Probability for the case that tower does not have shielding wire is shown on figure 6.

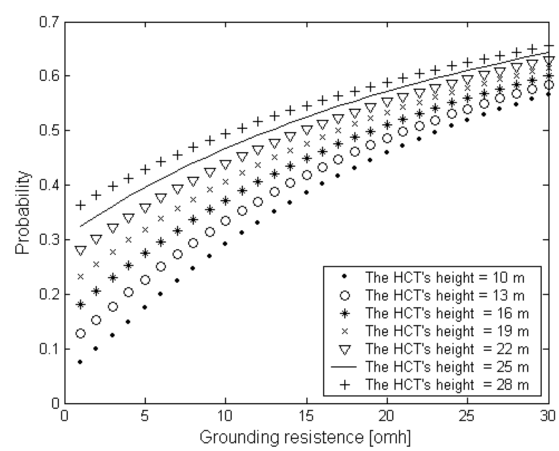


Fig. 1. Probability appearance of phase to ground overvoltages with value greater than U = 550 kV on 110 kV transmission line with shielding wire

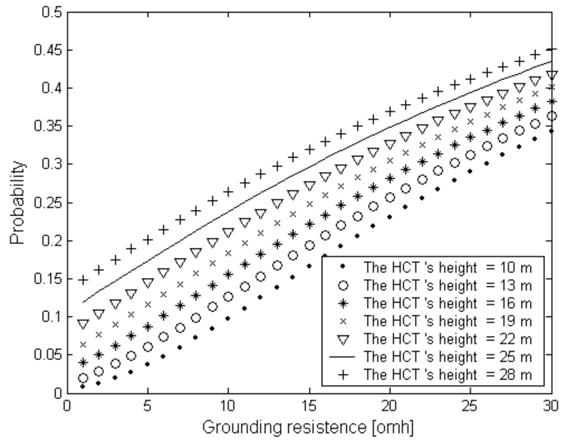


Fig. 2. Probability appearance of phase to ground overvoltages with value greater than U = 1050 kV on 220 kV transmission line with shielding wire

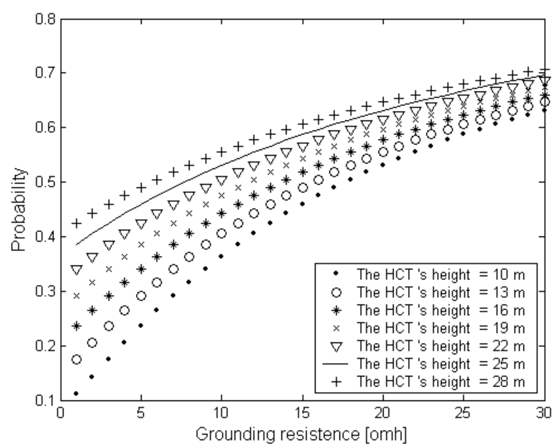


Fig. 3. Probability appearance of phase to ground overvoltages with value greater than U = 550 kV on 110 kV transmission line without shielding wire

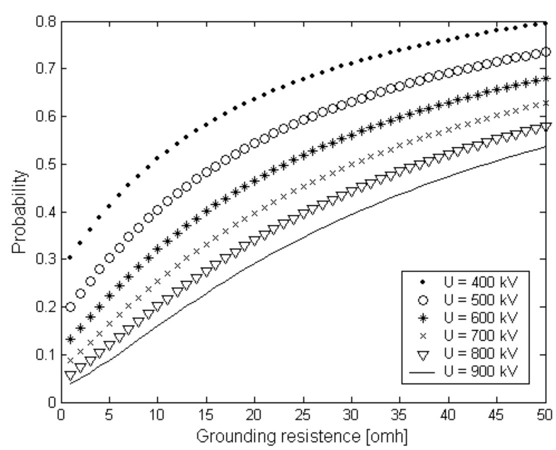


Fig. 4. Probability of certain phase to ground overvoltages appearance on 110 kV transmission line with shielding wire

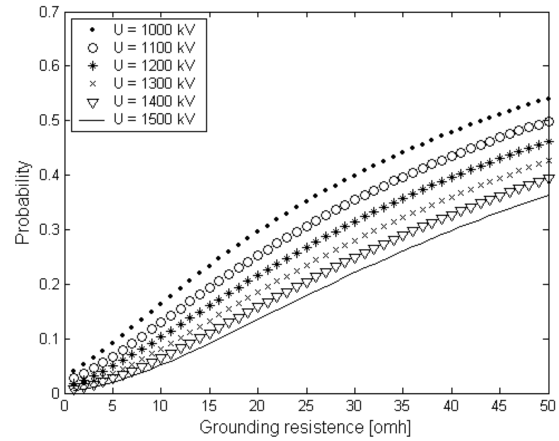


Fig. 5. Probability of certain phase to ground overvoltages appearance on 220 kV transmission line with shielding wire

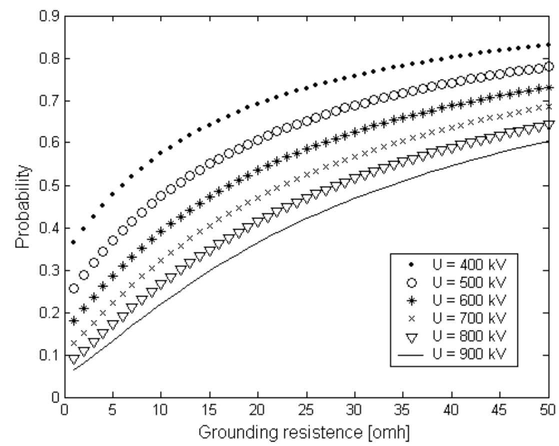


Fig. 6. Probability of certain phase to ground overvoltages appearance on 110 kV transmission line without shielding wire

Note that figure 4, 5 and 6 are obtained for: $T_c$ = 1.2 μs, α = 26.1, $l_s$ = 0.6 mH, $m_s$ = 0.2 mH, $h_k$ = 15 m.

The highest probability for flashover on phase to ground insulation, due to lightning stroke in phase conductor, occurs in the case when working voltage has maximum value and same polarity as lightning wave. The smallest probability is in the case when lightning stroke happens in moment when working voltage has maximal value and opposite polarity to lightning wave. Curves on figure 7, which represent results obtained by relations (10) and (11), show probability of certain phase to ground overvoltage appearance, in case of direct lightning stroke in 110 kV phase conductor, in the moment when working voltage has maximal value. Curves show two probability graphics obtained for same and opposite polarity of working voltage and lightning wave. All other moments of direct lightning stroke in phase conductor have probability of certain overvoltage appearance between those two curves shown on figure 7.

Note that figure 7 is obtained for: $Z_c$ = 400Ω, α = 26.1.

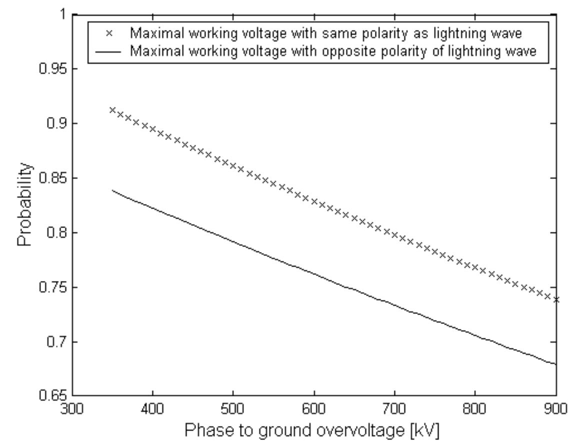


Fig. 7. Probability of certain phase to ground overvoltages appearance on 110 kV transmission line due to lightning stroke in phase conductor

Curves on figures 8 and 9 are related on direct lightning stroke in shielding wire. Figure 8 shows probability appearance of phase to ground overvoltages with value greater than U = 550 kV in the case of several values of height of HCT, and figure 9 in the case of several values of ground resistance. Note that figures 8 and 9 are obtained for: $T_c$ = 1.2 μs, α = 26.1, *ls* = 0.6 mH.

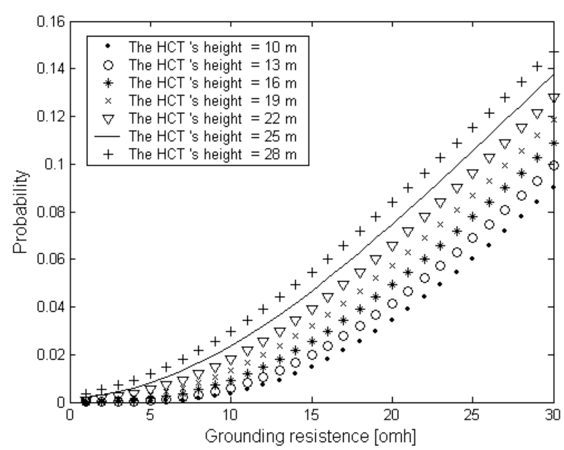


Fig. 8. Probability appearance of phase to ground overvoltages with value greater than U = 550 kV on 110 kV transmission line

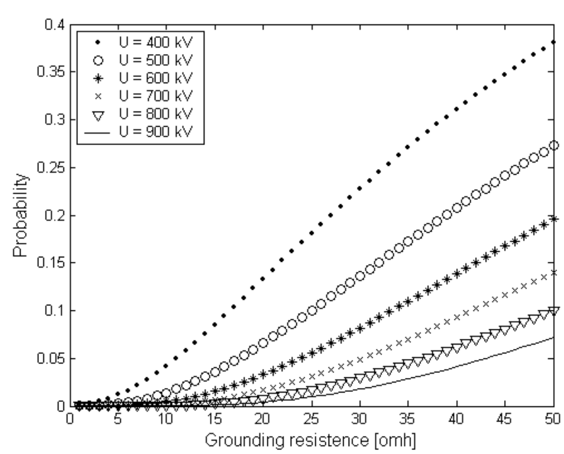


Fig. 9. Probability of certain phase to ground overvoltages appearance on 110 kV transmission line due to lightning stroke in shielding wire

## 5. Analyses of the results

Based on results presented on figures 1-9 the analyses have been made and the main observation and conclusions are given in paragraphs A, B, C and D.

### 5.1. Influence of height changes of the highest tower console on probability of appearance of overvoltage due to lightning stroke in tower

Curves on figures 1, 2 and 3 show that HCT, at same grounding resistance, have higher probability of certain phase to ground overvoltage appearance, i.e. with increasing of HCT height the risk of flashovers increase. For example, for grounding resistance of 10 Ω, the probability of phase to ground overvoltage higher than 550 kV appearance is 29.1 % in the case of 10 m height of HCT and 43.9 % in the case of 22 m height of HCT. In the case of 20 Ω grounding resistance these probabilities is 45.9 % and 55.3 %, respectively.
Probability of certain overvoltage value appearance increases when grounding resistance increases. For example, figure 1 shows that for 16 m height of HCT probability of 550 kV overvoltage appearance is in the case of 15 Ω and 30 Ω grounding resistance for amount of 20.6 % and 61.3 %, respectively, higher than in the case of 10 Ω grounding resistance. Similar conclusion can be obtained based on curves shown on figures 2 and 3. Comparing curves on figures 1 and 3 can be noticed that in the case of same height of HCT probability of certain overvoltage appearance is smaller if shielding wire is present. That is obvious because all amount of lightning current doesn't flow through tower. For example, for 19 m height of HCT and 20 Ω grounding resistance, probability of overvoltage over 550 kV appearance in the case of present shielding wire is 53.3 % (figure 1) and in the case of absent of shielding wire it is 59.7 % (figure 3).

### 5.2. Influence of changes of grounding resistance on probability of appearance of overvoltage due to lightning stroke in tower

According to results presented in figures 4, 5 and 6, can be concluded that lower value of grounding resistance provides less value of probability of phase to ground critical overvoltage appearance which can cause flashover. For example, figure 4 shows that probability of 500 kV overvoltage appearances in the case of 20 Ω grounding resistance is for amount of 34.4 % higher than in the case of 10 Ω grounding resistance. In the case of 50 Ω grounding resistance the probability is for amount of 81.7 % higher than in the case of 10 Ω grounding resistance.
Comparing results shown in figures 4 and 6 it is obvious that the less probability of appearance of certain value of phase to ground overvoltage is in the case of presence of shielding wire, because one part of lightning current flows over shielding wire and other towers in ground.

### 5.3. Probability of appearance of overvoltage due to lightning stroke in phase conductor

Probability of overvoltage appearance which can cause a flashover is quite high, as can be seen on figure 7. For example, if lightning stroke happens in phase conductor of transmission line with 110 kV nominal voltage in the least critical moment, in 7 of 10 cases phase to ground overvoltage over 900 kV will appear.

### 5.4. Probability of appearance of overvoltage due to lightning stroke in shielding wire

On the basis of results presented on figures 8 and 9 can be concluded that there is a significantly smaller probability of appearance of certain overvoltage in the case of lightning stroke in shielding wire, even in the case of great value of ground resistance, comparing to case of lightning stroke in tower. For example, for 16 m height of HCT and 10 Ω grounding resistance probability of overvoltage over 550 kV appearance in the case of lightning stroke in: shielding wire is 0.9 % , (figure 8), tower with shielding wire is 37.2 % , (figure 1), tower without shielding wire is 44.2 %, (figure 3).

## 6. Future works

Presented paper can be very good direction for finding a most economical solution for decreasing probability of overflash. Economical solutions are related on finding, on one hand, appropriate value of grounding resistance and, on the other hand, insulation level which can withstand certain value of overvoltage. Appropriate grounding resistance can be obtained by several grounding systems, and it will be necessary to find economical system between them.

Also, in the future, the obtained theoretical results should be verified and checked with the results obtained by experiments. Experimental results are very important for creation of finale conclusion about the topic presented in this paper. But, since those experiments requested very good laboratory equipments, the lack of necessary equipments was the main reason why in this paper the only theoretical results were discussed and analyzed.

## 7. Conclusion

For the fast and precise calculations and analyses of influences of direct lightning stroke on the transmission networks it is very important to calculate the probabilities of appearance of overvoltages.

The general conclusion from the obtained results is that highest probability of appearance of certain value of phase to ground overvoltage is in case of direct lightning stroke in phase conductor.

The less probability of flashover on phase to ground insulation is obtained in the case of lightning stroke in the tower without shielding wire, and even less probability is in the case with shielding wire.

The smallest probability is in the case of direct lightning stroke in shielding wire. With increasing of height of HCT and grounding resistance the probability of appearance of certain value of phase to ground overvoltage is higher.

The computer program, presented in this paper, allows designers to obtain results in an efficient, precise and comprehensive way. It provides the answer related to concrete steps that should be accomplished in order to reduce the risk of overvoltage at some satisfactory level.

Furthermore, in the paper the analyses that indicates the influence of several parameters (HCT, nominal voltage of line, grounding resistance) on probability that overvoltage due to lightning stroke will have the value that insulation cannot withstand, is given.

As it can be seen the acquired probability can be obtained changing many parameters of line. Direction for future research based on the scope of presented paper should be finding the economical solution for acquired probability, and obtaining the needed experimental results.

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