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METHODOLOGY OF INSULATION FAILURES FLASHOVER RATE ESTIMATION FOR METAL CONSTRUCTIONS IN OVERHEAD TRANSMISSION LINES

Summary of the Doctoral Thesis

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RTU Press
Riga 2016

Sliskis O. Methodology of Insulation Failures Flashover Rate Estimation for Metal Constructions in Overhead Transmission Lines. Summary of the Doctoral Thesis. – Riga: RTU Press, 2016. – 46 p.

Printed in accordance with the Decision No. 2016-4(60) of RTU Promotional Council P-14 dated June 20, 2016.

ISBN 978-9934-10-878-5

DOCTORAL THESIS
PROPOSED TO RIGA TECHNICAL UNIVERSITY
FOR THE PROMOTION TO THE SCIENTIFIC DEGREE
OF DOCTOR OF ENGINEERING SCIENCES

The Doctoral Thesis is proposed for achieving Dr. sc. ing. Degree and will be publicy presented on the 25th of November 2016 at Faculty of Electrical Engineering of Riga Technical University, 12/1 Azenes Street, in room 212.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Olegs Sliskis ....
(signature)

Date ....

The Doctoral Thesis is written in Latvian. It contains an introduction, 5 chapters, conclusions and a list of references. The total volume of the present Thesis is 127 pages, which include 59 figures and 19 tables. The list of references includes 154 literature sources.

CONTENTS

GENERAL DESCRIPTION OF THE WORK

The topicality of the Work

The component part of any power supply system represents the aggregate of complicated engineering–technical decisions. At construction of power supply systems, especially overhead high voltage electric networks, the most often widespread element is the metal construction, complicated by constructional performance. Functional significance of a metalwork in power engineering is very manifold, at the same time, operational requirements, taking into account both mechanical loadings and the level of reliability of power supply, are considerable.

Both in a stage of development of the project and during the exploitation of transmission line (TL), the specialists have to solve one of the most complicated problems – insulation failures flashover rate (IFFR). Direct lightning discharge on TL leads to emergency outages and power supply violations which generate economic losses both for a state economy and for separate enterprises. For example, in the USA on the 27th of August of 2003, more than 200,000 Washington and its agglomeration household was interrupted power supply resulting on a lightning storm. The lightning induced transmission line tripping caused operational blocking of the Washington's communications and transport infrastructure [26].

The main indicator of the IFFR of TL is the minimization of the probability of emergencies, which is irreversible destructions of the isolating TL designs. When using valid normative documents, for example, EN50341:2013 or RD.153-34.3-35.125-99 for an assessment of IFFR, it is necessary to use the data of the designs of a standard type with average geometrical parameters of lines. Using statistical and experimental data, the international research organizations and the leading scientific institutions of branch continuously consider and supplement recommendations about protection against lightning, even more often providing the use of atypical technical solutions [7], [23], [25].

The analysis of the existing situation, concerning the reaction of TL to recognition of direct lightning discharge is provided in this work for obtaining of scientific degree. It is noted that systematization in order existing methodologies could be used in practical engineering–technical tasks is necessary for the most part of the existing methods.

The Goal and the Tasks Solved by the Thesis

The present Thesis aims to develop a methodology for overhead power transmission line supports metal design solutions for evaluation of IFFR point of view, taking into account individual constructions geometry parameters, namely traverse dimensions, mechanical ties, insulation distances of up to earthed conductive elements, as well as load-bearing structural material magnetic properties.

The main objectives solved for the development of the Doctoral Thesis:

1. The research of the mathematical model of lightning current and possibility of its computer realization was carried out.
2. The analysis of a method of computer modeling for the definition of the reaction of TL to the impact of overvoltage was made.
3. The algorithm of the metal constructions of TL for the definition of IFFR which unites the analysis of the mechanism of distribution of electromagnetic waves of an overvoltage and the analysis of an electromagnetic condition of an object during the influence of lightning discharge was synthesized.
4. The analysis of the influence of the structural parameters of the metal constructions of TL tower on the process of distribution of lightning current was made.
5. Phase insulators/insulator flashovers for probabilistic characteristics, for metal TL tower, depending on the design features of the tower, the resistance of grounding of R_i, and the parameters of the isolating constructions were made. The received probabilistic characteristics are applied for ascertainment of a number of switchouts of TL for the concrete period of time.

Scientific Novelty of the Doctoral Thesis

The methodology, which is offered in the work for obtaining of the scientific degree, allows carrying out the developed analysis of TL metal construction and the isolating fittings in case of lightning discharge in a TL tower and making the conclusions about possible probable appearance of insulation/insulator flashover on separate sections of metal construction, and also counting the number of switchouts of TL for the concrete period of time.

The methodology considered in the present Thesis allows proving the expediency of the isolating design, and also checking the project of TL tower metal construction from the point of view of IFFR and further development of the accident rate.

Practical Significance of the Doctoral Thesis

The methodology of the establishment of IFFR of TL metal construction offered in this Thesis allows:

- stating and localizing the imperfection as existing in operation and TL tower metal construction under construction from the point of view of IFFR;
- finding out the efficiency of the chosen isolating constructions for a concrete tower construction;

- making easier the procedure of designing metal construction, also for atypical TL tower construction, thanks to the synthesis of computer modelling included in the methodology.

Methodology of the Research

The following theoretical methods are used: elements of the theory of the gas discharge and streamers, the theory of electromagnetic waves, and quantitative methods of electromagnetic fields – for the solution of the partial differential equations by the method of finite elements.

For processing of calculations and results, the *Microsoft EXCEL* environment is used; for modeling and the analysis of transition processes of electromagnetic waves, the software of *EMTP/ATP* is used; the processing and preparation of graphic data is realized by means of the software *AutoCAD*, *AutoDESK* and *SolidWorks*; and the *COMSOL Multiphysics* environment is used for the realization of a problem of the electromagnetic field.

Approbation of the Doctoral Thesis

The results obtained within the frames of the development of the Doctoral Thesis were reported and discussed at six international conferences:

1. „Specification of transmission tower structure for following surge protection simulation", 16th International Scientific Conference EPE 2015 (ELECTRIC POWER ENGINEERING), Kouty nad Desnou, the Czech Republic, May 20–25, 2015.
2. „Computer Simulation of Lightning Surge Propagation on Power Transmission System Metal Constructions", CIGRE International Colloquium on Lightning and Power Systems, Lyon, France, May 12–14, 2014.
3. „Computer Analysis of Lightning Surge Propagation on Overhead Transmission Line Towers", the 54th International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering, Riga, Latvia, October 14–16, 2013.
4. „Lightning Performance on Transmission Line Towers", Electrical and Control Technologies (ECT–2012): The 7th International Conference, Kaunas, Lithuania, May 3–4, 2012.
5. „Transmission Line Towers Structure Effect on a. Atmospheric Overvoltages Propagation", the 52nd International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering, Riga, Latvia, October 13–16, 2011.
6. „Application of ATP/EMTP Program for Solving of Some High-Voltage Engineering Problems", the 51st International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering, Riga, Latvia, October 14, 2010.

Publications

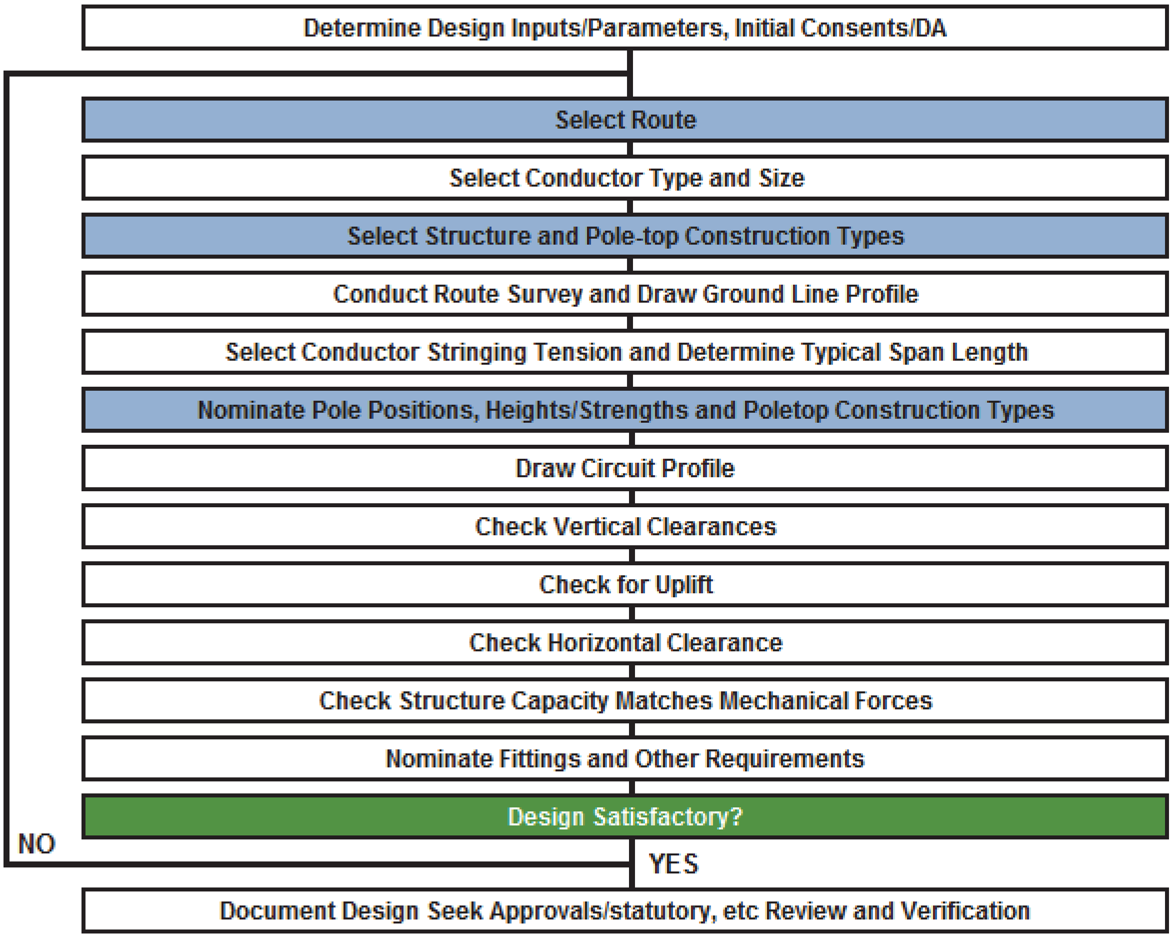
The results obtained within the frames of the development of the Doctoral Thesis are included in eight publictions in international proceedings:

1. O. Sliskis, I. Dvornikovs, K. Ketners, D. Sobolevsky. Specification of transmission tower structure for following surge protection simulation // 16th International Scientific Conference EPE 2015 (ELECTRIC POWER ENGINEERING), Kouty nad Desnou, the Czech Republic, May 20–25, 2015.
2. Dvornikovs, I., Sliskis, O., Ketners, K. Computer Simulation of Lightning Surge Propagation on Power Transmission System Metal Constructions // CIGRE International Colloquium on Lightning and Power Systems, Lyon, France, May 12–14, 2014. *Electronic version.*
3. Dvornikovs, I., Sļiskis, O., Ketners, K. Computer Analysis of Lightning Surge Propagation on Overhead Transmission Line Towers // The 54th International Scientific Conference of Riga Technical University: Digest Book and Electronic Proceedings, Latvia, Riga, October 14–16, 2013. Riga: RTU, 2013, P19.1.–P19.4.
4. Sļiskis O., Soboļevskis D., Ketners K. Zibens izlādes iedarbība uz gaisvadu līniju metālkonstrukcijām // RTU zinātn. Raksti, 4. sēr., Enerģētika un elektrotehnika. – 30. sēj., 2012, 59.–63. lpp.
5. Sļiskis O., Dvorņikovs I., Ketners K. Lightning Performance on Transmission Line Towers // Electrical and Control Technologies (ECT–2012): The 7th International Conference, Lithuania, Kaunas, May 3–4, 2012,– pp. 157–160.
6. Sļiskis O., Miesniece S., Ketners K. Transmission Line Towers Structure Effect on an Atmospheric Overvoltages Propagation // The 52nd Annual International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering: Abstract Book and Electronic Proceedings, Latvia, Riga, October 13–16, 2011,– pp. 45–45.
7. Sļiskis O., Miesniece S., Ketners K., Vanzovičs E. Application of ATP/EMTP Program for Solving of Some High-Voltage Engineering Problems // Abstract Book and Electronic Proceedings, Latvia, Riga, October 11–14, 2010,– pp. 137–140.
8. Sļiskis O., Miesniece S., Ketners K., Vanzovičs E. Zibensizlādes raksturīgie parametri pārspriegumaizsardzības skaitliskos uzdevumos // RTU zinātniskie raksti, 4. sēr., Enerģētika un elektrotehnika. – 26. sēj., 2010, 46.–49. lpp.

1. DEFINITION OF INSULATION FAILURES FLASHOVER RATE AT TL DESIGNING

In the first section of the Doctoral Thesis, within the frame of the research, TL is considered as an object of an automated designing. The necessity to check the TL IFFR, taking into account the properties of its bearing metal constructions and constructive differences, is established.

The standard flowchart of the algorithm of TL designing is given in Fig. 1.1. The actions included in the designing process can be repeated if the results of the project do not correspond to the design statement. In the end result, the developed project has to correspond to all initially specified conditions [2].



1.1. Fig. Typical steps in an overhead transmission line design.

From the flowchart of the algorithm of the TL project working out, given in Fig. 1.1., separate designing stages, which are essential when determining the IFFR, can be allocated, respectively [2]:

- Select Route – ideally, the line route should be as short and straight as possible in order to minimise the costs, minimise the stays and have a tidy appearance; from lightning protection estimation – impact ground resistivity value;

- Select Overall Structure and Poletop Construction Types – from lightning protection standpoint, it is a more important stage, taking into account construction geometry un mechanical stability;
- Nominate Strain Points, Pole Details and Poletop Constructions – should be used to isolate electrically different circuits (for conductors, catenary constructions, etc.).

When there is direct lightning discharge in TL tower or in a shielding wire, at passing of the lightning current through a metal construction or its basis, there is a difference of potentials on insulation. If the value of an indicator of insulation/insulator backflashover is exceeded, there an insulation lightning flashover will occur. The voltage, induced in the tower, depends on grounding resistance, at the same time it is one of the determined parameters at an estimation of IFFR of TL. [3]

It is known that calculations of the models of electromagnetic processes transition are the fundamental requirement at the implementation of the researches of a complete chain of the problems of power system, for example, at the choice of insulator or parameters of a protective discharger for a substation [5].

As it is seen in the Table 1.1. [19], almost a half from all lightning discharges of TL directly accounts for towers. Simply it is possible to accept that each such flashover of the insulation of TL passes into the arc discharge (the series methods of calculation indicates that the probability of the appearance of an arch will be a little less than 1). Then the number of switching outs of TL caused by the lightning is found by the expression:

$$N_{\mathrm{EPL}} = \left(D_{\mathrm{tr}} P_{\mathrm{tr}} + D_{\mathrm{bal}} P_{\mathrm{bal}} + D_{\mathrm{v}} P_{\mathrm{v}}\right) \cdot n \cdot \frac{L_{\mathrm{EPL}}}{100} \cdot \frac{T_{\mathrm{n}}}{100}, \tag{1.1}$$

where P_{tr}, P_{bal}, P_{v} – a possibility of insulation/insulator flashover of TL (r. v.), if lightning discharge occurs respectively in a shielding wire, in tower, or in phase conductors; D_{tr}, D_{bal}, D_{v} – discharge distribution (r. q.) on shielding wire, TL tower, or phase conductors; n – specific quantity of lightning discharges in TL; L_{EPL} – length of TL, km; T_{n} – the number of storm hours during a year around the TL area.

Table 1.1.

Lightning flash distribution on TL elements

Discharge distribution *D*, r.q.	**TL with shielding wire**	**TL without shielding wire**
To shielding wires span length, D_{tr}	0.5	0
To towers, D_{bal}	0.5	0.5
To phase conductors, D_{v}* * 80 % of discharge – to upper phase	0.005	0.5
$D_{\mathrm{tr}} + D_{\mathrm{bal}} + D_{\mathrm{v}} = 1$	≈1	1

As usual, the lines with one chain with horizontal placement of wires have better IFFR properties than the line with two chains, but on the lines with two shielding wires, the shutdowns which are caused by direct lightning discharge occur considerably less than on the lines with one shielding wire [25]. In Fig. 1.2., the constructions of TL towers of 110 kV, 150 kV (Portugal), 170 kV, 220 kV (Portugal, PRC), 400 kV, and 500 kV (Israel) are given.

It should be noted that the constructions of towers of *f* type given in Fig. 1.2. are not reliable from the point of view of IFFR, though the use of two shielding wires is structurally provided in them. The length of the traverses of shielding wires does not provide sufficient distance between them, which at the same time reduces the shielding effect on the top and average phase. Despite such shortcoming, in the lines of such type, statistically there are less outages which happen by the reason of direct lightning discharges than in the lines with two chains with one shielding wire and the smaller protection angle.

Constructions of TL towers given in Fig. 1.2., as *a, b,* and *d*, replaced the towers existing before the exploitation and which were not intended for areas with strong frosting at all. After dumping of ice, strong fluctuation of wires and shielding wires was observed, which inevitably was followed by short circuits [25]. Therefore, in the newest designs of TL towers, the vertical distances between wires and a shielding wire(-s) have been considerably increased, which has led to the general increase in the height of TL towers, on average on 4.5 m. Two considerably remote shielding wires have been provided in the new constructions instead of one shielding wire that provided the maximum protection angle.

When comparing with the data of exploitation, it is visible that TL with horizontal placement of wires as *c* and *e* in Fig. 1.2, from the point of view of IFFR, have considerable advantages, thanks to rather small heights and two mutually remote ground wires.

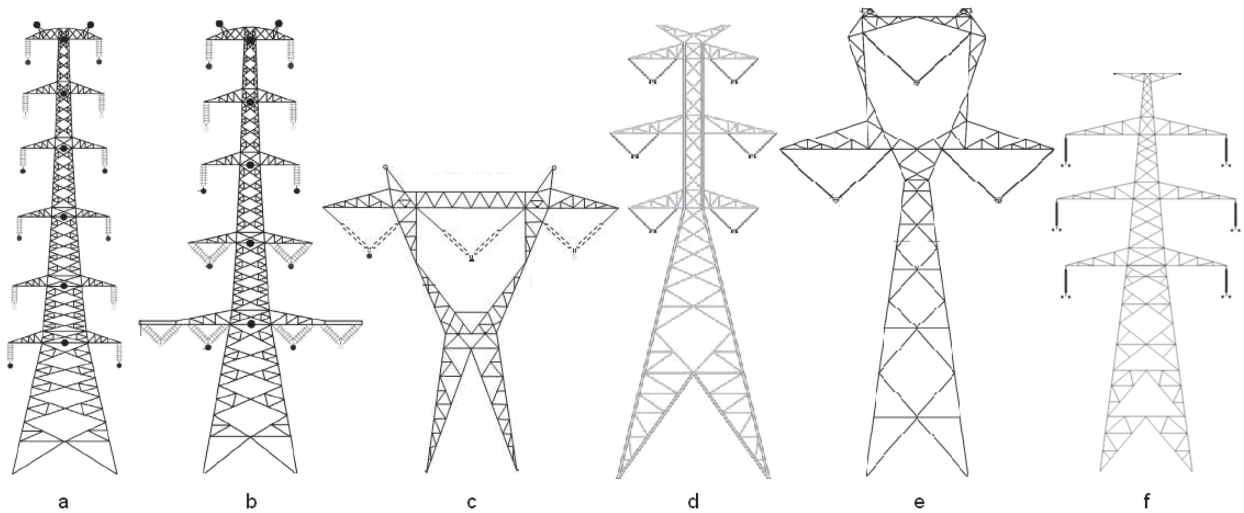


Fig. 1.2. TL towers: a, b and c – State Grid Corporation of China, SGCC; d – Israel Electric Corporation, IEC; e, f – *Energias de Portugal, EDP.*

In Table 1.2., the statistics [4] about successful action of the protection system against lightning on TL of the 500 kV lines in China is generalized. On TL from all registered lightning discharges, 129.52 discharges/100 km/year have been successfully taken away, and the part of outages that have arisen by the reason of the backflashover of insulation is 0.59 %. Thus, if the lightning discharge is taken away, in one of 168 cases there were outages of TL.

Table 1.2.

500 kV TL lightning protection success shielding

500 kV transmission lines	Non-outage (case/100km/year)	Lightning outage (case/100km/year)	Total (case/100km/year)
Shielding success (Lightning strokes to tower/GW)	**128.75 (98.4%)**	**0.77:** Back flashover **(0.59%)**	**129.52 (99.0%)**
Shielding failure (Direct lightning strokes)	**0.77 (0.59%)**	**0.51:** Flashover **(0.39%)**	**1.28 (0.98%)**
Total of lightning strokes to facilities	**129.52 (99.0%)**	**1.28 (0.98%)**	**130.80 (100%)**

Successful taking-away the lightning discharge is registered in 99.0 % of cases, that is, 101 of 102 of lightning discharge have been taken away. Direct lightning discharge in phase conductors is registered in 0.98 % of cases (1 of 102 cases of straight lightning discharges in TL). The share of lightning discharges in TL makes 0.98 %, in 0.59 % of them from the registered lightning discharge in TL, or 60.2 % of direct lightning discharge in TL have not led to their outages. In turn, 0.39 % of the registered lightning discharges, or 1 case from 256 (which makes 39.8 % of direct lightning discharges in TL) were the reason of switching out of TL as it is shown in Fig. 1.3. [4]

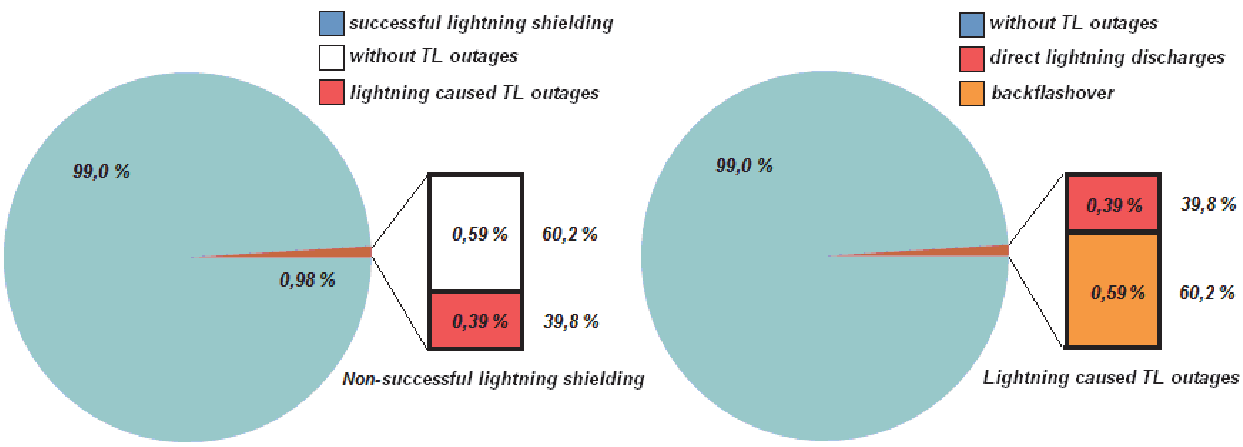


Fig. 1.3. Statistical data of shielded lightning discharges on TL.

On the normative base, according to which in the course of designing of TL the aspects of the impact of a lightning on TL have been also taken into account, it is technical reports of IEEE and CIGRE working committees, for example:

- *IEEE Guide for Improving the Lightning Performance of Transmission Lines* has been approved in 1977,
- *CIGRE Guide* to procedures for estimating the lightning performance of transmission lines has been developed in 1991 (Working Group 01 of Study Committee 33).

Also should be noted the regulations RD.153-34.3-35.125-99 «Руководство по защите электрических сетей 6-1150кВ от грозовых и внутренних перенапряжений», which coordinate the state joint-stock company of the Russian Federation «ЕЭС России», where the principles of IFFR of electric networks with various voltage are stated. However, despite the existence of the specified documents, there is no uniform approach how methodically to state the procedure of decision-making at an estimation of the number of outages of TL caused by a lightning, taking into account the properties of the bearing metal constructions of TL.

2. LIGHTNING CURRENT PARAMETERS AND MATHEMATICAL MODELS

As there is no uniform concept of definition of IFFR, experts sometimes are guided by systematized statistical data, for example, from the point of view of reliability of the exploitation of TL, the number of storm hours in a year is important; however, more often it is necessary to use the density of lightning discharges for concrete areas of exploitation.

Statistical data of the observations presented in Table 2.1. [4] show that in the zone of supervision by means of the system of monitoring the thunder-storm LLS (Lightning Location System) with super high rates on TL of 500 kV in China have stated the density of lightning discharge from 4.4 to 6.7 discharges/km^2/year. In the same place, during supervision of TL of 500 kV with super high voltage has respectively stated 4.7 and 4.9 outages/year/100km.

Table 2.1.

Lightning stroke density to 500 kV and UHV TL

	Lightning stroke density to ground for UHV-designed transmission lines, flash/km^2/year		Lightning stroke density to ground for 500kV transmission lines, flash/km^2/year	
	Lightning outage results	Observation of lightning strokes	Lightning outage results	Observation of lightning strokes
Shielding success	Back flashover 4.7	Lightning stroke to tower/GW 6.7	Back flashover 4.9	Lightning stroke to tower/GW 4.4
Shielding failure	Flashover 4.7	Direct lightning stroke to phase conductor 5.2	Flashover 4.9	Direct lightning stroke to phase conductor 4.9

The amplitude of the lightning current running through the damaged object, also, as the approximate height of the leader of a lightning, depends on the magnitude of a charge of the leader of a lightning. The parameters of calculations in tasks of TL IFFR are the amplitude of lightning current I_z, and the abruptness of lightning current α. In practical calculations, the amplitude and abruptness of lightning current are accepted as values of statistically independent case and are established in [4].

The lengths of the front of an impulse of lightning discharge τ_1 and waves τ_2 are also random variables magnitudes. Primary discharges characterize rather large lengths of the front of wave in comparison with secondary discharges [13]. The abruptness of the front is directly connected with the front length; therefore, there is an opportunity to consider both the abruptness of the front and its length according to the function of the division of the lightning current parameters (see Fig. 2.1.).

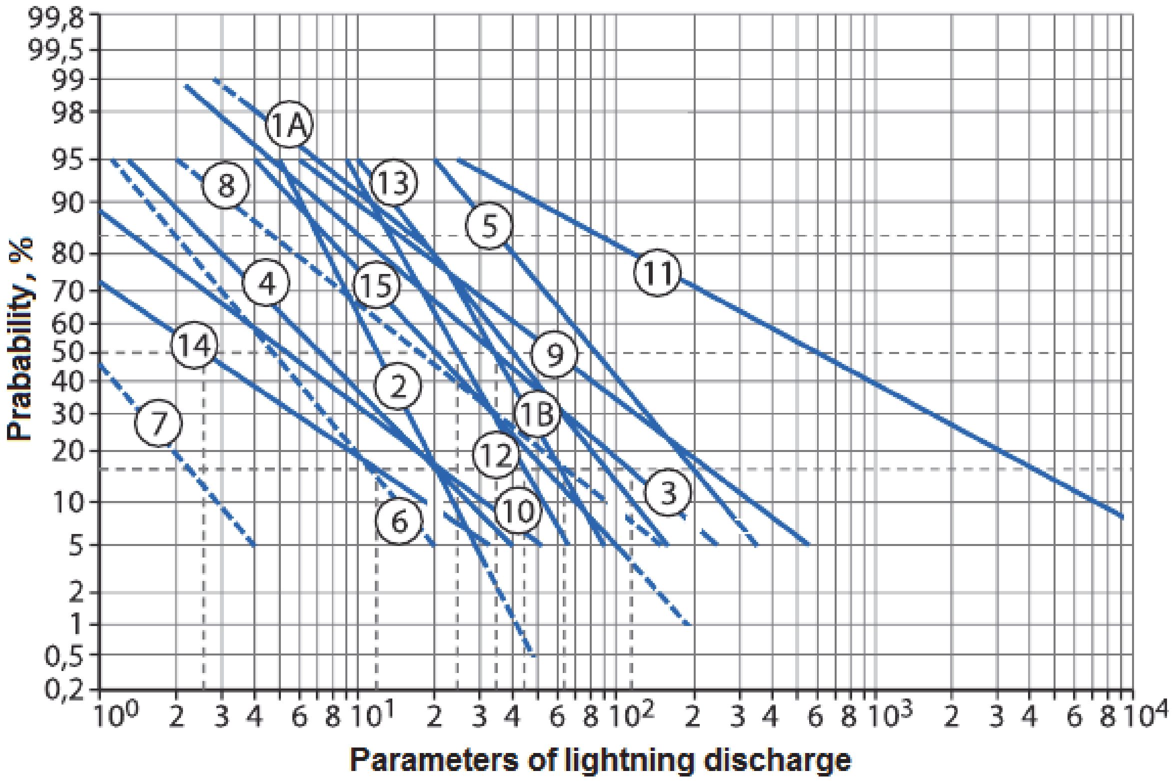


Fig. 2.1. Lightning stroke parameters according to IEC 62305-1 [13],
where for maximum lightning current *I*(kA): **1A**,**B –** first stroke; **2 –** secondary negative stroke; **3 –** first positive short stroke with electric charge *Q*(C); **4** – negative stroke; **5** – positive short stroke with electric charge *Q* (C); **6** – first stroke; **7** – secondary negative stroke; **8** – first positive short stroke with specific energy *W*/*R* (kJ/Ω); **9** – first stroke; **10** – secondary negative stroke; **11** – first positive short stroke with pulse steepness di/dt_{max}; **12** – first stroke; **13** – secondary negative stroke; **14** – first positive short stroke with pulse steepness $di/dt_{30\%/90\%}$; **15** – secondary negative short stroke.

The speed of distribution of lightning current is equivalent to the speed of light in the free premise [5], [13]. In some cases we accept the resistance of the channel of a lightning Zz as equal to 400 Ω [5]; however, in standard calculations, Cigré, IEEE, and also in the IEC standards and in technical reports, this value is equal to 1 kΩ.

The most closer to experimentally established impulses of lightning current, there are analytical expressions that represent the form of an impulse of lightning current in of discharge. The most widespread is the so-called “Heidler function”, which, as describing the form of impulse of lightning current, is offered by the German mathematician professor F. Heidler [6]:

$$I(t)=\frac{I_{\max}}{\eta}\frac{\left(\frac{t_1}{\tau_1}\right)^n}{1+\left(\frac{t_2}{\tau_1}\right)^n}\text{, kur }\eta=e^{-\left(\frac{\tau_1}{\tau_2}\sqrt[n+1]{\frac{n\tau_2}{\tau_1}}\right)},\qquad(2.1)$$

where I_{max} – maximum lightning current in discharge channel;

τ_1, τ_2 – pulse wave decrease and increase time coefficients;

t_1, t_2 – pulse wave decrease and increase time;

n – number of secondary strokes;

η – correction factor of lightning maximum stroke.

The derivative of the Heidler function becomes equal to 0 over time that corresponds also to real measurements of backflashover; at the same time, this function allows regulating precisely the current amplitude, as derivative of the maximum current does not depend on the electric charge.

Distinction between impulse forms is graphically shown in Fig. 2.2., which is derivable according to the Heidler function and the two-exponential impulse, according to (2.2) [6]:

$$i_0(t) = \frac{I_0}{\eta}\left(e^{-(-t/\tau_1)/\tau_2} - e^{(t-\tau_1/\tau_2)}\right)^{-1}, \tag{2.2}$$

where I_0 – maximum lightning current; η – correction factor of lightning maximum stroke, τ_1; and τ_2 – pulse wave decrease and increase time coefficients, in general case $t = \tau_1 ln(n)$ [6].

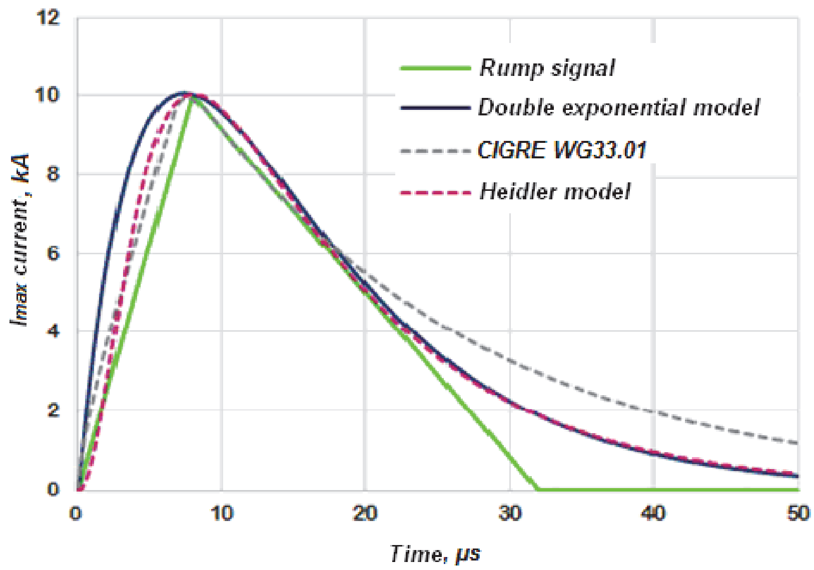


Fig. 2.2. Pulse forms of lightning current according to Heidler and double exponential functions [6].

According to [16], the magnitude of lightning current depends only on the level of the protection of the object, but, as specified before, it is not completely correct. In order to estimate more precisely the danger that the direct lightning discharges in TL can cause, it is necessary to consider the dependence of the lightning current value also from other aspects – first of all, from constructive properties and the dimensions of the object.

When there is lightning discharge in a shielding wire, along all wires up to the TL tower pass the reflected overvoltage waves, respectively, vectors U_{kr} and U_{lab} (see Fig. 2.3.). The circuit of replacement can be transformed as a network with scattered parameters, which create the active resistance and which are equal with mutual counteractions of a wave for the line without losses

[20]. Further, the vectors of waves U_{kr} and U_{lab} are summarized, but the equivalent scheme of the network is similarly given in Fig. 2.3.

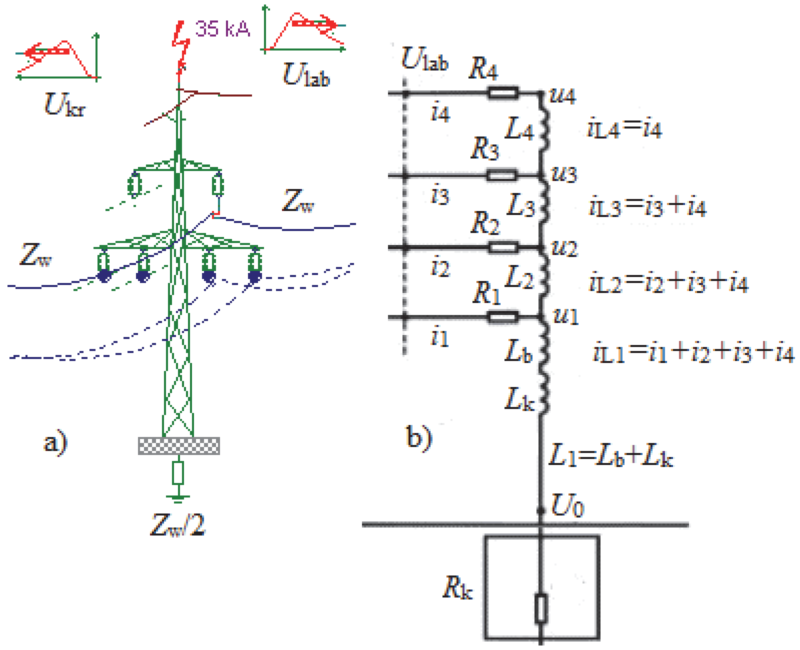


Fig. 2.3. TL tower equivalent scheme.

The system of the equations of replacement, given in Fig. 2.3., is the following [20]:

$$
\begin{aligned}
u_1 &= L_1 \frac{\mathrm{d}}{\mathrm{d}t}(i_1+i_2+i_3+i_4)+R_k(i_1+i_2+i_3+i_4);\\
u_2-u_1 &= L_2 \frac{\mathrm{d}}{\mathrm{d}t}(i_2+i_3+i_4);\\
u_3-u_2 &= L_3 \frac{\mathrm{d}}{\mathrm{d}t}(i_3+i_4);\\
u_4-u_3 &= L_4 \frac{\mathrm{d}}{\mathrm{d}t} i_4 .
\end{aligned}
\tag{2.3}
$$

Increasing the voltage at the moment of the impact of the wave of overvoltage in TL towers, standing nearby, depends on the surge impedance of tower Z_{bal}:

$$Z_{bal} = 60 \ln\left(\operatorname{ctg}\left[0{,}5\,\operatorname{tg}^{-1}\left(\frac{r_{ekv}}{H}\right)\right]\right), \tag{2.4}$$

where r_{ekv} – tower equivalent radiuss; H – tower height [9].

$$Z_{tr} = 60 \ln\left(\frac{2h_{vid}}{r}\right), \tag{2.5}$$

where h_{vid} – average hight of shielding wire, m; r – radius of shielding wire, m [18].

At the moment when the wave reflected from the grounding electrode with an opposite sign reaches the TL tower, the growth of voltage in tower increases. At the moment when the voltage in tower U_o reaches the maximum value, the equivalent circuit on tower is formed by consistently connected inductance of tower L_0 and pulse resistance with average value [9]:

$$R_{i\_\text{vid}} = \exp\left(\frac{1}{n}\right)\sum_{i=1}^{n} \ln R_i\,, \tag{2.6}$$

where n – tower quantity on the model.

The inductance of tower L_0 is calculated by formula $L_0 \approx L^*_0 h_0$, where h_0 – height of tower, and L^*_0 – inductance on a unit of height of tower – 0.5 μH/m for metal towers with two racks and 1.0 μH/m for metal towers with one rack. The amplitude of lightning current near the tower is smaller than the lightning current in tower $I_{\max}$, where there is lightning discharge, as a part of the current flows down in shielding wires and a part is reflected on the canal of a lightning. In practical calculations, the coefficient of a branching of the lightning current χ from expression is entered:

$$\chi = \frac{Z_{\text{bal}}\left[\frac{Z_{\text{tr}}}{2}\right]R_i}{R_{i\_\text{vid}}}, \tag{2.7}$$

where the elements Z_{bal} and Z_{tr} of a chain are connected in parallel [12].

In this case, the equation (2.1) will be transformed

$$I(t) = \frac{I_s}{\eta}\frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n}, \text{ where branched current } I_s = \chi I_{\max}. \tag{2.8}$$

3. MODELLING OF THE PROCESS OF DISTRIBUTION OF LIGHTNING CURRENT IN METAL CONSTRUCTIONS OF TL

Possibilities of the analysis of the various methods of the protection of TL against an overvoltage and application of software are reflected in technical literature. These methods cover both computer modelling and, for example, such specific method as the use of Monte-Karlo in the analysis of distribution of overvoltage waves with stochastic parameters of all consecutive chains. Among applied software it is possible to note *EMTP/ATP*, *PSCAD*, *Matlab SIMULINK* and others, its efficiency is also approved, for example, model of a network of artificial neurons, concerning the synthesis and analysis of complicated processes in power systems. [3], [10]

The development of the course of representation and drawing up the scheme of replacement for practical problems of the process of lightning discharge by means of an engineering and mathematical model is given in Fig. 3.1.

Electromagnetic coupling between the lumped and distributed components is replaced with the interacting capacities with mutual inductance, magnetic and electric fields, and, respectively, without mutual resistance adhere in the environment where there are losses. The general model of object is formed by the system of the elements *L, C,* and *R*, which is structurally divided into smaller sections with electromagnetic coupling. Each section includes the concentrated and scattered parameters *L, C*, and *R.* The concentrated and scattered elements are equipped according to Kirchhoff's laws on voltage and current, so that the solution of a task was possible on sites of time and frequency [5].

The use of equivalent schemes, which consist only of the lumped parameters, limits the wide range of frequencies necessary for the solution of a task. Application of this model is also limited because the magnitudes of the sections of the lumped elements is many times less than the minimum wave length [5]. Application of the schemes of replacement for TL with distributed parameters requires obligatory observance of coupling between the system of conducting elements and the earth [5].

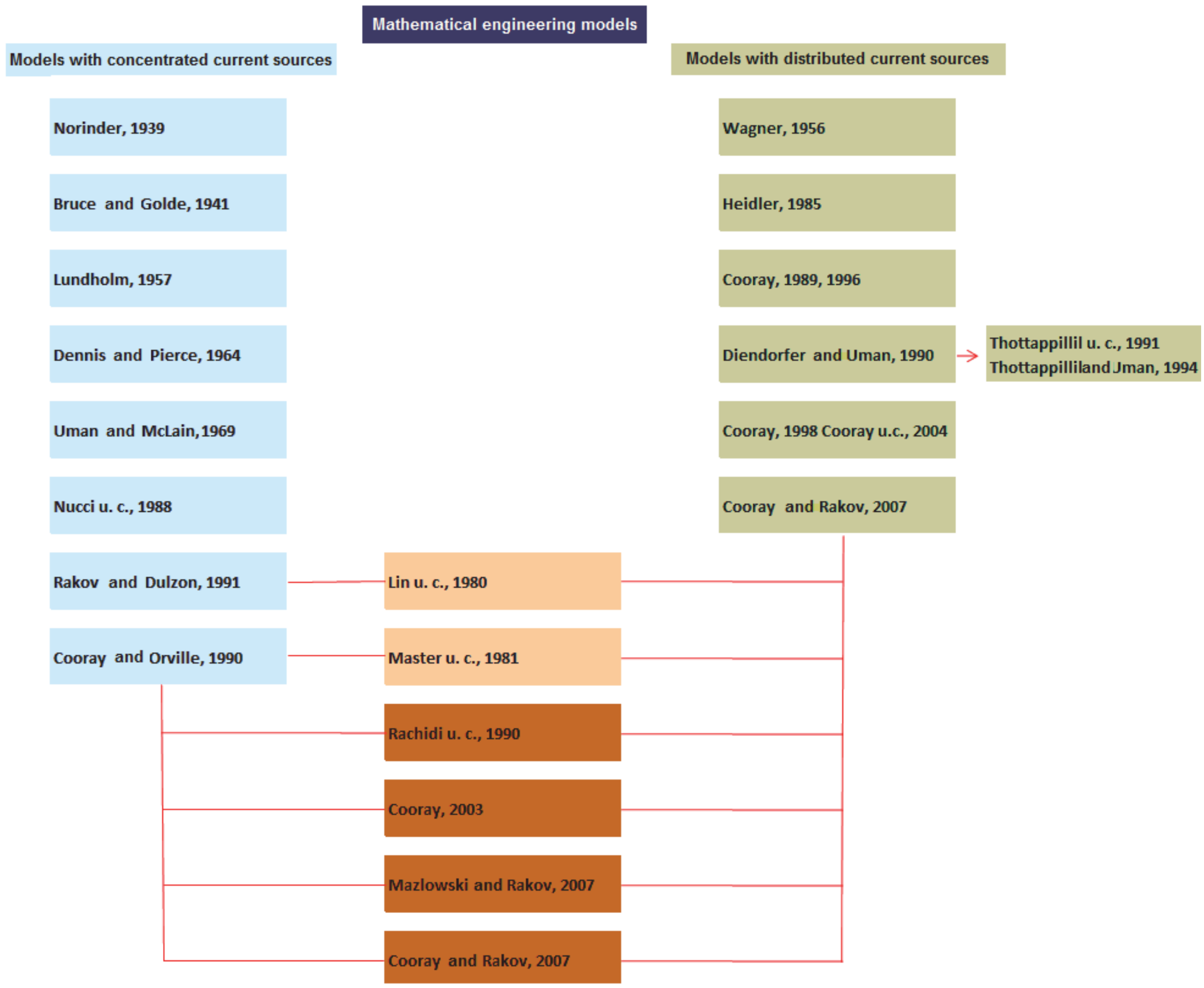


Fig. 3.1. Development of lightning discharge mathematical models.

It should be noted that the basic elements of the power network, with the exception of electromagnetic transient processes in conductors and ground wires, computer simulation techniques are described fully in order to be usable in practice. TL towers and TL portal bearing simplified structure models are offered in the literature, but only the initial detailed model analysis allows judging the permissible simplification option. A typical TL model structure designed surges process analysis (including *CIGRE* and IEEE) using *EMTP* software tool is given in Fig. 3.2.

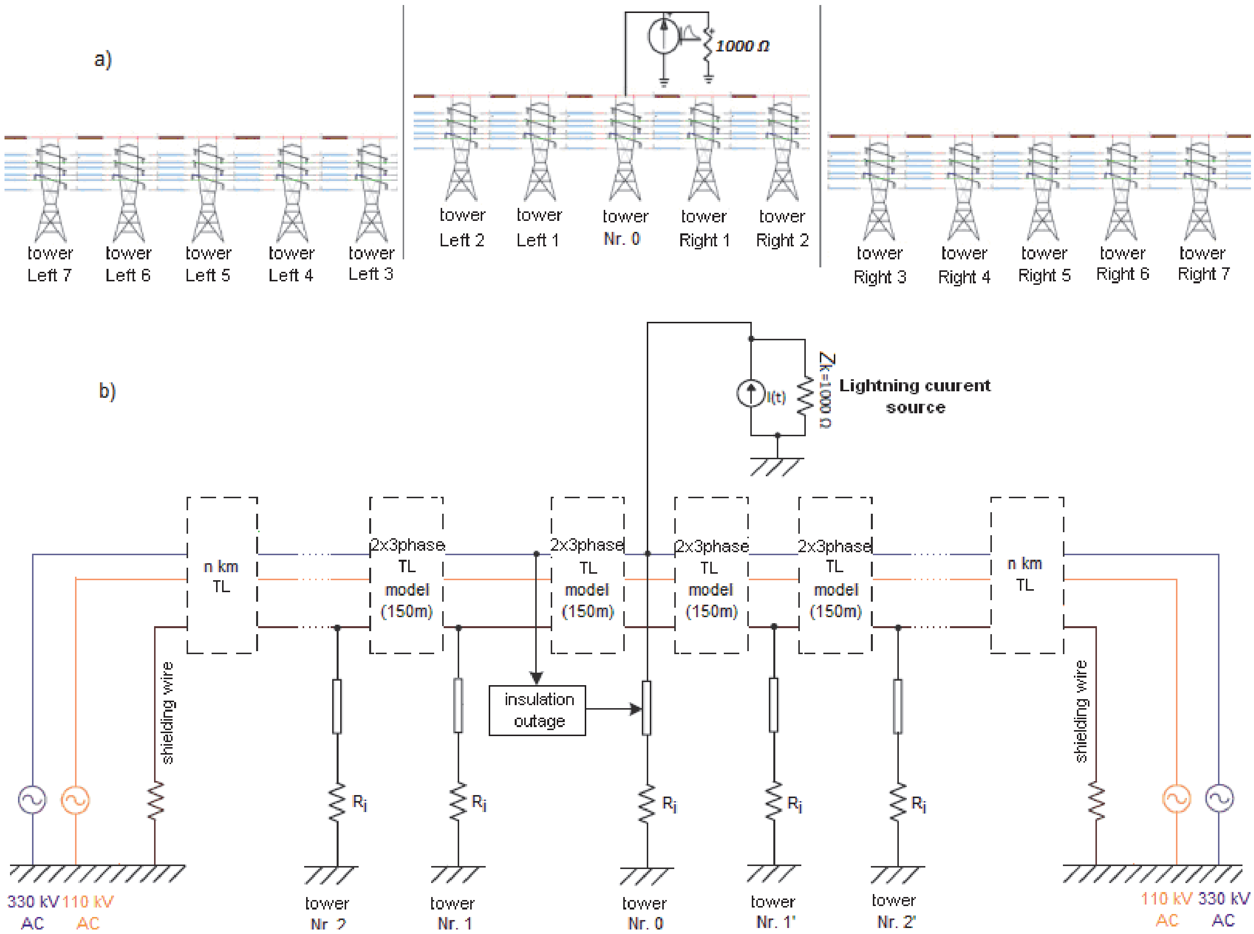


Fig. 3.2. Typical TL model structure designed surges process analysis [5]:
a) TL segment with 16 spans; b) *EMTP* TL block scheme.

The algorithm of the *EMTP* program provides a set of the models of replacement for spans of TL:

a) Model of *Bergeron* – model with constant parameters,

b) Model *PI* – for short, to several tens kilometers of TL,

c) the *JMarti* model – model of matrix type with the elements depending on frequency,

d) Semlyen – simplified model with the elements depending on frequency.

The model of Bergeron allows considering the processes of distribution of waves in the schemes with the scattered TL parameters and with the concentrated resistance. Like the *PI* model, the model of *Bergeron* allows using only the frequency of 50 Hz; therefore, by drawing up a scheme of replacement, the *JMarti* model for spans of TL has been chosen [5].

Considerating the processes that occur in the TL tower in the case of the impact of lightning discharges, it is necessary to consider the influence of the towers that are situated nearby and the reflection of the waves of an overvoltage. The parameters of TL spans are defined by electric properties of wires and shielding wires and placement geometry. The *JMarti* for spans of TL model provides actions in the range of frequencies from $5 \cdot 10^{-2}$ Hz up to $5 \cdot 10^{8}$ Hz, taking into account the influence of surface effect [1].

It is accepted that the analyzed site of TL is created by a model from four spans and five of TL towers. The maximum time that corresponds to the reflection of waves of overvoltage from the first near tower is estimated as a double run of a wave to the next tower and back, considering from the moment of discharge [1].

The tower of TL is formed of four sections with the scattered parameters (that allows observing the attenuations and distortions of waves), respectively from the earth to lower Z_{t1} traverses, from lower to average Z_{t2} traverses, from average traverses to the top of Z_{t3}, and from top traverses to the ground wire Z_{t4}. The values of R and L are established by expressions [5]:

$$
\begin{gathered}
R_i = \Delta R_i h_i,\ L_i = 2\tau R_i, \\
\Delta R_1 = \Delta R_2 = \Delta R_3 = 2Z_{1t} \ln \frac{1/\alpha_1}{h - h_4}, \\
\Delta R_4 = 2Z_{4t} \ln \frac{1/\alpha_1}{h},
\end{gathered}
\tag{3.1}
$$

where $\tau = h/c_0$ – wave travel time on TL tower, $\alpha_1 = 0{,}89$ – wave decreasing coefficient (on tower); H – TL tower height.

The resistance of grounding of TL tower is simulated as the linear resistance Ri*,* but also it is possible to replace it with the nonlinear resistance depending on the current. By means of *ETP/AMTP*, for example, characteristics of division of lightning current in traverses of TL towers, similarly shown in Fig. 4.3, can be received.

The variety of the bearing constructions of TL practically does not allow creating a universal scheme of replacement for it, with the observance of parameters of constructive elements, that is, supports, traverses, the bases and reactive parameters of stays.

The definition of a trajectory of distribution of lightning current in the constructive TL towers elements can be realized by means of the *COMSOL Multiphysics* program. The graphic model of the modeled object should not contain the gaps, all segments forming the model of construction have to be mutually connected. For preparation of the software of the graphic model of the object, as recommended, *SolidWorks* and *Autodesk AutoCad* 3D can be noted. Creating a graphic model in the *COMSOL Multiphysics* programs and similar to it, is technically a very complicated and labor-intensive process because designing of the model is carried out by the establishment of the coordinates of basic points.

The vector of electric potential $\boldsymbol{V}$ and the vector of magnetic potential $\boldsymbol{A}$ in a randomly chosen point of the construction can be described by means of the equations:

$$-\nabla\left(\left(j\omega\sigma-\omega^{2}\varepsilon_{0}\varepsilon_{r}\right)\boldsymbol{A}+\left(\sigma+j\omega\varepsilon_{0}\varepsilon_{r}\right)\nabla V\right)=0; \tag{3.2}$$

$$\left(j\omega\sigma-\omega^{2}\varepsilon_{0}\varepsilon_{r}\right)\boldsymbol{A}+\left(\sigma+j\omega\varepsilon_{0}\varepsilon_{r}\right)\nabla V+\nabla\times\mu_{0}^{-1}\mu_{r}^{-1}\nabla\times\boldsymbol{A}=0, \tag{3.3}$$

where ω – rotation frequency; σ – electric conductivity; ε_0 – dielectric permiability; ε_r – specific dielectric permiability; μ_0 – magnetic permiability; and μ_r – specific magnetic permiability [5].

Boundary conditions for steel elements of construction are established by wave resistance, accepting the element thickness ≈0, which is stipulated by distribution of lightning current on an element surface. The expression of resistance of a wave can be transformed in such a way that it would correspond to Fig. 3.3. [15]:

$$Z_{\mathrm{e}}=\frac{U}{I}=\frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{r}{\sqrt{r^{2}+h^{2}}-h}\right), \tag{3.4}$$

where μ – magnetic constant; ε – electrical constant; r – equivalent radius of one segment; h – one segment height.

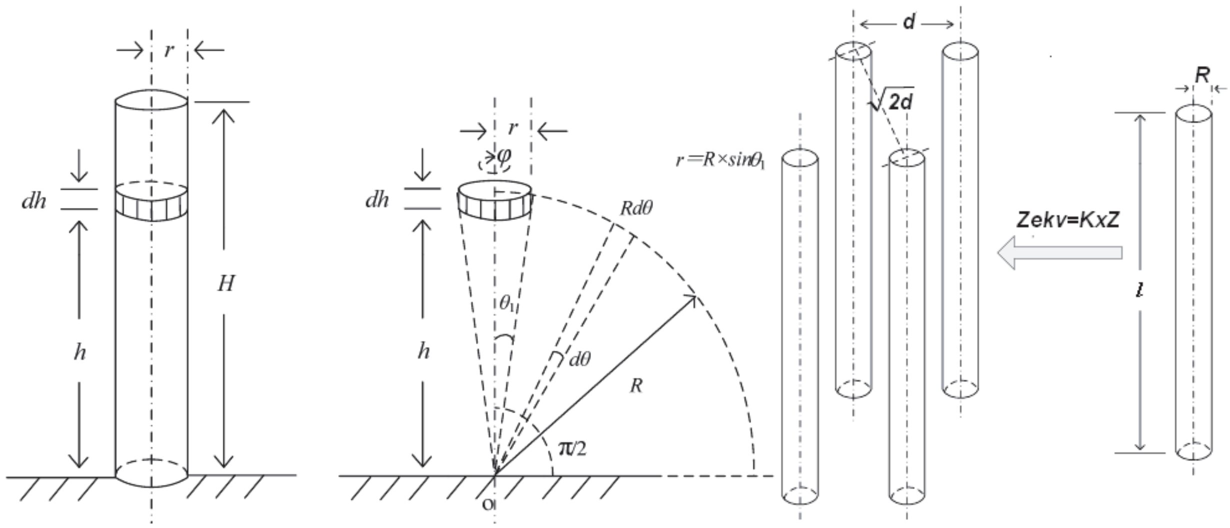


Fig. 3.3. System of four parallel segments [15].

It is accepted that the area of construction in space is formed by a system of four parallel segments located at identical distance from each other. Having entered the coefficient K, it is possible to pass from a single element to the system of segments, as shown in Fig. 3.3. So, for example, the figure of traverse's equivalent of TL tower creates four parallel segments, and the resistance of a wave of the traverse is determined by the theory of correlation of the model of an equivalent of parallel conductors (Fig. 3.4.).

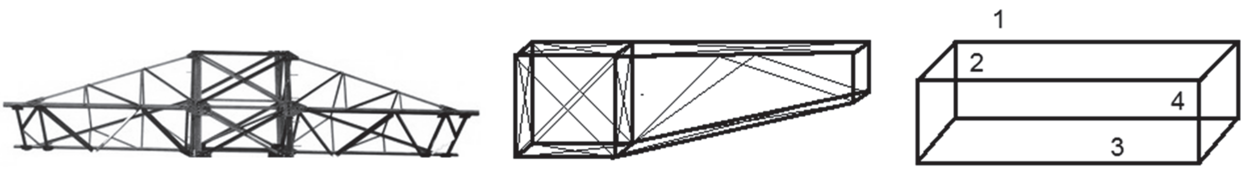


Fig. 3.4. Equivalent segment scheme of tower gantries.

The voltage for the system from four segments is defined from the expression [15]:

$$U=ZI, \tag{3.5}$$

where $U=[u_1, u_2 \dots u_n]^T$ and $I=[i_1, i_2 \dots i_n]^T$ – segment voltage and current vector column; Z – surge impedance matrix consisting of the mutual impedance and selfresistance.

Surge impedance of segment is described by the formula (3.6), and the mutual resistance of the wave of a segment is described by the formula (3.7.) [15]:

$$Z_{kk} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\left(\frac{h_{kk}}{r_k}\right), \tag{3.6}$$

$$Z_{km} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\left(\frac{h_{km}}{d_{km}}\right), \tag{3. 7}$$

where h_{kk} – length of vertical segments; h_{km} – length of horizontal segments; d_{km} – distance between segment k and segment m; and r_k – segment equivalent radius.

For the system from four parallel segments, the equation of potentials, where the potential of each segment is identical, is obtained: $u_1 = u_2 = u_3 = u_4 = u$. Accepting that the general system of the lightning current segments is identical in each segment, their value is the following: $i_1 = i_2 = i_3 = i_4 = i/4$; according to [15]:

$$\begin{cases} u_1 = Z_{11}i_1 + Z_{11}i_2 + Z_{13}i_3 + Z_{14}i_4 \\ u_2 = Z_{12}i_1 + Z_{22}i_2 + Z_{23}i_3 + Z_{24}i_4 \\ u_3 = Z_{13}i_1 + Z_{23}i_2 + Z_{33}i_3 + Z_{34}i_4 \\ u_3 = Z_{14}i_1 + Z_{24}i_2 + Z_{34}i_3 + Z_{44}i_4 \end{cases} \tag{3.8}$$

Space parameters, respectively, specific conductivity, dielectric and magnetic permeability, are set in each segment of construction before starting the process of calculations. The example of the results of previously described calculations for determination of the electric potential of a design is given in Fig. 3.5.

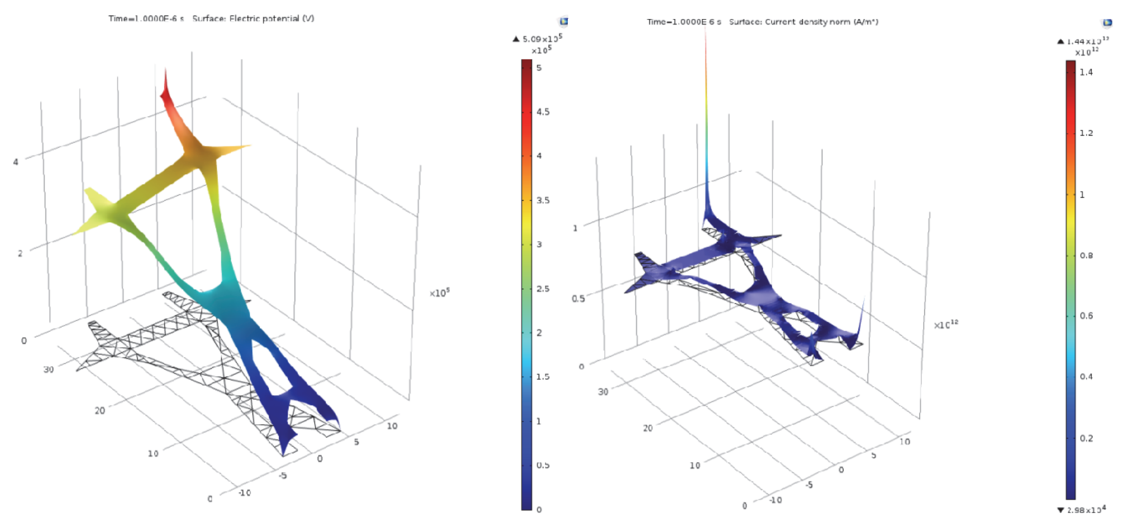


Fig. 3.5. The values of the electric potential of the P-1 type for TL tower at the moment of the beginning and the end of passing of lightning current.

The objects, the dimensions of which are less than the step of the network of calculations, are modeled by means of special methods. The so-called "Absorbing Boundary Conditions" or ABC belong to the special methods. The problem of these absorbing conditions: to ignore the influence of electromagnetic waves between two spaces, to absorb it, detaining the reflection of these waves from the borders of the area of calculations.

The source of lightning current is set by Heidler's function as an independent source of current, but the form of current is an impulse with the stage front. Electric potential on a surface of TL tower is established as an integral of electric field to the border of the area of calculations. Soil level also joins in the area of calculations and is modeled as the unlimited space, and the electromagnetic field there becomes calm because of the absorbing boundary conditions and is not reflected from the borders of the area of calculations.

4. METHODOLOGY OF INSULATION FAILURES FLASHOVER RATE ESTIMATION FOR METAL CONSTRUCTIONS IN OVERHEAD TRANSMISSION LINES

The main criteria of IFFR of the constructions of TL towers that are established already at the stage of development of the project and decision-making is the principle of prevention of the disruption of a phase conductor on metal elements (framework, traverses, and shielding wires).

As IFFR is called the ability to react steadily to the influence of an overloading from lightning. Within the offered methodology, the following criteria for evaluation of IFFR are considered:

1) the possibility of insulating construction flashover/disruption on TL tower in case of direct lightning discharge in a metal construction;
2) the possibility of dangerous distribution of waves overvoltage on TL and damage of insulating constructions nearby the towers;
3) the number of accidents n_b that occur due to insulation damage, the reason of which is atmospheric overvoltage.

To analyse the scenarios of the development of the mentioned dangerous modes and possible consequences, in this methodology, as the set parameters of calculations, are accepted:

1) overall dimensions of TL towers constructions;
2) longitudinal inductances L [μH/m] of the bearing constructions and traverses of towers;
3) the distances from the discharge to conducting elements.

As the changing parameters are accepted:

1) the range of impact resistance of grounding R_i [Ω] range;
2) the voltage of insulation/insulator flashover $U_{50\%}$ [kV].

In the present Doctoral Thesis, to consider the mutual influence of such parameters as lightning current and voltage between the conducting elements and the isolating constructions (towers between spans), the model of multi-wires long lines, which considers the spectrum of frequencies of grounding and resistance of wires, which corresponds to the lightning mode, is applied.

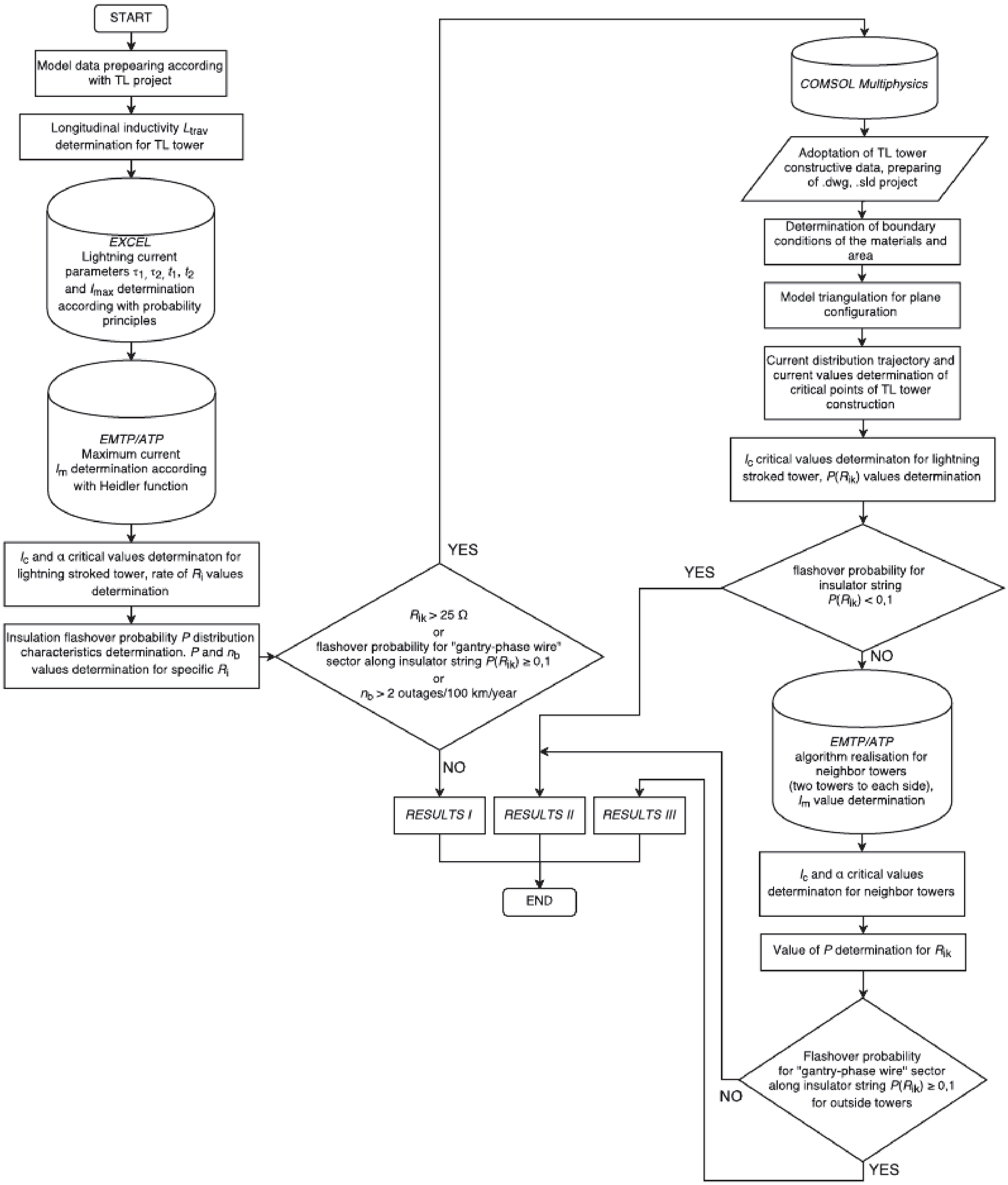


Fig. 4.1. IFFR of TL metal construction level determination algorithm.

The block scheme of the algorithm of the methodology is given in Fig. 4.1., and is provided for the cases when the task does not apply to the individual conditions, such as wind loading, frosting of shielding wires or phase conductors. The offered methodology of the evaluation of IFFR is provided for direct links of TL and is not provided for the protecting approaches to power plants and substations. The geometrical dimensions of TL are considered in the model, and each segment of construction (the sections of tower, traverses, etc.) is replaced with inductance. Thus, the task for a concrete situation can be solved more precisely, minimizing the influence of such factors as “average span”, “average height of a suspension bracket”, etc.

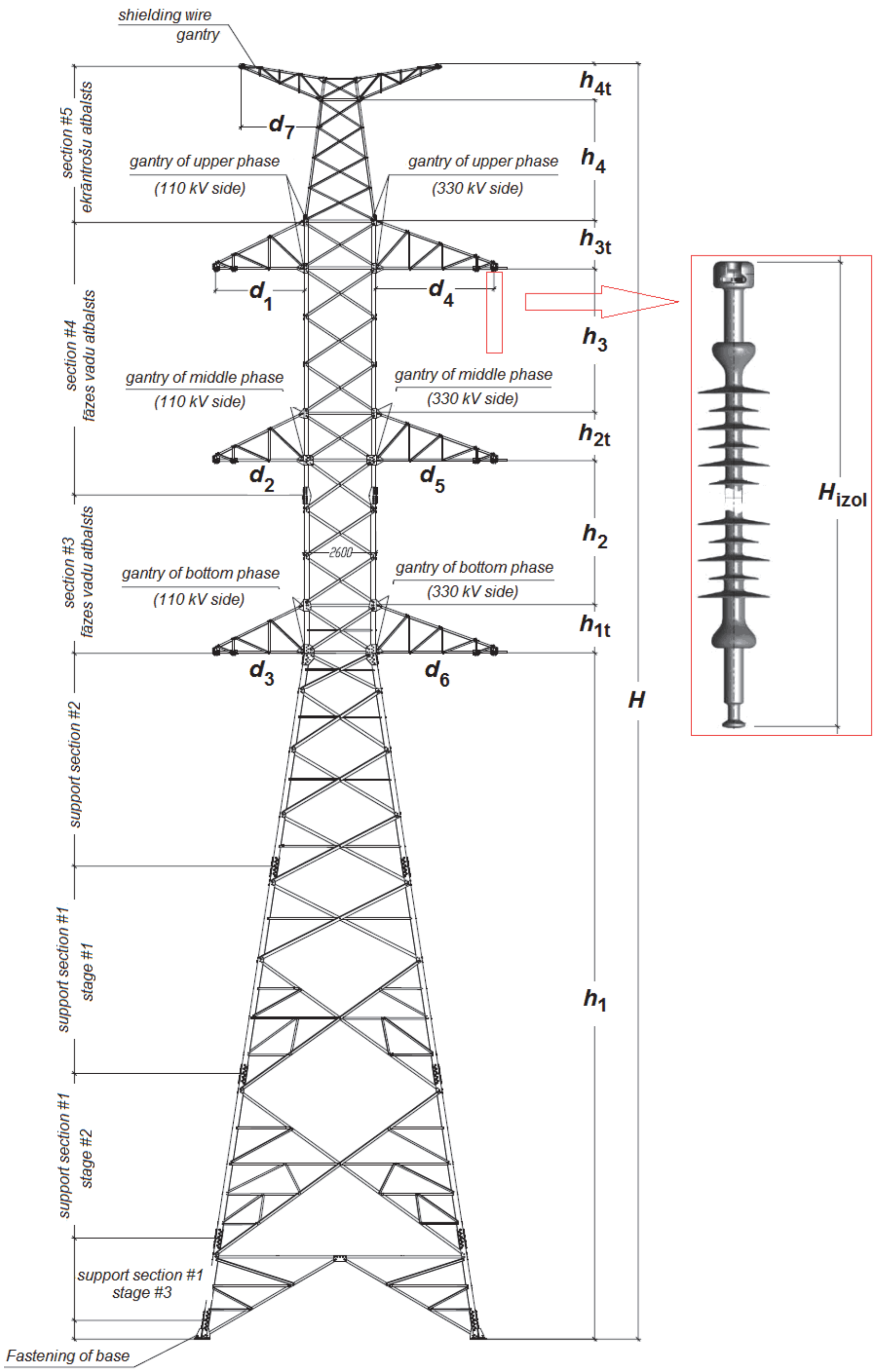


Fig. 4.2. 31T2 LS-25 TL tower for 330/110 kV voltage.

The realization of the algorithm begins with processing of the file with entrance data. All constructional parameters and communications are considered as entrance data, respectively, the height of the bearing constructions, especially up to the wire of each phase and the traverse of a shielding wire, the length of phase conductors and the traverses of shielding wires, the distance between traverses, according to the example given in Fig. 4.2. and corresponding to the data in Table 4.1., but in Table 4.2., the nominal and working voltages of electric systems used for calculations are given.

Table 4.1.

The data neccessary for determination of the double circuit
TL tower longitudinal inductivity L [μH/m]

Parameter	**Symbol**	**Value**	**Range**
Tower height	H	46.45	m
Mounting height of gantry of bottom phase	h_1	25.0	m
Mounting height of gantry of middle phase	h_2	5.25	m
Mounting height of gantry of upper phase	h_3	5.25	m
Mounting height of gantry of shielding wire	h_4	4.4	m
Height of gantry on 110 kV and 330 kV side	h_{1t}, h_{2t}, h_{3t}	1.75	m
Height of gantry of shielding wire	h_{4t}	1.2	m
Length of phase gantries on 110 kV side	d_1, d_2, d_3	3.2	m
Length of phase gantries on 330 kV side	d_4, d_5, d_6	4.3	m
Length of shielding wire gantry	d_7	2.69	m
Height of insulator string	H_{izol}	3.161	m
Mounting height of shielding wire	h_{tr}	46.45	m
TL span length	l	350.0	m
Distance between shielding wires	$d_{tr\text{-}tr}$	6.38	m
Average height of shielding wire on TL span	h_{vid_tr}	36.89	m
Sag of shielding wire	h_{tr}	14.34	m

Table 4.2.

Electric power system rated and maximum voltage

	U_{nom}, kV						
	110	150	220	330	500	750	1150
$U_{darba,\,max}$, kV	126	172	252	363	525	787	1200
$U_{f,\,max}$, kV	72.8	100	146	210	304	455	695

Except geometrical parameters of a metal TL tower, all lightning discharge parameters belong to entrance data: respectively, the maximum current of lightning discharge I_{max}, the time of weakening and increase of a wave t_1 and t_2, the coefficients of attenuation and increase of a wave τ_1 and τ_2; the number of secondary discharges n for the Baltic region is accepted as 2. For initial processing of these data – for the choice by the principle of probability in a statistically possible range, the MS EXCEL environment was used. In the model, the source of lightning current I_z influences the surface of TL tower. For definition of the variations of the value of the amplitude of lightning current $I_z(t)$, when using *EXCEL MS*, the following is filled in the calculation file for the values of the column of files:

- I_{max} in range 5÷100 kA,
- τ_1 in range $1.0 \cdot 10^{-6} \div 1.0 \cdot 10^{-5}$ s,
- t_1 in range $1.0 \cdot 10^{-6} \div 1.0 \cdot 10^{-5}$ s,
- t_2 in range $1.0 \cdot 10^{-6} \div 1.0 \cdot 10^{-5}$ s.

The resistance of the channel of a lightning is not changed and accepted as $Z_k = 1000\ \Omega$, but the coefficient of the increase of a wave is accepted as $\tau_2 = 60\ \mu s$ [7].

In Figs 4.3. and 4.4., the scheme of the replacement for tower *EMTP/ATP* for determination of the maximum value of traverses division at the moment of lightning discharge for TL towers with the equipped shielding wire is given. Determining the parameters of TL conducting elements, respectively, the number of phase conductors, their active resistance, length of span, and working frequency, *EMTP* chooses *JMarti* line's prototype.

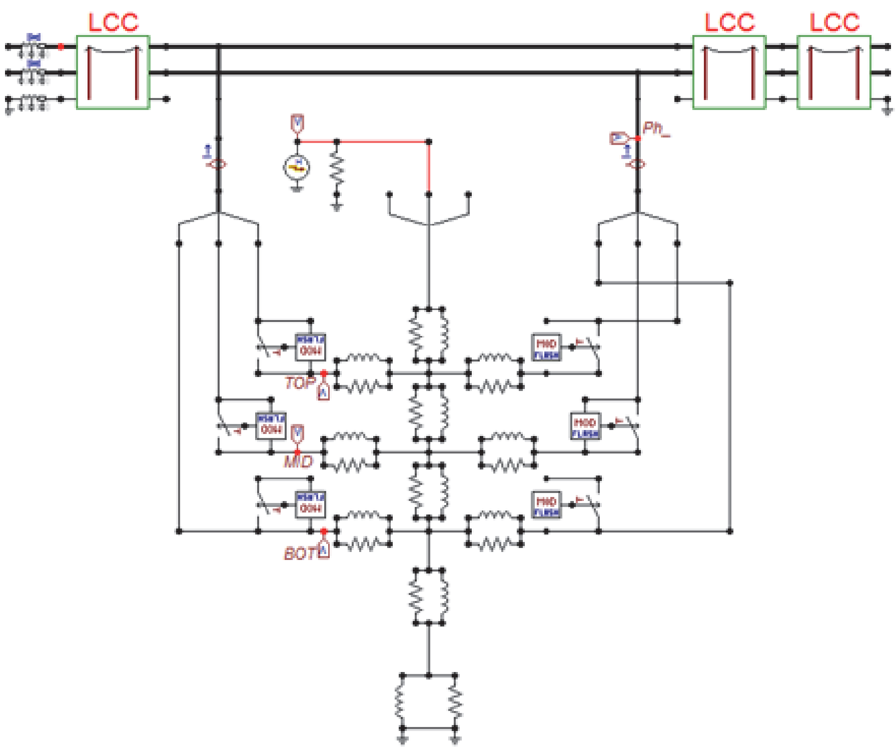


Fig. 4.3. Lightning current determination of TL tower on equivalent scheme

As it is specified in the recommendations of the working group of *CIGRE* C4.407 [14], the most applicable for imitation of the source of impact current of lightning is the source of the current of the back discharge. The source of the current of the anti-leader corresponds to the mathematical model of Heidler, which considers the resistance of the channel of lightning and the influence of the direct link of the object of discharge on the source of the current of the back discharge.

The traverses of TL tower are separated from the phase conductors by the isolating strings with concrete characteristics in volt-seconds – the *MODEL:Flash* block on the schemes of replacement. The *MODEL:Flash* block registers the increase in voltage, which influences the insulation of TL, according to characteristics in volt-seconds, block also registers the fact of insulation insulator flashover and "connects" the wire of the corresponding phase with the traverse of the tower. The block becomes more active only when the voltage of insulation exceeds the insulator flashover value. In the scheme of Fig 4.5., the characteristics of the division of lightning current I_m in the traverses of TL tower are given.

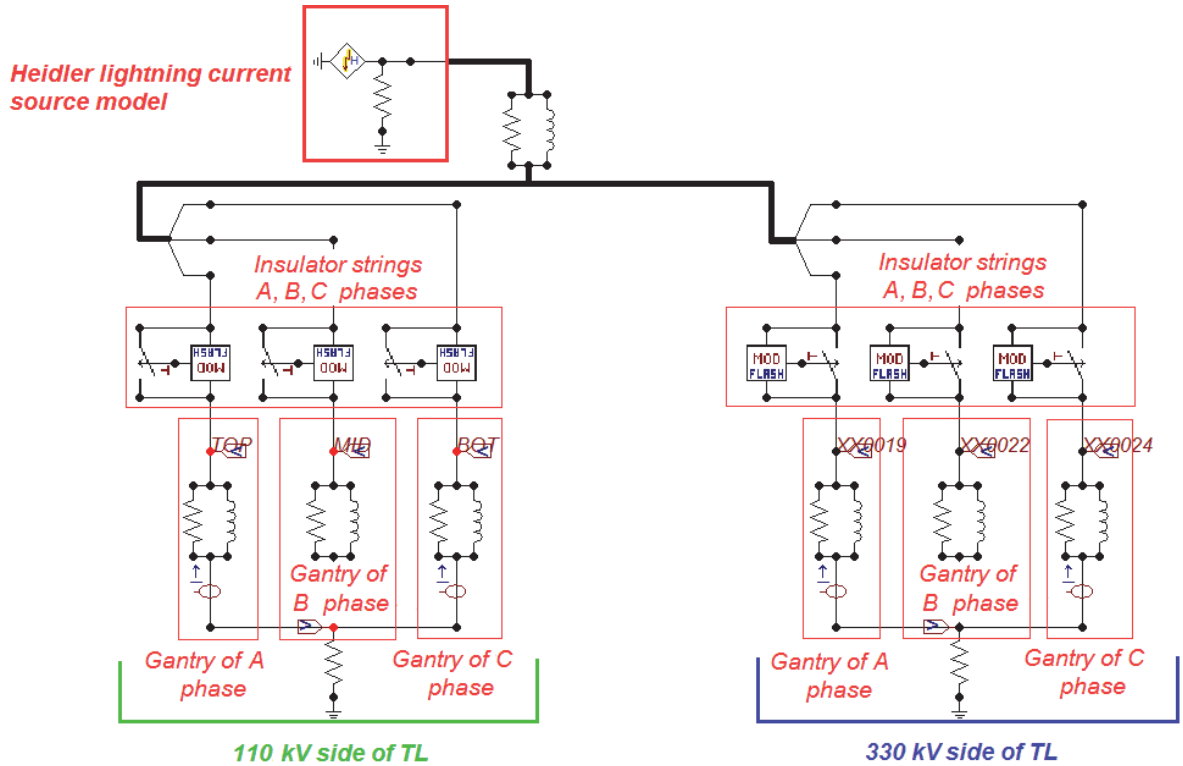


Fig. 4.5. A detailed EMTP equivalent scheme (without supporting constructions).

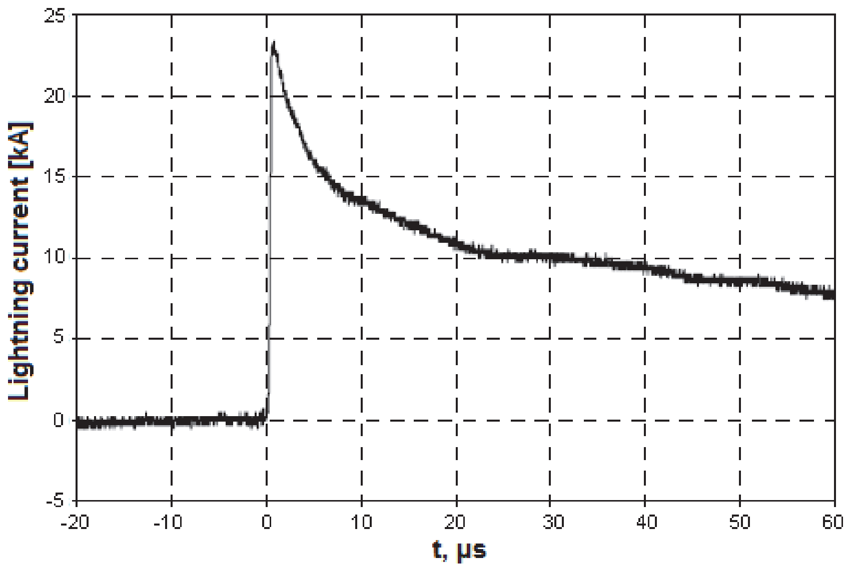


Fig. 4.5. Destribution of lightning current I_m on TL tower gantries.

The adoption of a particular type of insulator (insulator strings) 50% of the discharge voltage $U_{bal\text{-}v50\%}$ determined by the performance of the model and the construction of the TL regulatory requirements, the function of a possibility of division for sufficient value of the current for the area "wire–traverse" is found by the expression [25]:

$$P(I_c) = \left(1 + 2{,}1 \cdot 10^{-3} \cdot I_c + 1{,}4 \cdot 10^{-4} \cdot I_c^2 + 2{,}4 \cdot 10^{-5} \cdot I_c^3\right)^{-1}, \tag{4.1}$$

where I_c is a sufficient value of the current to secure against the insulation flashover.

Having accepted the voltage of the concrete insulator type (string of insulator) flashover as equal to 50 %, $U_{bal\text{-}v50\%}$, which defines the execution of the model and the regulating requirements of building of TL tower, the value of lightning current I_c will be found [25]:

$$I_c = \frac{\left(U_{bal-v50\%} - \alpha L\right)}{R_i}, \tag{4.2}$$

$$\text{but } \alpha = \frac{I_m}{\tau_1}, \tag{4.3}$$

where $U_{bal\text{-}v50\%}$ – insulator discharge voltage, kV; α – lightning current steepness, kA/μs, from EMTP calculation results; L – tower longitudinal inductivity (from lightning discharge point to phase conductor), μH/m; I_m – lightning current maximum value.

As the front length of the lightning current, which defines the distribution of the electromagnetic wave in the channel of a lightning, depends on the resistance of grounding of the channel of a lightning, the abruptness of lightning current decreases [18]:

$$\alpha(R_{ekv}) = \frac{\alpha(R_{ik} \approx 0)}{1 + \dfrac{R_{ik}}{Z_z}}, \tag{4.4}$$

where R_{ik} – measured soil pulse resistivity, Ω; Z_z – lightning channel resistivity (Z_z = 1000 Ω).

Probability of transition of the spark discharge to the area of a power arch "traverse–phase conductor"[24]:

$$\eta_{tr\_v} = (0{,}92E_{vid} - 6)10^{-2}, \tag{4.5}$$

but $E_{vid} = \dfrac{U_d}{H_{izol}}$, where U_d – TL maximum line voltage, kV; H_{izol} – height of insulator, m.

Thus, the probability of insulator flashover value for the area "traverse–phase conductor" will be found by the expression [25]:

$$P_{tr\_v} = \eta_{tr\_v} P_c. \tag{4.6}$$

For a case when lightning discharge occurs in the grounding elements of the construction of the tower, given in Fig. 4.2., at the change of the value of the impact resistance R_i and at reproduction of calculations by *EMTP*, and when using the expressions (4.1)–(4.6), the characteristics given in Fig. 4.6. will be obtained.

The characteristics given in Fig. 4.6. show the well-known fact that for the decrease in probability of insulation flashover the decrease in the resistance of grounding and the increase in the length of the string of the insulators H_{izol} are necessary.

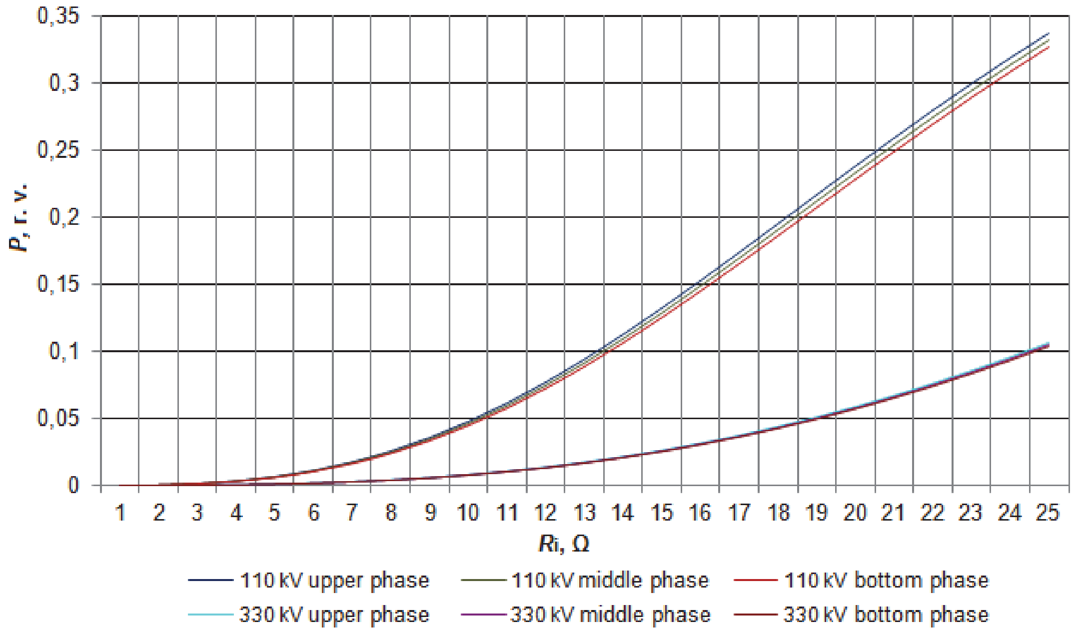


Fig. 4.6. Probability of the insulator breakdown for the double circuit TL 31T2 LS-25 tower, depending on the tower's R_i and H_{izol} values, on the 330-kV line: H_{izol} = 3161 mm – 3FLx-177-3SB10; and on the110-kV line: H_{izol} = 1601 mm – 3FLx-085-3SB10.

Depending on the number of storm hours in the concrete area, the number of damages of the isolating equipment changes *pro rata*. For reliability of the exploitation of TL, in the operational or "emergency" reserve the quantity of insulators (counted with provisional precision) has to be established [26]:

$$n_b = N_b P(R_{ik}), \tag{4.7}$$

where

$$N_b = 4N(h_{tr}/l), \tag{4.8}$$

n_b – the number of accidents which have happened because of the damages of the insulation caused by an atmosphere overvoltage; N_b – quantity of lightning discharges in TL tower; $h_{tr.}$ – ground wire instalation height, m; height of the suspension brackets of a shielding wire, m; l – length of the span of TL on the observed section, m; N – total of lightning discharges on 100 km length of TL, which is found by the expression:

$$N = 0{,}2\rho_0\left(\frac{d_{tr-tr}}{2} + 5h_{vid\_tr} - \frac{2h_{vid\_tr}^2}{30}\right), \tag{4.9}$$

where $\rho_0 = 3$ – the density of the impact of lightning discharges on the earth, discharge/year/km^2, under the climatic conditions of Latvia [20]; $d_{tr\text{-}tr}$ – distance between two cables, m; h_{vid_tr} – the average height of the suspension of cables, m, which is found by the formula

$$h_{\text{vid\_tr}} = h_{\text{tr}} - \frac{2}{3} f_{\text{tr}}, \tag{4.10}$$

where f_{tr} – the bend of shielding wire, which in the case when

$h_{\text{tr-v}} > h_{\text{tr}} - h_{\text{v}}^{\text{augs.}}$, is equivalent for $f_{\text{tr}} = h_{tr} - h_{\min}\left(h_{\text{v}}^{\text{augs.}} - h_{\text{v}}^{\text{apaks.}}\right) - h_{\text{tr-v}}$ and $f_{\text{v}} = h_{\text{v}}^{\text{apaks.}} - h_{\min}$,

$h_{\text{tr-v}} \le h_{\text{tr}} - h_{\text{v}}^{\text{augs.}}$, is equivalent for $f_{\text{tr}} = f_{\text{v}} = h_{\text{v}}^{\text{apaks.}} - h_{\min}$,

where $h_{\text{tr-v}}$ – distance between the shielding wire and the top phase conductors; $h_{\text{v}}^{\text{augs.}}$ and $h_{\text{v}}^{\text{apaks.}}$ – the average height of suspension of the top and lower phase conductor, m; $h_{\min}$ – the minimum admissible distance between the lower phase conductor and the earth, m [26].

According to the expressions (4.7)–(4.10), n_b value in the case under consideration (for example, at R_i = 10 Ω for the line of 330 kV) is equal to 0.25 outages/year/100 km.

The solution of the task of the definition of the trajectory of distribution of lightning discharge in the constructions of TL towers is realized in the environment of the computer software *COMSOL Multiphysics*. The creation of the model of simulation begins by means of the dialogue *Space Dimension*. There is given the task type of 2D (calculations and construction of the plane-parallel field), measure units, and the depth of the model (the direction on which is directed transversely to cross sections). In *COMSOL* calculation file design depth was set. The model was set in a two-dimensional space, but to clarify the calculated surge impedance results, the correction factor of k_{lab} should be used, introducing it as multiplication with Z_{bal} results in the *"Geometric Entity Selection" COMSOL* parameter window. The end result of k_{lab} introduction also provides a dangerous currents I_c clarification, but P (I_c) calculation results are clarified at approximately 0.9 % to 1.3 % (at $R_i \le 25$ Ω).

By means of the *Study Type* block (*Stationary or Time Dependent*), a type of the analysis and the material of the model (metal, overhead, soil, and other parameters) is given; then boundary conditions are given in the program, and the network of final elements is constructed.

Also, as in *EMTP* block, the source of lightning current I_z becomes isolated on the surface of TL tower, and the *COMSOL Multiphysics* on the lower block *Global Definitions* gives the parameters of the source of the electric current. The form of the lightning current is given by an impulse, but the values $I_{\max}$, τ_1, τ_2, t_1, t_2 remain the same as given by *EMTP*. By means of the *Settings–Time Dependent* and *Settings–Mesh Settings* functions, the exactness of the task solution is defined, which regulates the relative errors of the investigated process.

By means of the function *Results – 2D/3D Plot Group-Streamline Current Density*, the required values of the current in the construction elements and the trajectory of a flowing-down lightning current on a metal construction of TL tower are found, as it is shown in Fig. 4.7., but the calculation results show the values of lightning current in traverses. Generally it can be accepted for any point of construction and turn gives the possibility of finding the critical places of construction. Thus, when the values of the lightning current that is flowing down on the construction are defined, by using the expressions (4.1)–(4.3), the possibility of insulation flashover of the isolating section at the concrete value R_{ik} is established (Table 4.3.).

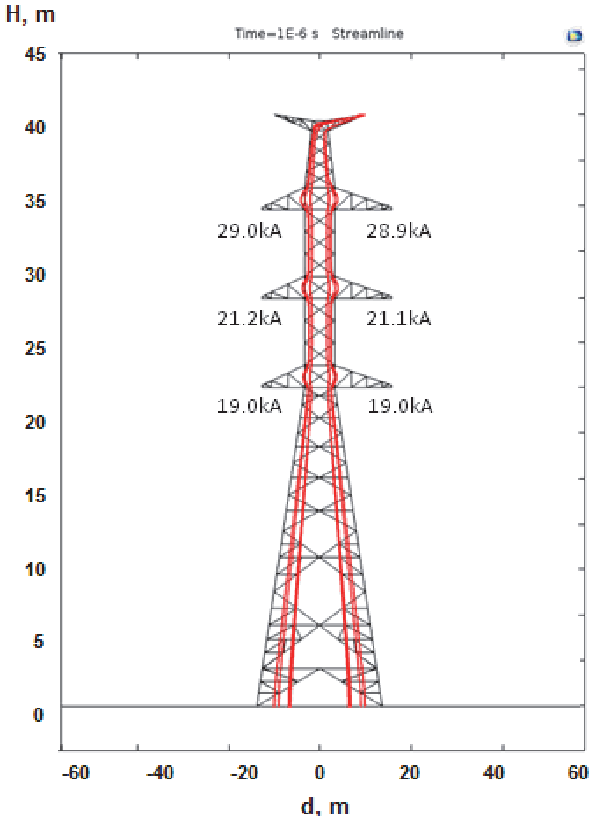


Fig. 4.7. Lightning current flow trajectory on TL tower in the case when $R_{ik} = 10\ \Omega$.

Table 4.3.

The results of probability calculations of insulating constructions flashover by means of *COMSOL Multiphysics*

31T2LS-25 tower 330 kV side						
R_{ik}, Ω	$P(I_c)_{augš.\ trav.}$	$P_{tr\_v\ augš.\ tr.}$	$P(I_c)_{vid.\ trav.}$	$P_{tr\_v\ vid.\ tr.}$	$P(I_c)_{apakš.\ trav.}$	$P_{tr\_v\ apakš.\ tr.}$
10	0,0081	0,0080	0,0079	0,0079	0,0078	0,0078
31T2LS-25 tower 110 kV side						
R_{ik}, Ω	$P(I_c)_{augš.\ trav.}$	$P_{tr\_v\ augš.\ tr.}$	$P(I_c)_{vid.\ trav.}$	$P_{tr\_v\ vid.\ tr.}$	$P(I_c)_{apakš.\ trav.}$	$P_{tr\_v\ apakš.\ tr.}$
10	0,0720	0,0478	0,0696	0,0462	0,0673	0,0447

When calculating the values of the current in the construction elements of TL towers by *COMSOL Multiphysics*, the mechanical connections of diagonal segments with vertical segments of the bearing constructions (supports) are taken into account; therefore, changes in the configuration of the model take place. Besides, also the calculated values of the inductive and capacitative components change, which results also in changes in the energy of electric and magnetic fields.

Calculations of the division of the dangerous currents in the traverses of TL towers and of the possibility of insulation constructions flashover near towers are realized similar to that as shown in the case of a separate tower, accepting that the lightning current, according to Heidler's function, at the peak of each tower standing nearby, corresponds to (2.8); the scheme of replacing is given in Fig. 4.8.

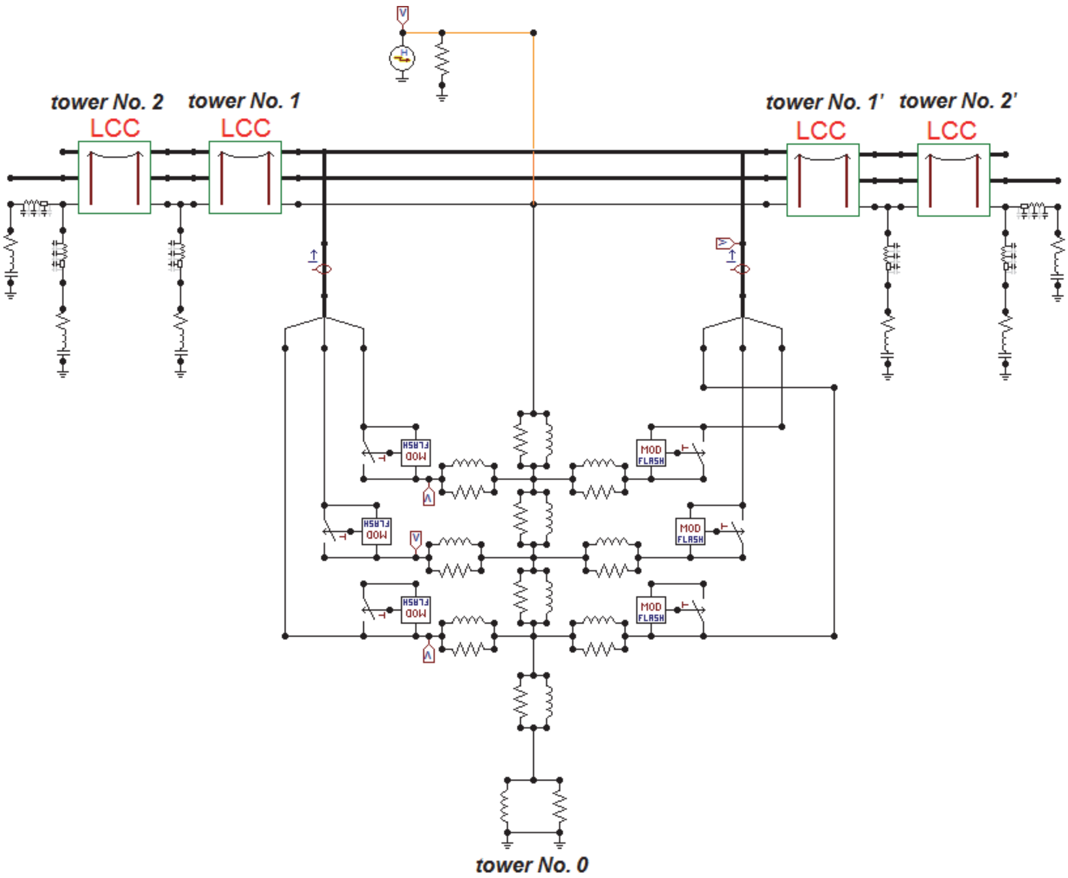


Fig. 4.8. EMTP/ATP equivalent scheme of a two-span simetric model of TL.

The diagram of Fig. 4.9. shows the characteristics of the division of the lightning current I_m in the traverses of TL towers standing nearby.

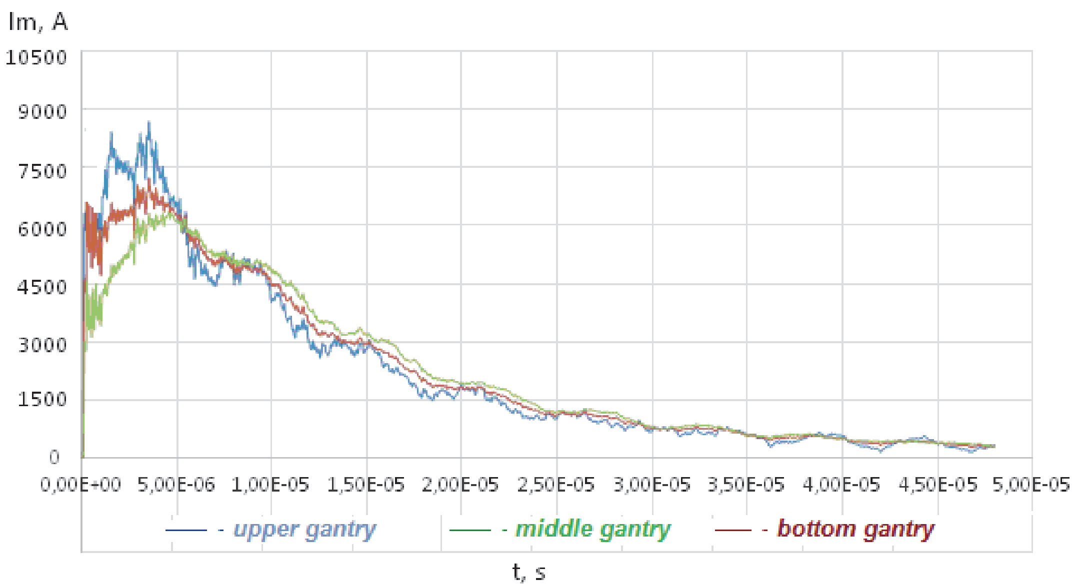


Fig. 4.9. Lightning current distribution characteristics of towers Nos 2 and 2' when R_i is equal.

When lightning currents in the towers standing nearby are defined using the expressions (4.4)–(4.8), the possibility of isolating sections flashower at the concrete values R_{ik} is established (Table 4.4.).

Table 4.4.

The results of probability calculations of insulating constructions flashover for two neighbouring TL towers Nos 1, 1', 2, and 2', 110 kV and 330 kV EPL.

31T2LS-25 towers Nr. 1; 1' (110 kV side)						
R_{ik}, Ω	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ aug\check{s}.\ tr\text{-}}$	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$
10	0,88	0,0079	0,54	0,0076	0,38	0,0074
31T2LS-25 towers Nr. 1; 1' (330 kV side)						
R_{ik}, Ω	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ aug\check{s}.\ tr\text{-}}$	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$
10	0,88	0,0077	0,54	0,0075	0,38	0,0074
31T2LS-25 towers Nr. 2; 2' (110 kV side)						
R_{ik}, Ω	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ aug\check{s}.\ tr\text{-}}$	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$
10	0,41	0,0075	0,31	0,0074	0,37	0,0074
31T2LS-25 towers Nr. 2; 2' (330 kV side)						
R_{ik}, Ω	$\alpha = I_m/\tau_1$ (kA/μs)	$P_{tr\_v\ aug\check{s}.\ tr\text{-}}$	$\alpha = Im/\tau 1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$	$\alpha = Im/\tau 1$ (kA/μs)	$P_{tr\_v\ vid.\ tr\text{-}}$
10	0,41	0,0074	0,31	0,0074	0,37	0,0074

From the point of view of designing metal constructions of TL, the most favorable situation arises when immediately after verification, by means of *EMTP* for IFFR of isolating constructions, the admissible values are obtained (block *RESULTS I* in the flow-block of the algorithm, see Fig. 4.1.). In this case, changes in the project are not necessary.

When using for concrete constructive decisions the received characteristics of resistance R_i within the range of 0÷25 Ω for the probability of the division of P, the value of P and the calculated value of n_b for the concrete measured R_{ik} value, which is received at carrying out the measurements at the object, are defined. In the cases when

- $R_{ik} > 25$ Ω,
- $P(R_{ik}) > 0.1$,
- $n_b > 2$ switchouts/year/on 100 km,

an additional check-up for the purpose of defining the trajectory of distribution of lightning current in the metal construction of TL tower is necessary.

With use of concrete constructive decisions at the measured R_{ik} resistance, by means of *COMSOL Multiphysics*, the value P for each of critical points is defined. The value of probability of flashover along a string of insulators P for the section "traverse–wire" (or for other critical points) is defined – the same as in the previous case – by (4.8). If $P(R_{ik}) < 0.1$, it is established that the chosen metal construction of TL corresponds to the criteria of IFFR; however, a decision was made for constructive changes in the isolating constructions (the block *RESULTS II* in the flow block of the algorithm), respectively:

- strings of insulators with a greater value $U_{50\%}$ are chosen;

- actions for decrease in R_{ik} value are provided.

Calculation is repeated to check whether the admissible values for estimation of IFFR (the *RESULTS I* block) are received.

If as the result of calculations by means of *COMSOL Multiphysics*, the values of the current which give $P(R_{ik}) > 0.1$ are received, the realization of the algorithm is enabled for the nearby towers in order to define the danger caused by distribution of lightning current.

The value of probability of the flashover along the string of insulators P for the area of "traverse–wire" for the towers that are nearby (for two towers on each side of the tower where the lightning discharge occurred) is defined for the concrete constructive decision at the measured resistance R_{ik}. In case $P(R_{ik}) < 0.01$ in the following nearby towers, the task is applied as it was considered before (the *RESULTS II* block in the block-scheme of the algorithm). In case $P(R_{ik}) > 0.01$, the decisions are made about:

- necessary changes in configuration of the bearing constructions of TL, respectively, at the increase in the distance between phase traverses, the upper phase and shielding wire, or at the increase in the lengths of phase traverses in itself, etc;
- artificial decrease in the R_{ik} value for the towers that are nearby;
- installation of the protective equipment of "non-linear overvoltage protection" type.

After corrective action in the project, the calculation is repeated to check whether the admissible values for estimation of IFFR (*RESULTS I* block) are received.

5. ESTIMATION OF INSULATION FAILURES FLASHOVER RATE OF TL METAL CONSTRUCTIONS USING THE OFFERED METHODOLOGY

One of the cases considered in the present Doctoral Thesis is the TL equipped on a two-chain towers with vertical arrangement of wires, as shown in Fig. 4.2. The solution of the task is realized according to the flow block (Fig. 4.1.) of the algorithm of IFFR definition. For drawing up the scheme of replacing of TL section and the model of the tower, the LCC block of the computer program *EMTP/ATP* is used, introducing the parameters of the elements of the scheme (see Fig. 5.1.); for inductance calculations, the data of the Table 4.2 are used.

The source of lightning current l_z in the model is connected to the top of TL tower, as shown in Fig 5.2., at preset values I_{max}, τ_1, t_1, and t_2.

The R_i values are accepted in a changed range, but L and the variation $U_{bal\text{-}v50\%}$ correspond to the concrete model of TL tower; the values of the parameters of lightning current $I_{max} = 30$ kA, $t_1 = 1.016$ µs, $t_2 = 1.190$ µs, and $\tau_1 = 2.5$ µs, used in the example, are defined when using the data array created by *MS EXCEL*. The values τ_2 = 60 μs and n = 2 are accepted, which corresponds to the data of supervision over lightning discharge in the conditions of Latvia.

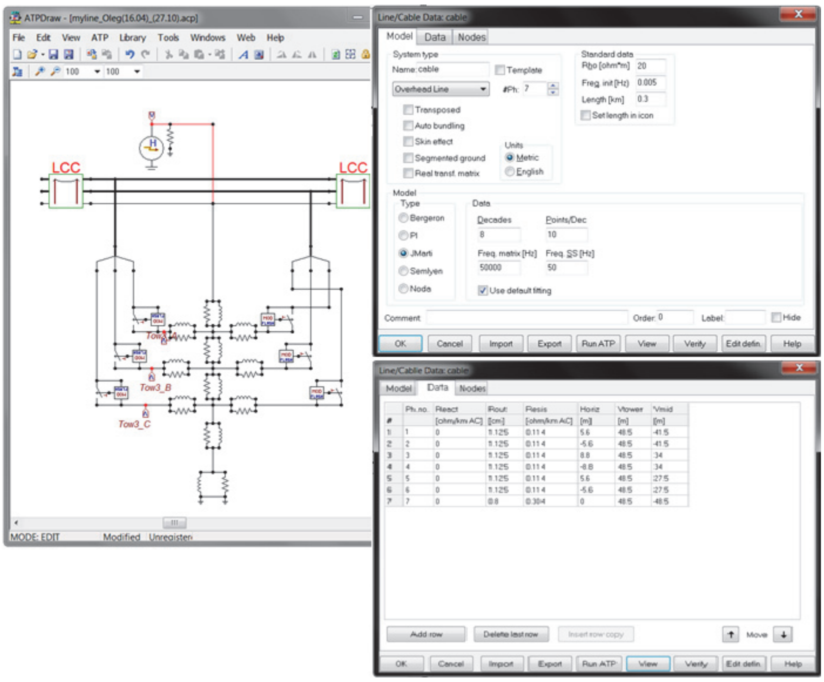


Fig. 5.1. TL and tower geometrical data input on *EMTP/ATP*.

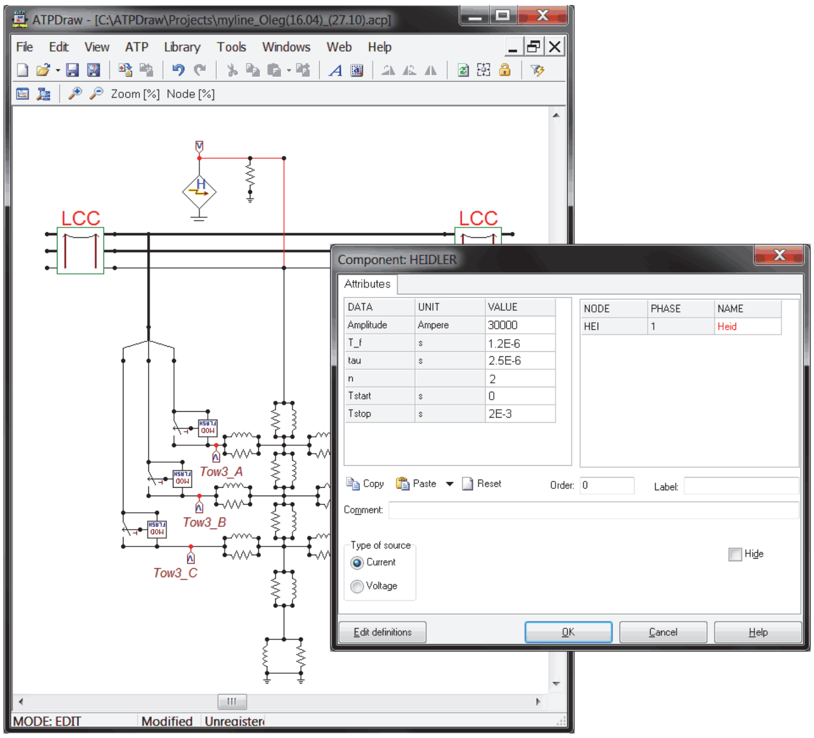


Fig. 5.2. Lightning current source data input on *EMTP/ATP*.

The maximum values of the current I_m, which influences the traverses of the TL tower that has undergone the lightning discharge, are graphically reflected in Fig. 4.5. The results of probability calculations of the insulation flashover of tower constructions *P* for the area “traverse–

phase conductor” are generalized in the schedule given in Fig. 4.6. According to the expressions (4.9)–(4.12), the n_b value in the case under consideration (for example, if R_i = 10 Ω for the 330 kV line) makes 0.25 switch outs/year/100 km.

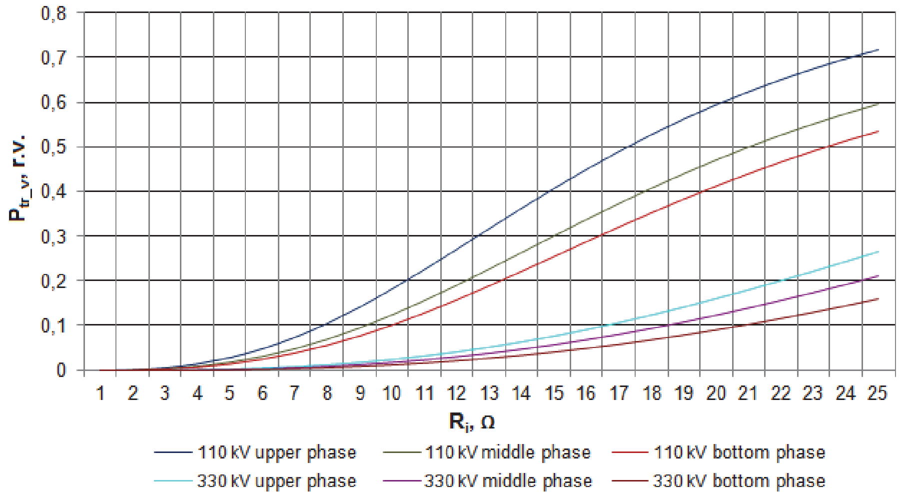


Fig. 5.3. Probability of insular breakdown for the TL 31T2 LS-25 tower, depending on the values of tower R_i and H_{izol} and insulator $U_{50\%}$, with no appropriated insulating parameters.

Fig. 5.3. demonstrates that IFFR of TL is provided at the soil resistance R_i within the range of 1–7 Ω. Assuming that the grounding resistance R_i = 10 Ω, it is necessary to take technical measures to require IFFR provision of TL, namely, to reduce the artificial supporting of the grounding resistance and to change the type of the insulator, increasing its $U_{50\%}$.

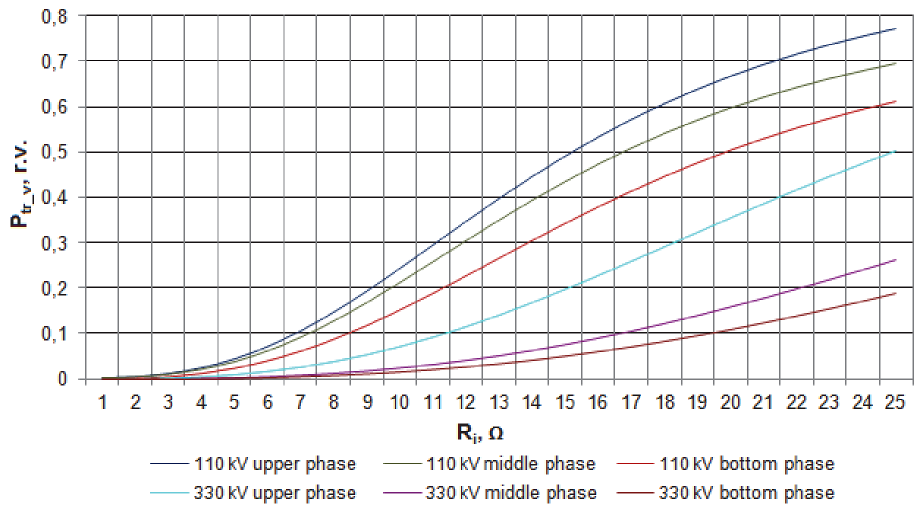


Fig. 5.4. Probability of insulator breakdown for the TL 31T2 LS-25 tower, depending on the values of tower R_i and H_{izol} and insulator $U_{50\%}$, when I_m = 50 kA.

Fig. 5.3. demonstrates that IFFR of TL is provided at the soil resistance R_i in the range of 1 to 6 Ω. Assuming that the grounding resistance R_i = 10 Ω, it is necessary to take technical measures. In addition to those mentioned above, in the areas where the lightning recorded with the

maximum current over 35 kA, provides for additional measures, such as installation of adittional shield wire(-s), increase in the height of the tower, and reduction in the length of the gantry.

To define the trajectory of the lightning current for metal construction of TL tower, the *COMSOL Multiphysics* computer software is used to perform the actions in the following sequence.

1. .dwg is imported (or .sld, also other variations of the execution of graphic files are possible) by *COMSOL Multiphysics* to prepare the graphic task in the file.
2. *COMSOL Multiphysics* automatically checks the imported model for geometrical convergence, gives notices about the stated imperfections in performing of model, but, stating the fundamental mistakes in the graphic execution of the model, informs also on the existence of syntactic mistakes, stopping further actions in the program.

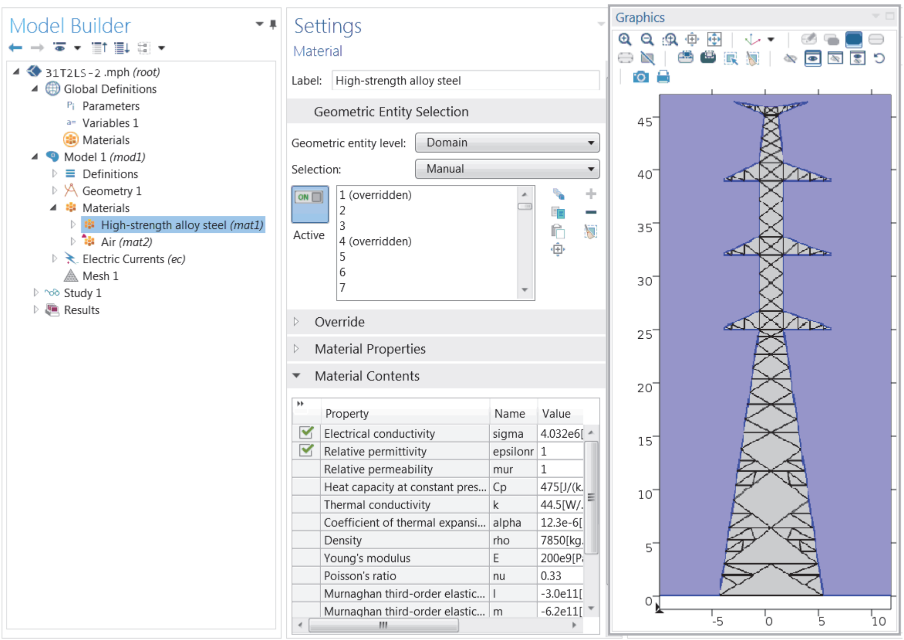


Fig. 5.5. Material physics data determination on *COMSOL Multiphysics* software for the 31T2 LS-25 TL tower.

If syntactic mistakes are not stated, in the window of the dialogue of the program it is necessary to pass to determination of properties of material, being guided by material of a framework of TL tower-31T2 LS-25- it's high-strength steel alloy with the corresponding electric and magnetic parameters, having repeated this procedure for space of model (or *COMSOL Multiphysics* accepts the corresponding parameters of the environment by default) (see Fig. 5.5.).

3. Also, as in the task of *EMTP/ATP*, *COMSOL Multiphysics* in the lower block *Global Definitions* has to preset the parameters of the source of the electric current; just as before, the form of the lightning current is preset by means of the impulse. In the model, the source of lightning current I_z is connected to the peak of TL tower, as shown in Fig. 5.6., the parameters of

the lightning current and the values of resistance of the channel of the lightning are entered the same as in the *EMTP/ATP* program.

4. In this model it is also necessary to define the grounding point, in case of necessity, investigating the transition processes in grounding electrode; there is also an opportunity to preset the configuration of the grounding electrode. The program automatically divides the model into elementary segments – points and lines; in this concrete case, the point No. 88 corresponds to the point of grounding (see Fig. 5.7).

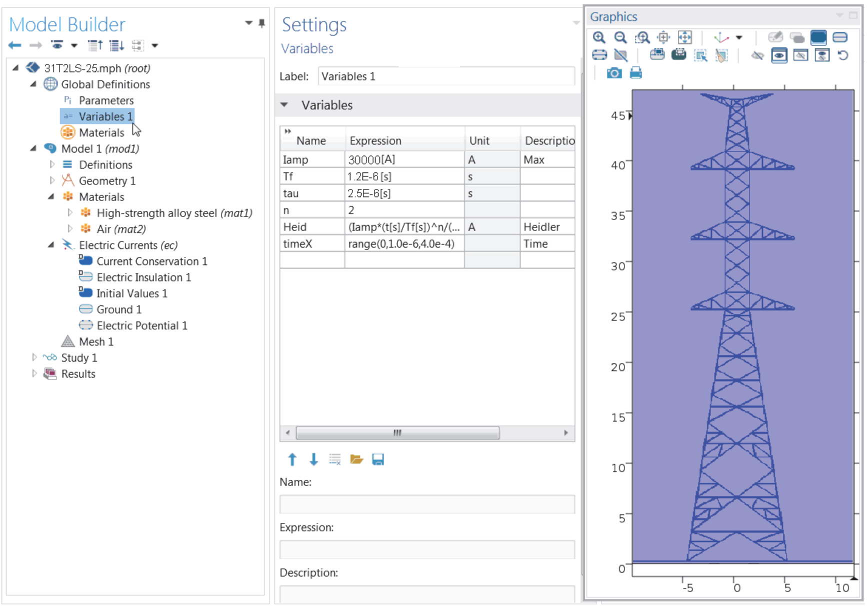


Fig. 5.6. Lightning current source parameters datermination on *COMSOL Multiphysics* software.

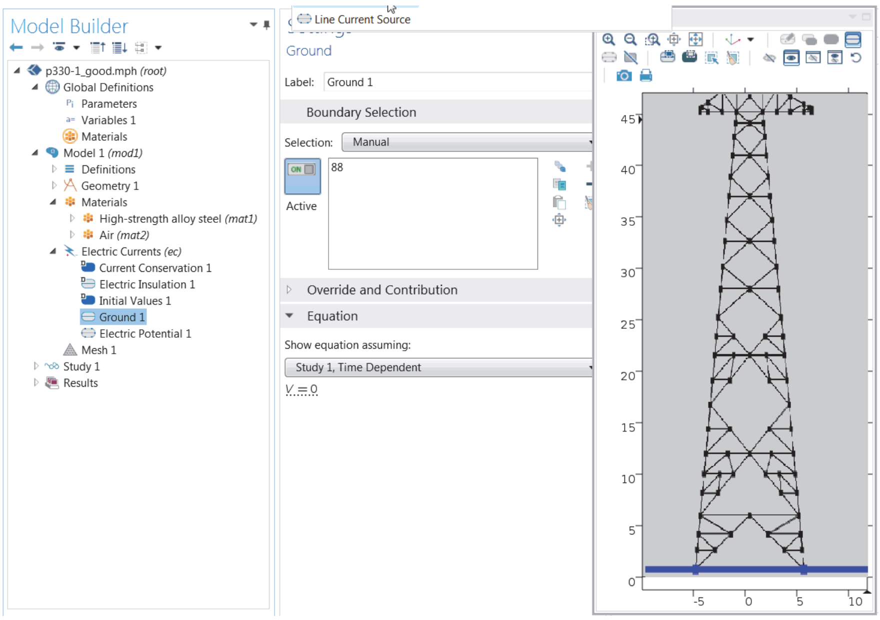


Fig. 5.7. Soil contact point No. 88.

5. By means of the function *Results – 2D Plot Group–Streamline Current Density*, the required trajectory of flowing down of the lightning current in the metal construction of TL tower is found (Fig. 5.8.).

In Fig. 5.8., the trajectory of flowing down of the lightning current is designated by red lines, and calculated results show the values of lightning current in traverses. Thus, when the values of the flowing-down lightning current in the construction are defined with the use of the expressions (4.3) and (4.8), the probability of insulating section's flashover at the concrete values R_{ik} is established.

The increase in the voltage in the nearby TL towers, which in the offered methodology are to be considered as two towers on each side of the tower where the lightning discharge occurred, the overvoltage wave at the time of impact depends on the wave resistance of tower Z_{bal}. Thus, when performing calculations according to (2.4)–(2.7), the modification of the Heidler function for an impulse of lightning current which reaches the nearby towers, respectively (2.8), is obtained as a result.

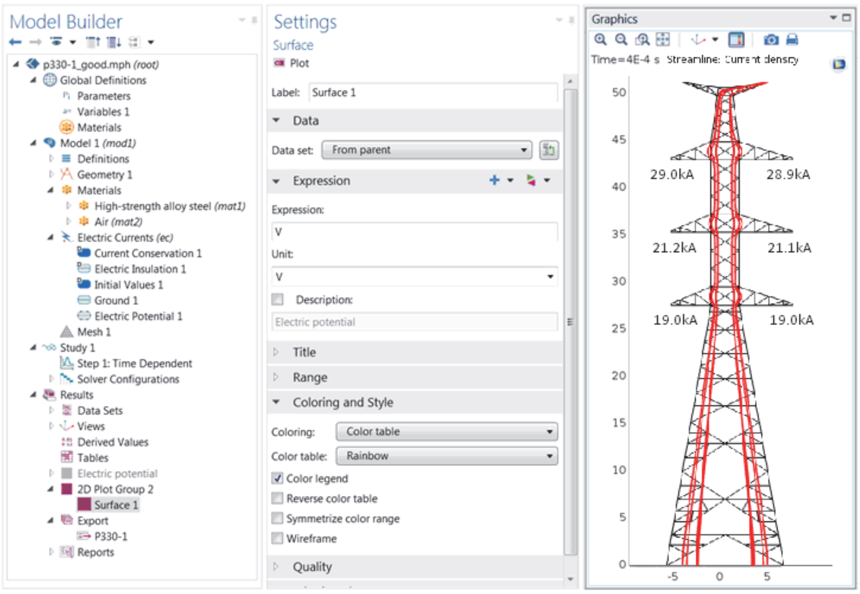


Fig. 5.8. Lightning current flow trajectory on the TL tower.

When performing the calculations by means of replacing the scheme of *EMTP/ATP*, given in Fig. 4.9., the diagrams of distribution of the lightning current on the TL section for the nereby towers are obtained, just as shown in Figs 4.10 and 4.11. When determining the lightning currents in the towers that are nereby, the probability of insulating the section's flashover at the concrete values R_{ik} will be established, using the expressions (4.3)–(4.8), but the characteristics of the probability of the phase insulation flashover are given in Fig. 5.9.

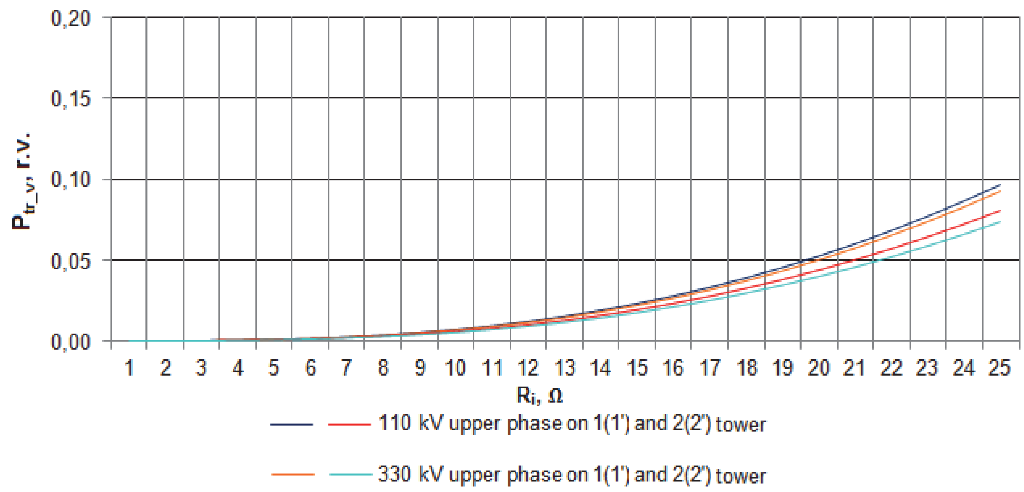


Fig. 5.9. Probability of insulator breakdown for the TL 31T2 LS-25 neighbour towers.

In order to check the trustworthiness of the received results when calculating the probability of insulation flashover of the line, the calculation is carried out with the use of standard methods, at which the height of tower H is entered into the expression (4.4), which for the towers of type 31T2 LS-25 equals to 46.45 m, and the value α = 10.8 kA/μs of standard abruptness of the impulse current of lightning of 30 kA is applied, which corresponds to the front length τ_1 = 4.5 μs, which is accepted according to [24]. The value of lightning current, sufficient to state the insulation flashover, is found from (4.4). Just as before it was accepted that the inductance of a tower per unit of length, or longitudinal inductance, is 1.0 μH/m, which for the towers of type 31T2 LS-25 equals to 46.45 μH/m.

According to [24], the probability that the amplitude of lightning current will exceed the preset value is determined by the expression:

$$P(I_c) = e^{-0,04 I_c}, \tag{5.1}$$

but in the case of abruptness of lightning current it is defined by the expression:

$$P(\alpha) = e^{-0,08\alpha}. \tag{5.2}$$

As at a preset value α these changes within the range of R_i from 1 to 25 Ω, according to (4.6), make up only 2.4 %, the probability of insulation flashover is found just as before, from the expressions (4.7) and (4.8), not in view of (4.6). The calculation results are given in Fig. 5.10., where it is seen that, when performing calculations according to the recommendations of the norms [24], the probability of insulation flashover is less on average by 22–28 % compared to the results calculated by the offered methodology.

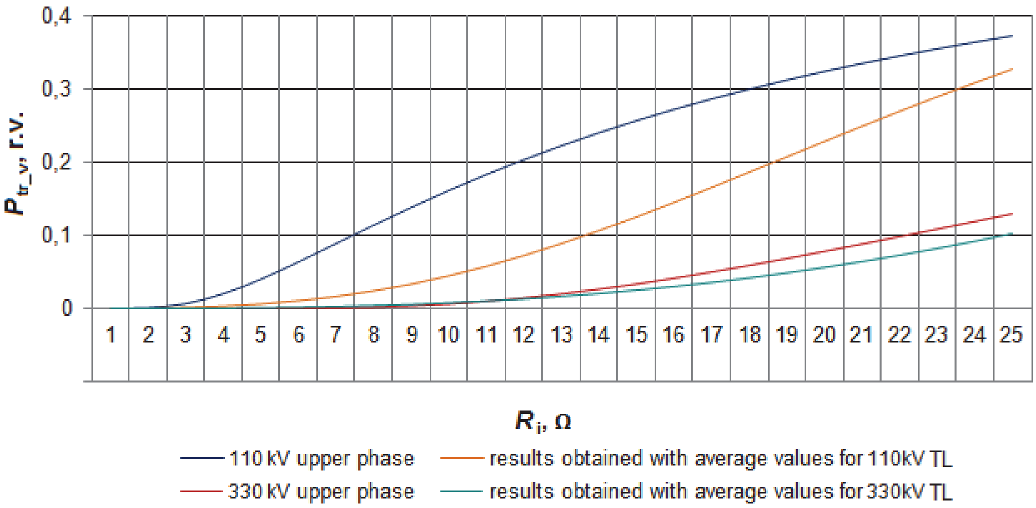


Fig. 5.10. Probability of insulator breakdown for the TL31T2 LS-25 tower, depending on the R_i .

According to the characteristics of the probability of insulation breakdown P_{tr_v}, given in Fig. 5.10. and obtained for TL tower of the type 31T2LS-25, depending on pulse resistance of soil R_i, according to [24] and the methodology offered by the author, it is possible to see:

- for example, if R_i = 13 Ω, the value of probability of insulation breakdown P_{tr_v} for TL of 330 kV is within the allowed range, i. e., $P_{tr\_v} < 0.1$, which can be explained by a stronger insulation. Whereas for TL line of 110 kV at the same value R_i, the value of P_{tr_v} , the value of which is obtained according to [24], is at least twice less than the value calculated by the offered technique. Namely, R_i = 13 Ω, which is an atypical case for the Baltic region and the TL „Kurzemes loks";
- if the minimum value of soil pulse resistance R_i < 5 Ω, the results received according to both methodologies coincide and do not contradict to the physical properties, which are the basis of both methodologies;
- namely, ideal grounding does not interfere with the processes of flowing of the lightning current in the soil. The reflected wave is not able to present the hazard for lines insulation;
- if R_i > 25 Ω, the characteristics obtained according to both methodologies approach thanks to atypically high values of R_i for longitudinal inductance value of TL tower, the influence on dangerous current I_c, which value will be sufficient to create insulation breakdown, will decrease.

THE MAIN RESULTS AND CONCLUSIONS OF THE DOCTORAL THESIS

1. The analysis of modern researches of the estimates of IFFR of TL has proved that the researches executed in the present research for obtaining the scientific degree, concerning the parameters of metal constructions of LT towers having an influence on IFFR of TL and based on individual constructive properties have not been carried out in such aspect up to the present day.

2. The offered methodology of the calculations of the degree of IFFR of TL metal constructions is based on the constructive (mounting height of phase conductors, longitudinal inductivity from gantries to the ground, and others) and physical parameters ($U_{50\%}$ value of insulator string, soil resistivity, and others) of each unique construction, but realization of the methodology is possible at application of specialized complexes of computer software. The method allows revealing constructive imperfections for the specific project of TL, namely:

- non-compliant discharge distances between conductive and grounded elements,
- TL response to dangerous discharge current exposure with an increased earth resistance condition,
- with an incorrectly selected inappropriated breakdown voltage values of TL insulation.

3. It should be noted that the offered methodology enables facilitating the procedure of project development for determining the level of TL lightning protection in cases when atypical elements for TL towers constuctions or constructive materials are used.

4. It is stated that the probability of the rise of emergency conditions, respectively, the flashover of insulation strings of TL towers, depends on the height of a suspension bracket of phase conductor, of insulator's string value $U_{50\%}$,, of longitudinal inductance of metal construction at the section "traverse–earth", namely, the compiled specification of computer model also exerts unambiguous influence on the results of calculations. It should be noted that the offered methodology does not complicate the process of designing by obtaining of additional data, because all necessary information is available in the course of the project development stage.

5. The developed algorithm provides three options of scenarios, namely**:**

- in the case of direct hit of lightning in the metallic tower of transmission line, the probability of insulating structure flashover with consequent outages of the power line is very small;
- performed calculations indicate the need of additional research for the purpose of definition of lightning current distribution trajectory in the construction of metal tower and determination of its critical sections from the point of view of insulating flashover;
- the analysis of the situation by the example of separately taken power line's towers is insufficient, and it is necessary that the research of the reaction of the transmission line

to storm influence is amplified with the definition of the reaction of linear insulation of the adjacent towers of power lines.

Developed methodology ultimately enables technological design stage in the course without the problems related to additional data, as well as fixes the lightning tolerance level of the new designed power lines, but, if necessary, the measures already envisaged for power lines service for the prediction of the dangerous situations could be planned**.**

6. It has been found that the synthesized calculation algorithm for the definition of lightning protection of TL metal construction being in service and a new TL, which in the present Doctoral Thesis has been tested by means of individual commercial softwares, can be used in fact as a base for a new TL designing analysis for software creation.

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