PROGRAM FOR MODELING ELECTROMAGNETIC COMPATIBILITY OF OVERHEAD POWER LINES

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Abstract

When corona wires, partial discharges and corona of insulators and fittings, sparking in the contacts of linear fittings, radio interference occurs. The harmful effects of a person's stay in a strong electric field depend on the field strength E and on the duration of its exposure. Electromagnetic compatibility of technical means (EMC) is the ability of a technical means to function with a given quality in a given electromagnetic environment and not create unacceptable electromagnetic interference to other technical means. Corona discharge on power lines interferes with radio and television reception, as well as acoustic noise. Currently, there is no software for assessing the electromagnetic compatibility of overhead lines. Mathematical modeling of the influence of corona wires of overhead lines, electromagnetic interference, corona discharge, radio interference in wires is considered. Radio interference on overhead lines can occur both due to corona on wires, and due to partial discharges and corona on insulators, breakdown or overlap of defective insulators, corona on linear fittings and spacers of split-phase wires, as well as due to sparking in poor contacts of linear fittings, spacers wires and between insulators. The EMC software was developed to assess the environmental impact of high voltage AC transmission lines. On the example of a 500 kV overhead line results of simulation are represented.

Keywords: Overhead lines, corona losses, acoustic noise, radio interference, electromagnetic compatibility

1. Introduction

The issues of the environmental impact of high-voltage transmission lines are becoming relevant in connection with the development of high-voltage 110, 220, 330 kV, ultra-high voltage (UHV) 500-750 kV and 1150 kV electrical networks [1-5]. The harmful effect of the magnetic field on living organisms, and primarily on humans, manifests itself only at very high intensities of the order of 150–200

A/m, which occur at distances up to 1–1.5 m from the wires of the overhead line (OHL) phases, and is dangerous when working under voltage.

The direct influence of the electromagnetic field of the power lines on a person is associated with the effect on the cardiovascular, central and peripheral nervous systems, muscle tissue and other organs [1]. In this case, changes in pressure and pulse, palpitations, arrhythmia, increased nervous excitability and fatigue are possible.

The harmful effects of a person's stay in a strong electric field depend on the field strength E and on the duration of its effect to 5 kV/m. Permissible duration of periodic and prolonged stay in the electric field: 20 kV/m - hard-to-reach - 10 min; 15 kV/m - uninhabited area 90 min; 10 kV/m for road crossings 180 min. The fulfillment of these conditions ensures the self-recovery of the body during the day without residual reactions and functional or pathological changes.

Radio interference occurs during corona on wires, partial discharges and corona on insulators and fittings, sparking's in the contacts of linear fittings [6–7].

Electromagnetic compatibility of technical means is the ability of a technical means to function with a given quality in a given electromagnetic environment and not create unacceptable electromagnetic interference with other technical means.

2. Influence of a corona discharge

Radio interference occurs with corona on wires, partial discharges and corona on insulators and fittings, sparking in the contacts of linear fittings [6-8].

Electromagnetic compatibility of technical means (EMC) is the ability of a technical means to function with a given quality in a given electromagnetic environment and not create unacceptable electromagnetic interference with another technical means [1, 8, 9].

To eliminate radio interference in the security tone, the permissible tension on the wire surface is reduced [15-17]. Corona discharge on power lines interferes with radio and television reception, as well as acoustic noise. The main cause of radio interference and noise is the streamer corona on wires. Since the most favorable conditions for the emergence of a streamer corona are formed during precipitation, when the initial field strength is significantly reduced, the strongest radio interference and acoustic noise occur during corona of ultrahigh voltage lines during rain and snow. In good weather, interference increases as the wires get dirty. The frequency spectrum of radiation that creates radio interference covers the range from 10 kHz to 1 GHz. Interference at frequencies above 30 MHz has an interfering effect on television reception and occurs only during corona lines of 750 kV. To solve the problems of EMC overhead lines and radio receivers for various purposes, the real levels of the field strength of interference generated by overhead lines are important.

The initial value in the development of standards for radio interference is the guaranteed level of the protected useful signal. In accordance with international practice, the minimum field strength of the radio signal, which must be protected from interference at a frequency of 1 megahertz, is 60 decibels, and at a frequency of 0.5 megahertz - 66 decibels.

Corona on wires is the main source of radio interference on high and extra high voltage overhead lines and interference to high-frequency communication channels. Corona also leads to additional losses of electricity on overhead lines. On wires of overhead lines, in addition to irregularities caused by wires of the upper layer, there are always surface damage (scratches, burrs), contamination (traces of grease, particles of organic and inorganic origin) and atmospheric deposits (raindrops, dew, snow, frost, ice, frost). This leads to a local increase in the electric field strength and, as a result, to the appearance of a local corona at individual points of the wire. The characteristics of radio interference and local corona losses depend mainly on the electric field strength on the wire, its diameter, surface condition, meteorological conditions and are subject to significant scatter.

Precipitation has a strong influence on the level of radio interference and the amount of corona loss, so it is necessary to have information about the average annual duration of the following main weather groups, each of which is characterized by its average loss level: - the first group - fine weather (H.P.); - the second group - dry snow (s.s.). Dry snow also includes snow groats, snow grains, ice needles, blizzards, blizzards with snowfall (with the exception of a blowing snowstorm and snowfalls that do not reach the wires); - the third group - rain (d). Drizzle and sleet should also be classified as rain, since their effect on corona losses and on the level of radio interference is close to that of rain; - the fourth group - frost (from). The frost group also includes: ice, frozen snow and wet frozen snow. All other types of weather belong to the group of good weather [8].

To eliminate radio interference in the security tone, the permissible tension on the surface of the wire is reduced. Corona discharge on power lines interferes with radio and television reception, as well as acoustic noise. The main cause of radio interference and noise is the streamer corona on the wires. Since the most favorable conditions for the appearance of a streamer corona are formed during precipitation, when the initial field strength is significantly reduced, the strongest radio interference and acoustic noise occur during corona of ultrahigh voltage lines during rain and snow. In good weather, interference increases as the wires get dirty. The frequency spectrum of radio interference radiation covers the range from 10 kHz to 1 GHz. Interference at frequencies above 30 MHz has an interfering effect on television reception and occurs only during corona effect of 750 kV lines. To solve the problems of EMC of overhead lines and radio receivers for various purposes, the real levels of the field strength of interference generated by overhead lines are important.

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3. Normative base of noise

To solve the problems of EMC of power lines and radio receivers for various purposes, the real levels of the field strength of interference generated by overhead lines are important. Interference from overhead lines can occur not only due to corona on wires, but also due to partial discharges and corona on insulators, breakdown or overlap of defective insulators, corona on linear fittings and spacers of split-phase wires, and also due to sparking between elements of linear fittings, spacers wires and between insulators. The reduction of radio interference from overhead lines and the improvement of the electromagnetic situation along the routes is facilitated by the regulation of the levels of radio interference from overhead lines.

Most countries have national regulations for interference field strengths from overhead power lines and high voltage equipment.

Corona on wires is the main source of radio interference on high and extra high voltage overhead lines and interference to high-frequency communication channels. Precipitation has a strong influence on the level of radio interference and the magnitude of corona losses, so it is necessary to have information on the average annual duration of the following main weather groups, each of which is characterized by its average level of losses: - the first group - fine weather; - the second group - dry snow. Dry snow also includes snow groats, snow grains, ice needles, blizzards, blizzards with snowfall (with the exception of a blowing snowstorm and snowfalls that do not reach the wires); - the third group - rain. Drizzle and sleet should also be referred to as rain, since their effect on corona losses and on the level of radio interference is close to that of rain; - the fourth group - frost. The frost group also includes: ice, frozen snow and wet frozen snow. All other types of weather belong to the group of good weather.

At E≤5 kV/m, it is allowed to stay in the electric field for a full working day.

For 5 < E ≤ 20 kV/m, the residence time in the electric field is calculated as

$$T_E = \frac{50}{E} - 2 \text{ h}.$$

At 20 < E ≤ 25 kV/m, the residence time in the electric field is no more than 10 min.

At E ≥ 25 kV / m, staying in an electric field without protective equipment is not allowed.

If the personnel during the working day is in an area with different electric field strengths, then the allowable time of stay

$$T_{dur} = 8 \cdot \left(\frac{t_1}{T_{E1}} + \frac{t_2}{T_{E2}} + \cdots + \frac{t_i}{T_{Ei}}\right),$$

where T_{dur} is the reduced time of the normalized intensity, t1, ... ti, is the time of stay in zones with intensity E_1, ... E_i, T_{E1}, T_{E2}, ..., T_{Ei} is the allowable time of stay in each zone.

Table 1

Permissible duration of work of personnel in the electric field of industrial frequency

Tension electric field kV/m	Permissible duration staff stay during the day, min
5 10 15 20-25	Unlimited (during the working day) 180, 80, 10

Regulatory framework for radio interference and acoustic noise.

To solve the problems of electromagnetic compatibility of power lines and radio receivers for various purposes (i.e., to ensure their operation without deteriorating quality indicators), real levels of interference field strength generated by overhead lines are important

Interference from overhead lines can occur not only from corona on wires, but also due to partial discharges and corona on insulators, breakdown or overlap of defective insulators, corona on linear fittings and spacers of split-phase wires, and also due to sparking between elements linear fittings, wire spacers and between insulators.

The reduction of radio interference from overhead lines and the improvement of the electromagnetic situation along the routes is facilitated by the regulation of the levels of radio interference from overhead lines.

In most countries, national standards have been established for the magnitude of the interference field strength generated by overhead power lines and high-voltage equipment [8-10].

Table 2 shows the standards for radio interference from overhead lines in a number of countries.

Table 2

Norms of various countries for radio interference from power lines

Countries	Frequency measu rements	Place Measure ments	Norms dB	Permissible radio interfe-rence levels at a distance of 100 m, dB	
		Distance from extreme phase		good weather	80% time
RF	0,5 MHs	100 m	43	37,0	43,0
USA	1 MHs	the OHL 362 kV -14 m, OHL> 550 kV - 20 m	52	27,3 29,6	33,6 35,6

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Corona on wires is the main source of radio interference on high and extra high voltage overhead lines and interference to high-frequency communication channels. Corona also leads to additional losses of electricity on overhead lines. On wires of overhead lines, in addition to irregularities caused by wires of the upper layer, there are always surface damage (scratches, burrs), contamination (traces of grease, particles of organic and inorganic origin) and atmospheric deposits (raindrops, dew, snow, frost, ice, frost). This leads to a local increase in overhead line wires on the environment is shown in Figure 1.

4. Calculation of the electric field strength on the surface of the wires

The main factor determining corona losses and radio interference on overhead lines is the ratio of the electric field strength on the surface of the wires to the initial corona strength. A small change in this ratio leads to a significant change in corona loss and radio interference. For overhead lines with single wires, the electric field strength E on the surface of the wire is determined by the formula [6-7].

$$E = \frac{q \cdot 10^{-3}}{2\pi\varepsilon_0 r_0}. \quad (1)$$

In a split wire, the field strength is unevenly distributed over the surface of the component wires. In this case, the average strength E of the field is determined by the formula (3)

$$E = \frac{q \cdot 10^{-3}}{2\pi\varepsilon_0 r_0}. \quad (2)$$

where r_0 is the radius of the components of the split wire, cm

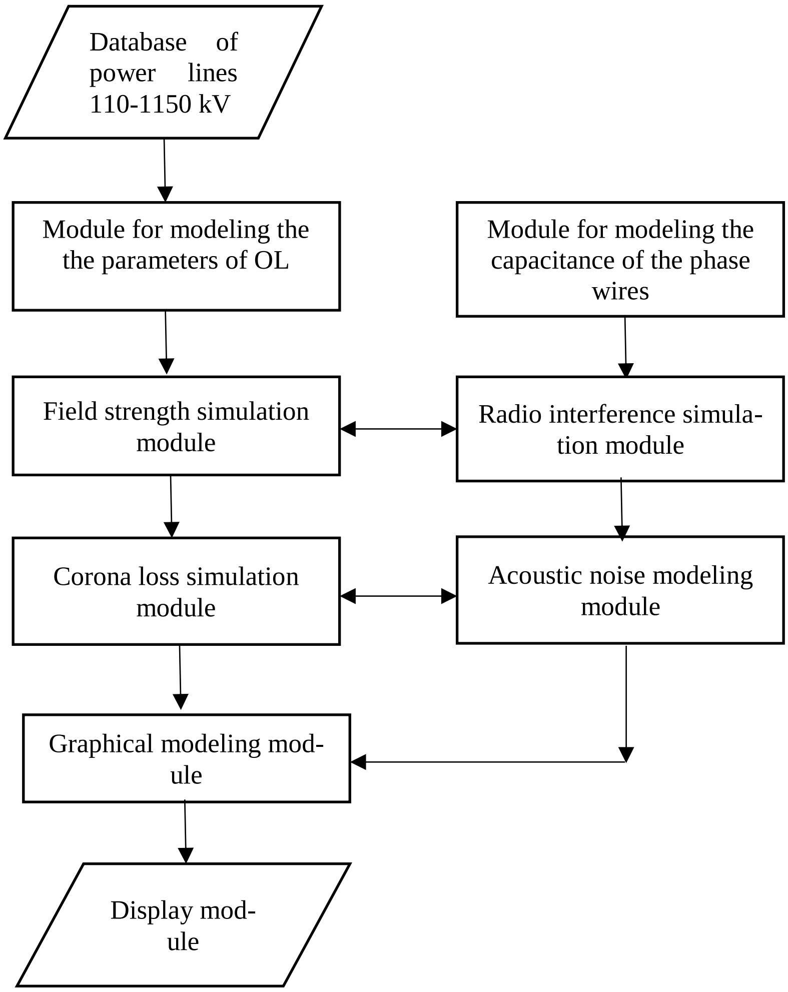

Figure1: Block diagram of modeling the electromagnetic impact of high-voltage power lines

Maximum intensity for split wire

$$E_M = k_H E, \quad (3)$$

where $\kappa_н$ is the coefficient of uneven distribution of the charge over the surface of the component wire.

$$k_H = 1 + (n-1)\frac{r_0}{r_p} = 1 + \beta\frac{r_0}{a}, \quad (4)$$

where r_p is the splitting radius; a - splitting step of the split wire cm.

The value of β depending on the number of component wires in a split wire is determined by the formula

$$\beta = 2(n-1)\, sin\frac{\pi}{n}. \quad (5)$$

The basis of the calculation for an arbitrary 3-phase overhead line with two cables is the solution of the system of Maxwell equations [1].

To calculate the field strengths on the wires, the working capacitance of the wire is used, which is defined as the ratio of the linear charge density of the wire to the phase voltage of the overhead line.

In the developed program for calculating power loss due to corona, algorithms for calculating the capacitance of a three-phase overhead line with an arbitrary arrangement of wires with one and two cables (Figure 1) are implemented.

For a three-phase AC overhead line with single (n = 1) and split wires

$$E = 0.0147\frac{C_k U}{n r_0}, \quad (6)$$

where $C_к$ is the working capacitance of the k-th phase of the overhead line, pF/m; U - average operating voltage per year along the overhead line, kV.

When calculating the corona power loss on split wires, the equivalent electric field strength E_E is used.

E_E is determined by the formula

$$E_E = \frac{E + E_M}{2} = \frac{1 + k_H}{2} E, \quad (7)$$

To unify the calculations of corona power loss for all weather groups, the basic value of the initial field strength E_0 on the surface of the wires was introduced, which corresponds to the appearance of a common corona in good weather

$$E_0 = 24.5m\delta\left(1 + \frac{0.613}{(r_0\delta)^{0.4}}\right), \quad (8)$$

where m is the coefficient of non-smoothness of the wire; δ - relative air density; r_0 is the radius of the components of the split wire or the radius of a single wire, cm.

5. Permissible levels of radio interference

Radio interference on overhead lines can occur both due to corona on wires, and due to partial discharges and corona on insulators, breakdown or overlap of defective insulators, corona on linear fittings and spacers of split-phase wires, as well as due to sparking in poor contacts of linear fittings, spacers wires and between insulators. Radio interference generated by overhead lines in the frequency range from 0.15 to 30 MHz is normalized at the following distances from the projection of the outermost wire to the ground:

- for overhead lines 110 and 220 kV - 50 m;
- for overhead lines 330 kV and above - 100 m.

In the norms of Russia, the frequency spectrum of the permissible values of the field strength of radio interference from overhead lines is given (Figure 2).

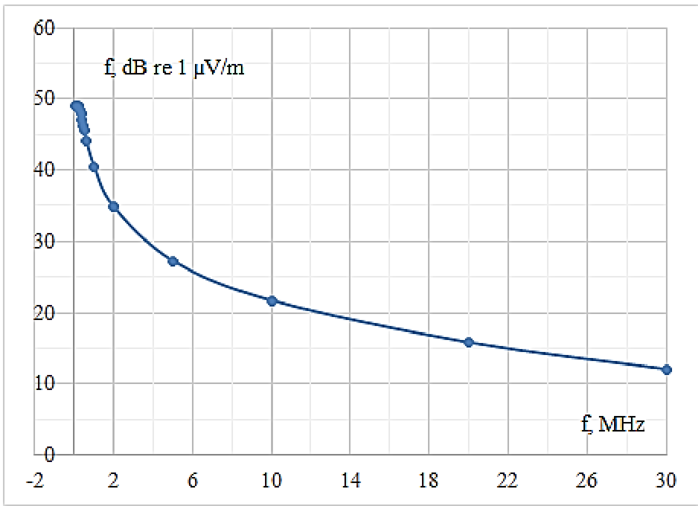

Figure 2: Permissible values of the radio interference field strength

The dependence of radio interference in good weather at E_m= 23÷30 kV/sm has the form

$$E_{surf} - E'_{surf} = 2.3 \times 10^{-5}(E_m - E'_m), \quad (9)$$

where E_{surf} and E'_{surf} are the levels of radio interference at maximum voltages of the electric field, on the surface of the split wire, respectively, E_m and E'_m.

The dependence of radio interference on the radii of the wires (in the case of a split phase - on

the radii of the constituent wires) at E_m=const has the form

$$E_{surf} - E'_{surf} = 40\, lg\frac{r_0}{r'_0}, \quad (10)$$

The dependence of radio interference on frequency is determined by the expression

$$\Delta f E_{surf} = 5[1 - 2(lg10 \times f)^2], \quad (11)$$

where f - frequency, MHz; $\Delta f E_{surf}$ - change in the

The radio interference level decreases with distance from the overhead line. The cross profiles of radio interference for 500 kV OHL are shown in Figure 3.

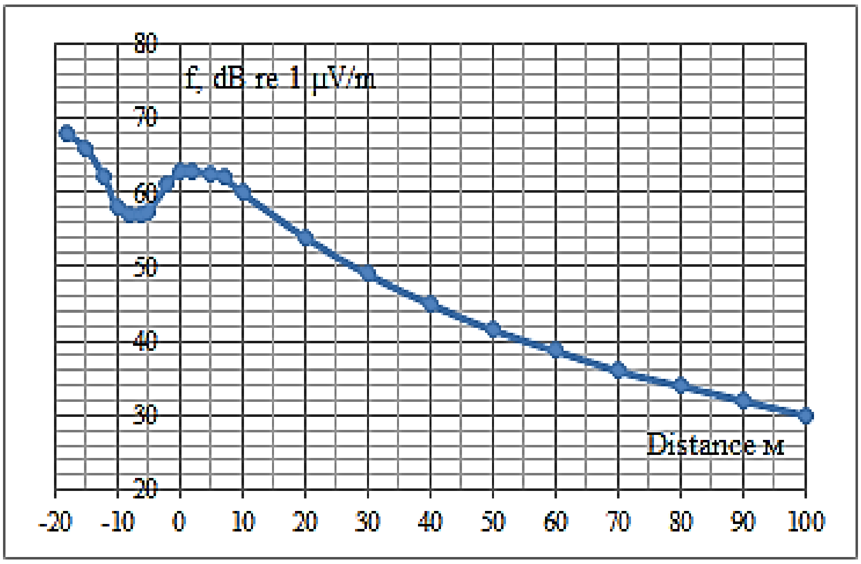

Figure 3: Cross profiles of radio interference from 500 kV overhead lines with wires

The shape of the cross profile of radio interference is determined from the expression

$$E_{surf} - E'_{surf} = 20\,lg\,\frac{R^k h^{k-1}}{R_1^k h^{k-1}}, \tag{12}$$

where En and E'n are the radio interference levels, respectively, at distances R and R1 from the nearest outer wire of the overhead line at its suspension heights at the measurement points h_1 and h_2; k - coefficient of transverse attenuation of radio interference, equal to 1.6.

To calculate the distribution of the radio interference level during the year, three weather groups are distinguished: fine weather, rain and dry snow. The radio interference levels, taking into account the received weather groups, are distributed according to a law close to normal, with a standard deviation σ equal to 4-6 dB.

In rain, the average levels of radio interference are higher than in good weather by 10 dB, and in dry snow - by 6 dB. The percentage of time in year B, during which the radio interference level does not exceed the permissible value E_{surf}^{perm}, is determined by the formula

$$B = 100\begin{bmatrix} \psi_{gw} F\left(\frac{E_{surf}^{perm} - \bar{E}_{surf}^{(gw)}}{\sigma_{gw}}\right) + \\ \psi_r F\left(\frac{E_{surf}^{perm} - \bar{E}_{surf}^{(r)}}{\sigma_r}\right) + \\ + \psi_s F\left(\frac{E_{surf}^{perm} - \bar{E}_{surf}^{(s)}}{\sigma_s}\right) \end{bmatrix} \times E_{surf}^{perm} \% \tag{13}$$

where ψ_{gw}, ψ_r, ψ_s - relative duration, respectively, of good weather, rain and snow during the year; $\bar{E}_{surf}^{gw.}$, $\bar{E}_{surf}^{r}$, $\bar{E}_{surf}^{s.}$ - average values of radio interference levels at a given standardized distance, respectively, in good weather, rain and snow; σ_{gw}, σ_r, σ_s - standard deviations of the distribution of radio interference levels, respectively, in good weather, rain and snow.

F-normal distribution function is determined by the formula

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{X} e^{-\frac{t^2}{2}} dt. \tag{14}$$

Determination of the radio interference levels from overhead lines is carried out in the following order: - for the basic level of radio interference E_{surfB} is taken the average value of the radio interference levels at a normalized distance, determined for a 500 kV overhead line (E_{surfB} = 30 dB, the maximum field strength on the wires of the overhead line is calculated according to [7] section; calculation of the average level of radio interference in good weather at a frequency of 0.5 MHz at a normalized distance of 100 m from the overhead line is produced by the formula (dB)

$$\overline{E}_{surf}^{(gw)} = E_{surfB} + 2.3 \times 10^{-5}(E_M - E_{Mb}) + \\ +40\,lg\,\frac{r_0}{r_{0b}} + \frac{H}{300} \tag{15}$$

where the field strength E_M is taken for the middle phase; - the value of B is calculated by formula (13), where for the base frequency of 0.5 MHz, the value E_{surf}^{perm} = 45 dB (see Figure 3);

$$\overline{E}_{surf}^{(r)} = \overline{E}_{surf}^{(gw.)} + 10;\ \overline{E}_{surf}^{(s.)} = \overline{E}_{surf}^{(gw.)} + 6;$$

the value $\sigma_{gw}=\sigma_r=\sigma_s$ is taken equal to 5 dB.

For power lines with a horizontal arrangement of wires for regions with a temperature of climate, the calculation of the permissible values of the maximum field strength E_{perm} on the surface of the wires of overhead lines according to the condition of the permissible level of radio interference is carried out according to the formulas:

- for 330 and 500 kV overhead lines

$$E_{perm} = 31.1 - 17.4\,lg\,r_0; \tag{16}$$

- for 750 kV overhead lines

$$E_{perm} = 32.2 - 17.4\,lg\,r_0. \tag{17}$$

The maximum field strengths allowed under radio interference conditions on the wires of three-phase AC overhead lines: curve 1 - for 330 and 500 kV overhead lines; curve 2 - for 750 kV overhead lines

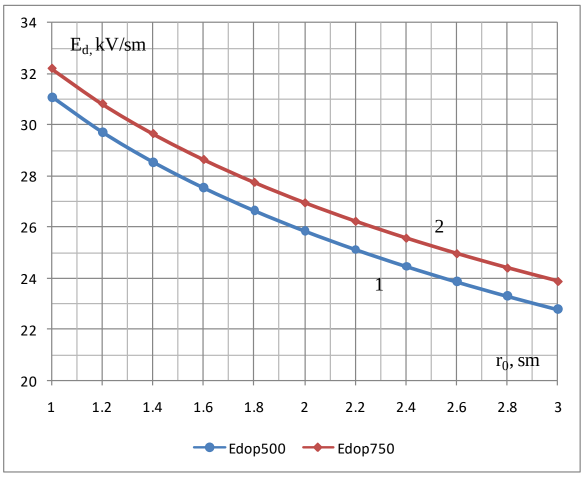

Figure 4: Dependences of the maximum field strengths on the wires of three-phase AC overhead lines allowed under the conditions of radio interference on the radius of the wire

The level of distributed interference $P_{int}.f_B$ in any frequency band (Δf) other than 1 kHz is determined by the formula

$$P_{int}.f = P_{int} + 10lg\Delta f. \quad (18)$$

Initial information on power transmission line supports.

The basis for calculating the calculation of the capacitance of an overhead line for an arbitrary 3-phase overhead line with two cables is the solution of the system of Maxwell equations [1].

Solving the system of equations, we obtain the coefficients of electrostatic induction, α_{ki}, having the dimension of the capacitance.

To calculate the field strengths on the wires, the working capacitance of the wire is used, which is defined as the ratio of the linear charge density of the wire to the phase voltage of the overhead line. The developed program implements algorithms for calculating the capacitance of a three-phase overhead line with an arbitrary arrangement of wires with one and two cables. Calculation of charges on VL drives. The calculation for an arbitrary N-wire overhead line is based on the solution of the system of Maxwell equations

$$\dot{U}_k = \sum_{i=1}^{N} \alpha_{ki}\dot{q}_k (k = 1,2,\dots,N), \quad (19)$$

where is the voltage of the k-th wire; - linear charge density of the i-th wire; α_{ki} - potential coefficients equal to

$$\alpha_{kk} = \frac{1}{2\pi\varepsilon_{0ek}} ln\frac{2h_k}{r};$$
$$\alpha_{ki} = \alpha_{ik} = \frac{1}{2\pi\varepsilon_{0ki}} ln\frac{D'_{ki}}{D} \quad (20)$$

Here hk is the equivalent height of the k-th wire above the ground; D_{ki} - distance between the k-th and i-th wires; - distance between the k-th wire and the mirror image of the i-th wire in the ground plane; rec - equivalent radius of the k-th wire.

The equivalent radius of a wire split into n components is understood as the radius of a single wire, equivalent in capacitance to the split one. The value of re is determined from the expression

$$r_e = (nr_o r_p^{n-1})^{1/n}, \quad (21)$$

where is the wire splitting radius

$$r_p = \frac{a}{2\sin\frac{\pi}{n}} \quad (22)$$

Solving the system of equations (19), we obtain

$$\dot{q}_k = \sum_{i=1}^{N} \beta_{ki}\dot{U}_i (k = 1,2,\dots,N), \quad (23)$$

where β_{ki} are electrostatic induction coefficients having the dimension of capacitance.

The coefficient matrix β_{ki} can be obtained by inverting the coefficient matrix α_{ki}. The coefficients β_{ki} can also be calculated using the formula

$$\beta_{ki} = \frac{(-1)^{k+i} M_{ik}}{\Delta}, \quad (24)$$

where □□is the determinant of the system of equations (24);

M_{ik} - minor, obtained from the determinant □ by deleting the i-th row and the k-th column.

The values of complex charges obtained in expression (24) can be used to calculate the field strengths on wires using formulas (19) and (20).

To calculate the field strengths on the wires according the working capacitance of the wire is used, which is defined as the ratio of the linear charge density of the wire to the phase voltage of the overhead line.

Figure 4 shows a screen form for entering initial information on overhead line support.

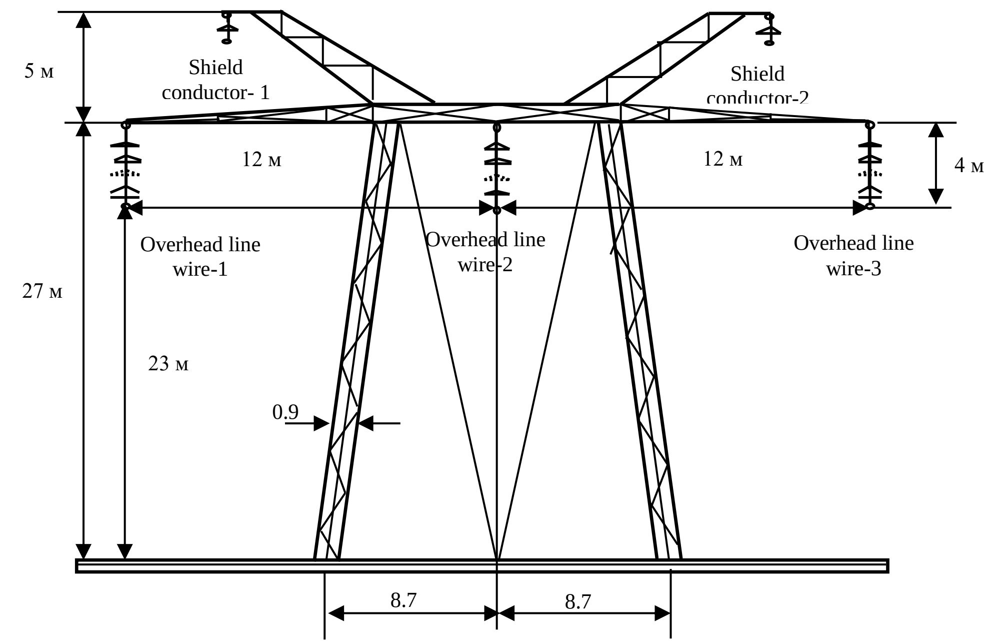

Figure 4: Data entry screen form information on the program complex

Figure 5 shows the general screen form of the program for entering initial information for modeling the software package Figure 5 shows the screen form for entering

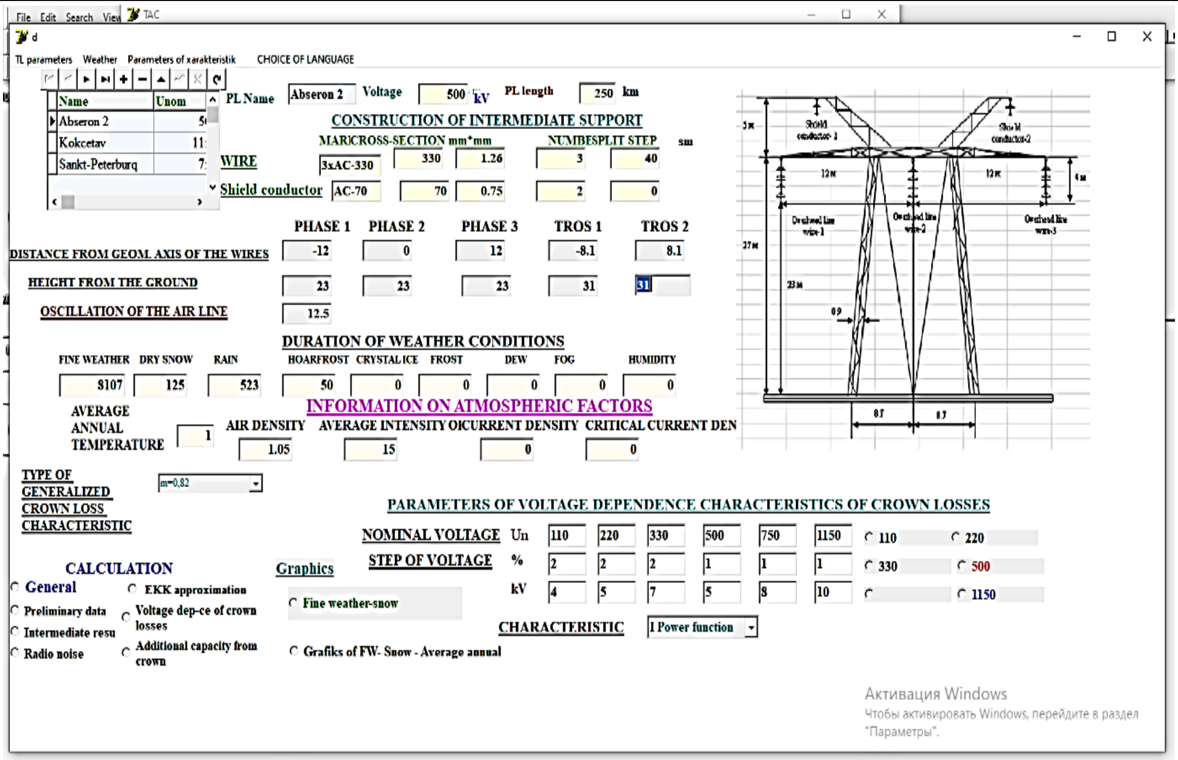

Figure 5: Data entry screen form information on the program complex

Wire brand ACO-300.

Nominal wire cross section 300 mm^2.

Wire radius 1.2 cm Rope radius 0.77 cm. E_{adm}=29.7 kV/cm.

Voltage OH 330.0 kV.

Number of wires 1 cables 1.

Wire splitting pitch 0.0 cm Rope 0.0 cm.

Distance between wires and geometric axis in m-s -5.80 4.8 8.30 0.00 0.00

Phase suspension height on the support in m-s 22.5 29.5 22.5 37 0.0.

Wire sag in m-s 14.50 m.

Wire roughness 0.82.

Critical current density 0.00 A/mm^2.

Relative air density 1.05.

Average annual air temperature 15^0C.

Duration of weather type in hours T_{gw}= 7960 T_{ds}= 150 T_r= 600 T_{fr}= 50

Precipitation intensity DI= 1.00 mm/hour.

The calculation is made for mining overhead lines

Generalized characteristic type 1

Air Density 1.05

Average annual temperature 15.0^0C

Height above sea level 100.0 m.

Intermediate results.

Wire splitting radius 1.20 cm.

Equivalent wire radius 0.069 m.

Irregularity factor 1.06.

Phase capacitances pF/m 10.808 11.35 11.486. Critical corona tension 31.5.

Critical corona stress 442.9 kV/cm.

The level of radio interference from overhead lines is unacceptable $E_{max} = 25.3 > E_{perm} = 29.7\ kV/sm$.

6.Conclusion

A program has been developed for modeling the levels of radio interference at various distances from overhead lines of ultra-high voltage alternating current.

The Overhead Line Electromagnetic Compatibility Program assesses the environmental impact of high voltage transmission lines in terms of radio interference, acoustic noise, corona losses and electromagnetic fields. It is an all-in-one design and analysis software package available in the industry.

All EMC-related overhead line parameters are presented in one main window, which contains a multi-tab control providing quick access to parameter groups such as radio interference, acoustic noise, corona loss, atmospheric conditions, and wire surface conditions.

The software can be used in the design of constructive parameters of power lines and in the analysis of the actual state of the electromagnetic compatibility of operated AC power lines.

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