Determining electromagnetic fields generated by overhead power transmission lines

V P Zakaryukin¹, A V Kryukov¹,² and N V Buyakova³
¹Transport Electric Power Engineering department, Irkutsk State Transport University, 15, Chernyshevsky Str., Irkutsk, 664074, Russia
²Power Supply and Electrical Equipment department, Irkutsk National Research Technical University, 83, Lermontov Str., Irkutsk, 664074, Russia
³Power Supply of the Industrial Enterprises department, Angarsk State Technical University, 60, Tchaikovsky Str., Angarsk, 665835, Russia

E-mails: zakar49@mail.ru, and_kryukov@mail.ru, bn_900@mail.ru

Abstract. Under actual operating conditions of electrical networks, it is hard to obtain experimental data that correspond to the maximum levels of the electromagnetic field strengths generated by overhead power transmission lines. Therefore, the analysis of the electromagnetic environment in electric power systems, both at the operated and newly created facilities, is recommended to be performed on the basis of mathematical modeling. The modeling methods and tools developed in IrGUPS and the Fazonord software package implemented on their basis make it possible, after determining the power system mode, to calculate the electromagnetic field strengths generated by multi-wire power transmission lines. In this case, the analyzed lines are considered in close connection with a complex electric power system. To check the adequacy of the simulation, measurements of electric and magnetic field strengths were performed, including comparative calculations for a 110 kV double-circuit line with a ground-wire located within the city. The comparison carried out in rather complex conditions is indicative of the correctness of the method of calculating a multi-wire line electromagnetic field developed in IrGUPS.

1. Introduction
Electromagnetic fields (EMF) generated by high-voltage or high-current transmission lines are a dangerous form of environmental pollution [1–4]. Interference resulting from exposure to EMF can cause disruptions in the operation of electrical and electronic systems, can cause inflammation of flammable substances, etc. [5–6]. Electromagnetic fields have a negative impact on humans [5]. Therefore, the task of determining the strengths of electromagnetic fields generated by power transmission lines is of particular relevance in modern conditions. Under actual operating conditions of electrical networks, it is difficult to obtain experimental data that correspond to the maximum levels of the electromagnetic field strengths generated by overhead power transmission lines. Therefore, the analysis of the electromagnetic environment in electric power supply systems, both at the operated and newly created facilities, is recommended to be performed on the basis of mathematical modeling.

The methods and tools for simulating sinusoidal modes [9, 10] developed in IrGUPS in phase coordinates make it possible to simultaneously calculate the electric power system mode to determine the EMF strength of multi-wire power lines [11–17]. In this case, the analyzed lines are considered in
close connection with a complex electric energy system (EES).
When calculating the EMF generated by multi-wire lines, it is necessary to consider the following factors that influence the level of strengths:

- irregularities of the underlying surface;
- grounded metal objects (fencing of territories, buildings with grounded elements inside walls, ceilings and roofs, large metal objects);
- adjacent lines capable of creating significant electromagnetic fields.

The Fazonord software package (SP) makes it possible to use up to one thousand wires in models. This results in the possibility of modeling irregularities of the underlying surface, extended metal objects, adjacent power lines or electric traction networks of AC railways. The use of computational methods requires checking the adequacy of the means used and the correct consideration of the environment that can affect the electromagnetic field.

2. The simulation technique
After determining the EES mode according to the method described in [9], one can calculate the strengths of the electromagnetic field generated by any of the multi-wire power transmission lines belonging to the simulated system. The components of the electric field strength of a system of \( N \) wires at a point with coordinates \((x, y)\) are calculated using the following formulas:

\[
\begin{align*}
\dot{E}_x &= -\frac{1}{\pi\varepsilon_0} \sum_{i=1}^{N} \frac{y_i [(x-x_i)^2 - y^2 + y_i^2]}{[(x-x_i)^2 + (y+y_i)^2][(x-x_i)^2 + (y-y_i)^2]^2}; \\
\dot{E}_y &= \frac{2}{\pi\varepsilon_0} \sum_{i=1}^{N} \frac{y_i (x-x_i) y_i}{[(x-x_i)^2 + (y+y_i)^2][(x-x_i)^2 + (y-y_i)^2]^2},
\end{align*}
\]

where \( \dot{r}_i \) is the wire charge \( i \) per unit length, determined from the first group of Maxwell formulas:

\[
T = A^{-1} \cdot \hat{U}.
\]

Here \( \hat{U} = [\hat{U}_1 \ldots \hat{U}_N]^T \) is the column vector of the voltage of the wires relative to the earth; \( \hat{T} = [\dot{r}_1 \ldots \dot{r}_N]^T \) is the column vector of wire charges per unit length; \( A \) is a symmetric matrix of potential coefficients, in which:

\[
\alpha_{i i} = \frac{1}{2\pi\varepsilon_0} \ln \frac{2y_i}{r_i}, \quad \alpha_{i j} = \frac{1}{2\pi\varepsilon_0} \ln \frac{\sqrt{(x_i-x_j)^2 + (y_i+y_j)^2}}{\sqrt{(x_i-x_j)^2 + (y_i-y_j)^2}},
\]

\( x_i, y_i \) are the coordinates of the location of the wire \( i \) of radius \( r_i \) above the ground (axis \( Y \) is directed vertically upward; \( y = 0 \) corresponds to the surface of the flat earth, axis \( X \) is perpendicular to the line, axis \( Z \) is directed against the chosen positive current direction in the wires of the line); \( \varepsilon_0 \) is the electric constant.

After the transition from the complex RMS values of the components \( \dot{E}_x \) and \( \dot{E}_y \) to the time dependencies, one can obtain the parametric hodograph equations of the electric field strength vector:

\[
E_x(t) = \sqrt{2} E_x \sin(\omega t + \varphi_x); \quad E_y(t) = \sqrt{2} E_y \sin(\omega t + \varphi_y),
\]

where the factor \( \sqrt{2} \) is required since the strengths are calculated according to the RMS values, \( \omega = 314 \text{ rad/s} \).

Field strength reaches the maximum value \( E_{\text{MAX}} \) at times determined by the following equation:

\[
t_{\text{MAX}} = \frac{1}{2\omega} \arctan \left( \frac{E_x^2 \sin 2\varphi_x + E_y^2 \sin 2\varphi_y}{E_x^2 \cos 2\varphi_x + E_y^2 \cos 2\varphi_y} \right).
\]

The choice of one of the two values of the arctangent is made according to the condition of the negative value of the second derivative:
In a small hill, at a distance of about 70 m from the site of the railway, at a distance of about 70 m from the installation of the “Fazonord” software package [9]. In this case, the magnetic fields at a frequency of 50 Hz with comparative calculations were measured for a 110 kV double-circuit line with a ground wire located within the city. The measurements were carried out in the interval between the two supports at the intersection of the electric power transmission line with the railway electrified by the 1 × 25 kV system. At this point the railway is located in a sufficiently deep ditch cut, which did not require the construction of high supports. The measurement site was located on a small hill, at a distance of about 70 m from the site of the railway.

The RMS value of the field strength in a certain direction \( \Psi \), measured from the positive direction of the axis \( X \), is equal to:

\[
E_y = \frac{1}{2\pi} \int_0^{2\pi} \left| 2E_x \cos \psi \sin(\omega t + \varphi_x) + E_y \sin \psi \sin(\omega t + \varphi_y) \right|^2 d(\omega t) =
\]

\[
= \sqrt{E_x^2 \cos^2 \psi + E_y^2 \sin^2 \psi + 2E_x E_y \sin \psi \cos \psi \cos(\varphi_x - \varphi_y)}.
\]

Extreme values of strength are calculated by the formula:

\[
E_{\Psi \max} = \frac{E_x^2 + E_y^2}{2} \pm \sqrt{\left(E_x^2 + E_y^2\right)^2 - 4E_x^2 E_y^2 \sin^2(\varphi_x - \varphi_y)} / 2
\]

The plus sign corresponds to the maximum, and the minus sign corresponds to the minimum value.

This formula is given in paper [18], the authors of which indicate that when calculating the field near the surface of the earth, the error of a simple quadratic summation \( E = \sqrt{E_x^2 + E_y^2} \) usually does not exceed 10% in the direction of overstating the maximum of the RMS value.

The vertical and horizontal components of the magnetic field strength are calculated using the following formulas:

\[
H_x = \frac{1}{2\pi} \sum_{i=1}^{m} \frac{y - y_i}{(x_i - x)^2 + (y_i - y)^2}; \quad H_y = \frac{1}{2\pi} \sum_{i=1}^{m} \frac{x - x_i}{(x_i - x)^2 + (y_i - y)^2}.
\]

To determine the strengths of the electric and magnetic fields, the computational scheme mode is calculated, the charges and currents of the wires, including the grounded ones, are determined, and the components of \( \bar{E}_x, \bar{E}_y, H_x, H_y \) are found.

The described technique is implemented in the “Fazonord” software package [9]. In this case, the strengths of the electromagnetic field can be determined both for a particular mode and for their combination, on the basis of which one can obtain the dynamics of changes in the EMF intensity over time.

The method allows significantly simplifying the calculation of EMF strengths. Indeed, in the traditional formulation, this problem requires the solution of differential equations in partial derivatives. Its solution is much more complicated in the presence of heterogeneities of the underlying surface, as well as the need to take into account not only the earth’s surface and the underlying conductive objects (metal fences, underground pipelines, etc.).

Using a set of grounded wires to simulate inhomogeneity of the earth’s surface (with the transmission line route passing along) and conductive objects allows the proposed method to be applied to determine EMF with proper consideration of environmental conditions without additional complications and modifications.

Calculations of EMF strengths by the proposed method can be referred to as integral methods with charge distribution on fictitious grounded conductors located on the surface of a non-flat earth or conductive boundary of the structure. Unlike the applied types of integral methods, the charges on grounded conductors are determined by calculating modes in phase coordinates. After calculating the mode of the system, one can determine the charges of wires per unit length.

3. Experimental conditions

Strengths of the electric and magnetic fields at a frequency of 50 Hz with comparative calculations were measured for a 110 kV double-circuit line with a ground wire located within the city. The measurements were carried out in the interval between the two supports at the intersection of the electric power transmission lines with the railway electrified by the 1 × 25 kV system. At this point the railway is located in a sufficiently deep ditch cut, which did not require the construction of high supports. The measurement site was located on a small hill, at a distance of about 70 m from the railway.
railway. The height of the wire suspension above the measurement site was approximately 19 m (ground wire), 16 m, 13 m, 10 m (phase wires). A single-circuit 110 kV dead-end feeder is connected to the line.

At a distance of 10 m from the electric power transmission line with a small lowering of the earth surface there is a metal fence of a garage cooperative, which should have a significant impact on the electric field. A sufficiently large distance to the electrified railroad made it possible to ignore its effect on the magnetic field in the calculations. The electric field of the catenary system also had no effect since the railway was located in the groove and the voltage was relatively small, 25 kV.

According to the regime measurements of double-circuit electric power transmission lines, a power flow of about $9-12 \, \text{MV} \cdot \text{A}$ passes through the circuit closest to the dead-end feeder (the minus sign corresponds to the positive direction of the feeder power flow). The flow in the second circuit is $6-9 \, \text{MV} \cdot \text{A}$; the dead-end feeder consumes $6+3 \, \text{MV} \cdot \text{A}$.

4. Description of the computational scheme
To correctly take into consideration a multi-wire system with facilities that affect the EMF, its model was built in the “Fazonord” software package, including 19 wires (Fig. 1).

![Figure 1. The cross-section of a multi-wire system model](image)

Numbers 1–6 denote phase conductors. Number 7 is assigned to a ground wire connected to the ends of the grounding conductors with a dissipation resistance of 10 Ohms. Numbers 8–10 denote wires of the dead-end feeder. Wires numbered 11–16 are introduced to take into consideration the uneven ground surface. When grounding with a shunt with a resistance of 1 ohm on one side, these wires make it possible to take into account the effect of the elevation of the earth on the electric field, without affecting the magnetic field strength. For the left, more loaded line circuit, the phase voltages were taken symmetrical, 65 kV each, and 66 kV each for the right one. When calculating the mode, the above loads, symmetrically decomposed in phases, resulted in the following currents: $77 \, \text{A}$ of the left circuit wires, $54 \, \text{A}$ of the right circuit wires and $34 \, \text{A}$ of the dead-end feeder. The computational scheme of the Fazonord SP is shown in Fig. 2.

Nodes 2, 4, 6, 7, 8, 9 of the computational scheme are declared balancing; the loads are specified in nodes 16–21. Nodes 10 and 22 correspond to the ground wire. Nodes 11–15 have shunts to earth with a conductivity of 1 S. As a result of the mode calculation, the current of the ground wire amounted to about 0.1 A. Thus, the ground wire, having a significant effect on the electric field, has practically no effect on the magnetic field.
5. Results of measurements and calculations of electromagnetic field strengths

Experimental measurements of the electromagnetic field strengths (Tables 1, 2 and Fig. 3, 4) are presented by three groups of measurements taken at different times. During the measurements, the same directions of the axes of coordinates are taken as in the calculation method. The origin of coordinates is located under the center of the electric power transmission lines on the ground surface. The measurements were carried out with a field strength meter P3-50 according to the projections of the strengths to the corresponding coordinate axes at a height of 1.5 m from the ground surface.

### Table 1. Maximum values of electric field strength and correlation coefficients of calculated and experimental values at measurement points

| Parameter | Calculation | Experiment | Differences, % |
|-----------|-------------|------------|----------------|
| $E_{\text{max}}$, kW/m | 0.53 | 0.54 | 0.49 | 0.59 | -1.6 | 9.6 | -17.0 |
| Correlation coefficient | 0.94 | 0.89 | 0.79 | - | - | - |

### Table 2. Maximum magnitudes of magnetic field strengths and correlation coefficients of calculated and experimental values

| Parameter | Calculation | Experiment | Differences, % |
|-----------|-------------|------------|----------------|
| $H_{\text{max}}$, A/m | 0.47 | 0.54 | 0.55 | 0.59 | -12.1 | -1.8 | -6.7 |
| Correlation coefficient | 0.92 | 0.80 | 0.84 | - | - | - |

In general, the nature of the dependence of the electric field strength on the coordinate $X$, obtained by calculation, corresponds to similar dependences, built on the basis of experiments. In the first experiment, the maximum values of strengths are almost equal to the design ones. All experiments are characterized by lower values of the field strength below the left chain, according to fig. 1. The calculated values for the right chain lie inside the limits of the scattering region of the experimental values. The simulation adequacy is confirmed by the high values of the correlation coefficients between the experimental and calculated data.

The results of some quantitative discrepancy between the calculated and experimental data on the electric field strengths of the left circuit are attributable to the following factors:

- shielding of the electric field by garages located on the north-east side of the electric power...
transmission lines at a distance of about 7 m from the measurement site with a coordinate of –12 m, and the garage cooperative buildings on the south side;

* an approximate account of the dead-end feeder;
* shielding of the electric field by the bodies of the crew members carrying out the measurements;
* the presence of errors in the determination of wire heights;
* inaccurate setting of voltage wires and the presence of asymmetry caused by unsymmetrical load.

Tabl. 2 and fig. 4 show the results of measurements and calculations of the magnetic field strength.

![Figure 3. The interval representation of the measurement results of electric field strengths](image1)

![Figure 4. The interval representation of the measurement results of magnetic field strengths](image2)

The problem of modeling a magnetic field differs from a similar problem for an electric field by a high level of uncertainty of the operating situation arising due to a large variation in the wire currents, while the voltages of the wires determining the electric field vary in a small interval. However, most
of the calculated points of the dependence $H = H(X)$ do not exceed the limits of the scattering region of experimental values.

A more detailed analysis shows that, with a fairly close similarity in the dependences of the $H$ module on the $X$ coordinate for all experiments, there is a difference in the horizontal component of the magnetic field strength obtained by calculation and experimentally. There is a particularly large difference for the third set of experimental data. This is due to the dependence of the magnetic field strength not only on the modules, but also on the phases of the currents in the electric power transmission lines. The latter are highly dependent on the current mode of the EES. Since a double-circuit electric power transmission line is part of a complex network and has two-way power supply, currents can change their phases over wide limits, up to a turn of 180°. This factor greatly affects the horizontal component of strength. The large difference in the current modules of the two circuits results in the emergence of a maximum of the vertical component at the center of the electric power transmission lines.

6. Conclusion
The comparison of the results of experimental measurements of the electric and magnetic fields strengths and the calculated values in fairly complex conditions is indicative of the correctness of the proposed method for calculating the electromagnetic field of a multi-wire line.

References
[1] Apollonsky S M and Bogarinova A N 2006 Strengths of the air environment on the electrified railways (St. Petersburg: collection of reports of the ninth Russian scientific and technical conference on electromagnetic compatibility of technical means and electromagnetic safety) pp 579–83
[2] Apollonsky S M 2001 External electromagnetic fields of electrical equipment and means to reduce them (St. Petersburg: Bezopasnost' Publ.)
[3] Apollonsky S M and Gorsky A N 2006 Calculations of electromagnetic fields (Moscow: Marshrut Publ.).
[4] Blake L B 2007 Protection against electromagnetic fields. On the impact of household electrical appliances, mobile phones, power lines and other electrical devices on the human body (Moscow: Ast, Astrel' Publ.)
[5] Sidorov A I and Okrainskaya I S 2008 Electromagnetic fields near electrical installations of extra high voltage (Chelyabinsk: South-Ural State Un-ty Publ.)
[6] Tikhonov M N 2011 The mechanism of the influence of natural and man-made electromagnetic fields on life safety The ecology of industrial production 4 24–32
[7] Kusmartseva E V and Yakubovich D M 2016 The influence of modern sources of electromagnetic fields on human safety in the technical field (Saratov: Innovations in environmental engineering and protection in emergency situations) pp 46–8
[8] Makhutov N A, Kalmykov V M, Balanovsky V L and Balanovsky L V 2014 Quality of life and electromagnetic safety (Quality and life. No. 2) pp 53–7
[9] Zakaryukin V P and Kryukov A V 2005 Complex non-symmetrical modes in electrical systems (Irkutsk: Irkutsk university Publ.)
[10] Zakaryukin V P, Kryukov A V 2013 Multifunctional approach to modeling of electric power systems Modern technologies System analysis Modeling 4 100–7
[11] Buyakova N V, Zakaryukin V P and Kryukov A V 2018 Electromagnetic safety in power supply systems of railways: modeling and control (Angarsk: Angarsk State Technical University Publ.)
[12] Buyakova N V, Zakaryukin V P and Kryukov A V 2018 Modeling of electrical fields in railway engineering structures Advances in Engineering Research: International Conference on Avia mechanical Engineering and Transport vol 158 pp 219–25
[13] Buyakova N, Zakaryukin V, Kryukov A and Nguyen T 2018 Electromagnetic Safety Enhancing
in Railway Electric Supply Systems E3S, Web of Conf. 58(01006) pp 1–6

[14] Buyakova N, Zakarukin V and Kryukov A 2018 Imitative Modelling of Electromagnetic Safety Conditions in Smart Power Supply Systems Advances in Intelligent Systems Research vol. 158 Vth International workshop “Critical infrastructures: contingency management, intelligent, agent-based, cloud computing and cyber security” pp 20–5

[15] Buyakova N, Zakaryukin V and Kryukov A 2018 Control of electromagnetic environment in smart traction power supply systems ES3 Web of Conf. (TPACEE-2018) 91(01009) pp 1–11

[16] Kryukov A V, Zakaryukin V P and Buyakova N V 2010 Modeling of the electromagnetic environment on AC railways Modern technologies, System analysis, Modeling 2 169–75

[17] Kryukov A V, Zakaryukin V P and Buyakova N V 2010 Electromagnetic environment control at railway facilities Modern technologies, System analysis, Modeling 3 34–8

[18] Katz R A and Perelman L S 1978 Calculation of the electric field of a three-phase power line Electricity 1 16–9