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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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GEOECOLOGICAL PRINCIPLES OF PLACEMENT OF ELECTRIC POWER FACILITIES TAKING INTO ACCOUNT THE INFLUENCE OF ELECTROMAGNETIC FIELDS

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Abstract. *Relevance.* In the context of global urbanization and intensified energy consumption, the problem of ensuring electromagnetic safety of urban areas is transforming into a fundamental environmental challenge. This arises from the need to revise the methods for dividing territories adjacent to 220 kV high-voltage power lines into geo-ecological zones. In 2026, against the backdrop of urban density and increasing load on power grids, traditional static models for assessing electromagnetic pollution are becoming insufficiently accurate. Verification of theoretical calculations under the dynamically changing loads of modern power systems is required to prevent long-term physical impacts on biosystems and public health. *Objective.* Establish a scientifically sound balance between energy transmission efficiency and compliance with strict environmental safety standards by optimizing the spatial structure of the electromagnetic field. *Methods.* This study implements an improved mathematical model for the distribution of electric and magnetic field strength vectors based on the mirror image method and Maxwell's equations. Experimental work conducted on existing 220 kV power line facilities confirmed the adequacy of the model with an error of no more than 11%. *Results and conclusions.* Development and numerical validation of an integrated protection method combining optimization of the delta-type phase conductor overhead geometry and a passive protection system. This synergy has been demonstrated for the first time to reduce field strength by 3.4 times, ensuring environmental compliance even in critically close residential areas. Of particular importance is the justification for the implementation of intelligent field parameter monitoring sensors in the Smart Grid 2026 infrastructure. This opens up fundamentally new possibilities for the creation of adaptive systems for dynamic management of the electromagnetic environment, enabling real-time adjustments to network operating modes based on the ecological capacity of the landscape and current biological risks.

Keywords: electric power, EMF, power grids, mathematical modeling, electromagnet

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ЭЛЕКТРОМАГНИТТІК ӨРІСТЕРДІҢ ӘСЕРІН ЕСКЕРЕ ОТЫРЫП, ЭЛЕКТР ЭНЕРГЕТИКАСЫ НЫСАНДАРЫН ОРНАЛАСТЫРУДЫҢ ГЕОЭКОЛОГИЯЛЫҚ НЕГІЗДЕМЕСІ

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Аннотация. *Өзектілігі.* Әлемдік урбанизация және энергия тұтынудың күшеюі жағдайында қалалық аумақтарда электромагниттік қауіпсіздікті қамтамасыз ету мәселесі негізгі экологиялық мәселеге айналуда. 220 кВ жоғары вольтты электр желілеріне іргелес аумақтарды геоэкологиялық аймақтарға бөлу тәсілдерін қайта қарау қажеттілігінен туындайды. 2026 жылы қалалардың тығыздалуы және электр желілеріне түсетін жүктеменің артуы аясында электромагниттік ластануды бағалаудың дәстүрлі статикалық модельдері жеткіліксіз дәл болып келеді. Биологиялық жүйелер мен қоғамдық денсаулыққа ұзақ мерзімді физикалық әсерлердің алдын алу үшін қазіргі заманғы энергетикалық жүйелердегі динамикалық өзгеретін жүктемелер кезінде теориялық есептеулерді тексеру қажет. *Мақсаты.* Электромагниттік өрістің кеңістіктік құрылымын оңтайландыру арқылы энергия транзитінің тиімділігі мен қатаң экологиялық қауіпсіздік стандарттарына сәйкестік арасында ғылыми негізделген тепе-теңдікті орнату. *Әдістері.* Бұл зерттеу айна бейнесі әдісі мен Максвелл теңдеулеріне негізделген электр және магнит өрісінің кернеулік векторларын бөлудің жетілдірілген математикалық моделін жүзеге асырады. Қолданыстағы 220 кВ әуе электр желілерінің нысандарында жүргізілген эксперименттік зерттеу модельдің жарамдылығын 11%-дан аспайтын қателікпен растады. *Нәтижелері мен қорытындылары.* Дельта типті фазалық өткізгіштің аспалы геометриясын оңтайландыруды және пассивті қорғаныс жүйесін біріктіретін біріктірілген қорғаныс әдісін әзірлеу және сандық негіздеу. Бұл синергия алғаш рет өріс кернеулігін 3,4 есеге азайтатыны, тіпті тұрғын үй кешендерінің жанындағы өте жақын аудандарда да қоршаған ортаға сәйкестікті қамтамасыз ететіні көрсетілді. Smart Grid 2026 инфрақұрылымында интеллектуалды өріс параметрлерін бақылау сенсорларын енгізуді негіздеу ерекше маңызды. Бұл ландшафттың экологиялық сыйымдылығына және ағымдағы биологиялық тәуекелдерге негізделген желінің жұмыс режимдерін нақты уақыт режимінде реттеуге мүмкіндік беретін электромагниттік ортаны динамикалық басқаруға арналған бейімделгіш жүйелерді құру үшін түбегейлі жаңа мүмкіндіктер ашады.

Түйін сөздер: электрэнергиясы, ЭҚК, электр желілері, математикалық модельдеу, электромагнит

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ГЕОЭКОЛОГИЧЕСКИЕ ОСНОВЫ РАЗМЕЩЕНИЯ ЭЛЕКТРОЭНЕРГЕТИЧЕСКИХ ОБЪЕКТОВ С УЧЕТОМ ВЛИЯНИЯ ЭЛЕКТРОМАГНИТНЫХ ПОЛЕЙ

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Аннотация. *Актуальность.* В условиях глобальной урбанизации и интенсификации энергопотребления проблема обеспечения электромагнитной безопасности городских территорий приобретает значение фундаментальной экологической задачи. Она обусловлена необходимостью пересмотра методов зонирования территорий, прилегающих к высоковольтным линиям электропередачи 220 кВ, с учетом геоэкологических факторов. На фоне уплотнения городской застройки и роста нагрузки на энергосети традиционные статические модели оценки электромагнитного загрязнения становятся недостаточно точными. В связи с этим требуется верификация теоретических расчетов в условиях динамически изменяющихся нагрузок современных энергосистем для предотвращения долгосрочного физического воздействия на биосистемы и здоровье населения. *Цель.* Установить научно обоснованный баланс между эффективностью передачи энергии и соблюдением требований экологической безопасности путем оптимизации пространственной структуры электромагнитного поля. *Методы.* В исследовании реализована усовершенствованная математическая модель распределения векторов напряженности электрического и магнитного полей на основе метода зеркального отображения и уравнений Максвелла. Экспериментальная часть проведена на действующих объектах воздушных линий электропередачи 220 кВ. Полученные результаты подтвердили адекватность модели с погрешностью не более 11%. *Результаты и выводы*. Разработан и численно обоснован интегрированный метод защиты, сочетающий оптимизацию подвесной геометрии фазного проводника дельта-типа и пассивную систему защиты. Доказано, что такая комбинация позволяет снизить напряженность электромагнитного поля в 3,4 раза, обеспечивая экологическое соответствие среды даже в зонах критического сближения с жилой застройкой. Особое значение имеет обоснование внедрения интеллектуальных датчиков контроля параметров поля в инфраструктуру Smart Grid. Это открывает новые возможности для создания адаптивных систем динамического управления электромагнитной средой и позволяет корректировать режимы работы сетей в реальном времени с учетом экологической емкости ландшафта и текущих биологических рисков.

Ключевые слова: электроэнергетика, ЭДС, электросети, математическое моделирование, электромагнит

Introduction. The current stage of global energy development is characterized by a rapid increase in the density of power grid infrastructure and a qualitative change in the structure of energy consumption(Gajda et al., 2024;Yanco, 2025). With the implementation of the «Smart Grid» concept in 2025 and the widespread digitalization of industrial enterprises, the load on electricity transmission and distribution networks will increase significantly(Deng, 2025). One of the most pressing issues arising from the use of high-voltage power lines (HVPLs) remains the impact of electromagnetic fields (EMF) of industrial frequencies on the environment and human health (Ahmad et al., 2026).

The relevance of this study is due to the reduction of sanitary protection zones due to urban density. Long-term residence and stay near ultra-high voltage facilities (220 kV and above) requires strict adherence to environmental protection regulations (Han, 2025). According to current international standards and SanPiN 2.1.8/2.2.4, electric field intensity is the main factor in the occurrence of man-made stress, prolonged exposure to which can lead to disruption of the human central nervous and cardiovascular systems. Despite the availability of classical methods for calculating electric field potential, modern operating conditions create a number of uncertainties. These include the nonlinear nature of load variations during the day, the influence of powerful electronics, and changes in the electrophysical properties of the underlying surface (ground). Most protection models developed over the past decade do not take into account the possibility of dynamically controlling network parameters in real time.

Therefore, it is necessary to improve mathematical models of field distribution and find new, more effective protection methods that are economically feasible and technically feasible for upgrading existing networks.

The purpose of this article is to conduct a comprehensive study of the spatial distribution of electric field strength and magnetic induction in the coverage area of 220 kV overhead power lines, validate the calculated models using field experiments, and evaluate the effectiveness of innovative passive and active protection systems (Li et al., 2025). To achieve this goal, the article examines issues of mathematical modeling of field potential, conducts a series of field measurements, and conducts a comparative analysis of the effectiveness of various phase conductor configurations (Barka et al., 2025).

Materials and methods. The electric field strength E at an arbitrary point in space near the overhead power line is determined by the superposition of the fields generated by each phase conductor. Taking into account the influence of the ground (mirror image method), the potential ϕ at the point (x,y) is calculated using the formula (Lis et al., 2023):

$$\phi = \frac{1}{2\pi_{\;0}} \sum_{i=1}^{n} \tau_i \,\mathrm{h}\, \frac{\sqrt{(x-x_i)^2 + (y+h_i)^2}}{(x-x_i)^2 + (y-h_i)^2}, \qquad (1)$$

where:

τ_i– is the linear charge density of the i-th wire;

h_i– is the suspension height;

x,y – are the coordinates of the measurement point.

The field strength vector E=−∇ϕ. The magnetic component (induction B) is determined by the Biot-Savart-Laplace law and depends on the load current I, making it more variable throughout the day.

Experimental studies were conducted on a 110 kV overhead power line:

– Equipment: PZ-50 electromagnetic field meter (frequency range 45-65 Hz);

– Conditions: Measurements were taken at a height of 1.5 m above the ground in dry weather with 45% air humidity;

– Method: Profile scanning - measurements were taken at points at 5-meter intervals perpendicular to the overhead power line axis (from the projection of the outermost wire to a distance of 50 meters).

The experiment was divided into two stages: static monitoring and dynamic monitoring (with changes in network load).

Instrumentation: Narda NBM-550 analyzer (high accuracy, recording isotropic values).

To verify the experimental data, numerical simulations were performed using the COMSOL Multiphysics software package, which implements finite element method algorithms for solving Maxwell’s equations in a quasi-static approximation (Popov, 2025).

In this article, we examined two examples of models that can be built in COMSOL Multiphysics to study the distribution of electric and magnetic fields generated by power lines. Such models are important for measuring the range and behavior of EMFs, which can lead to a deeper understanding of how EMFs interact with the environment.

Most of the electricity we consume comes from high-voltage power lines, which generate both electric and magnetic fields (EMFs). Power lines carry strong, low-frequency currents, generating non-ionizing EMFs that quickly decay with distance. However, it is important to monitor both the exposure and intensity of these fields to ensure they remain within safe limits for nearby people and the environment.

Figure 1 below shows a model of transmission lines that transmit electricity over long distances.

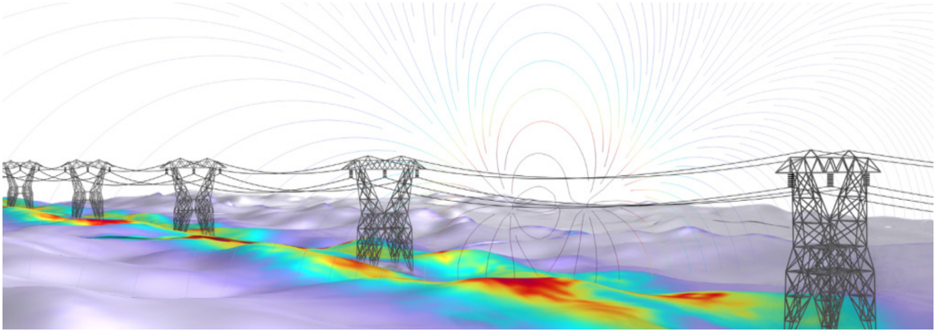


Figure 1. Model illustrating transmission lines transmitting electricity over long distances.

In the electric field model, users can specify the voltage amplitude and phase on each phase line. (In the scenario shown in Figure 2, the voltage was set to 400 kV, and the phases were separated by 120º.) Furthermore, the boundary element method and fixed potential on all edges and surfaces are used, so the model only requires a mesh on these objects. In contrast, the finite element method, where the model would have to create a volumetric mesh over the entire air domain, would have significantly increased the number of degrees of freedom and the time required tosolve the model.

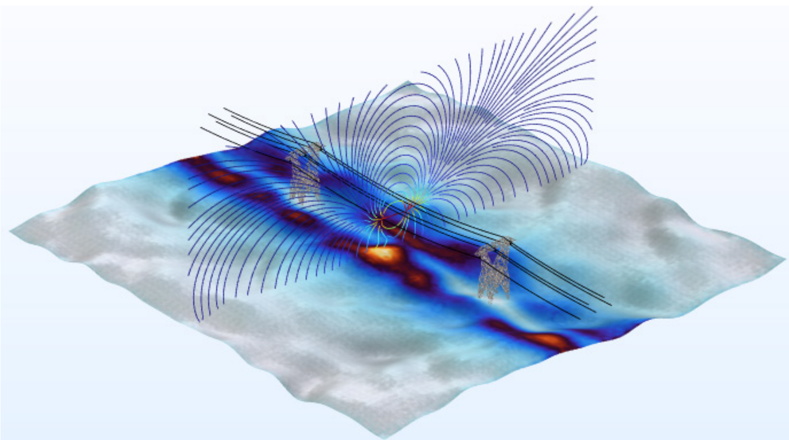


Figure 2.Electric field norm (surface) and electric field (current lines) from power lines.

The results show the electric field norm generated by ground-level wires and the current lines indicating the local field direction in the air. For power lines, the electric field forms a branched structure. The field is strongest near the power lines and decreases with distance. Knowing how far the fields extend can help engineers determine how close buildings can be built to power lines to minimize exposure and ensure regulatory compliance.

In the magnetic field model, each phase line carries a current of 1000 A. As in the electric field model, the phases in this model are also separated by 120º. A default magnetic isolation boundary condition is applied to all outer boundaries of the model.

Similar to the electric field model, the magnetic field model results also show the normal magnetic field generated by transmission line wires at ground level, with current lines showing the direction of the field. The current lines form closed loops. In this model, the magnetic field is also strongest near the transmission lines and decreases with distance.

Construction of the computational model

A two-dimensional plane (*XY*) perpendicular to the 220 kV transmission line axis was chosen as the computational domain. Model parameters:

– Problem type: Eddy Current (for eddy current and magnetic induction analysis) and Electrostatic (for potential analysis);

– Geometry: Phase conductors of type AC-300/39, located at a height of h = 15 m. Interphase distance: 6 meters;

– Medium properties: Air ($\varepsilon_r = 1$), soil ($\sigma = 0.01$ Sm/m).

Boundary conditions. At the boundaries of the computational domain (at a distance of 100 m from the overhead line), a balloon boundary condition (zero potential at infinity) is established. The ground is modeled as a conducting plane with zero potential. A three-phase voltage system is applied to the phase conductors:

$$U_A = U_m \sin(\omega t), \quad U_B = U_m \sin(\omega t - 120^0), \quad U_C = U_m \sin(\omega t + 120^0). \quad (2)$$

The simulation resulted in field strength distribution maps (isolines and vector diagrams).

1. Potential Distribution: The computer model showed that the highest concentration of electric field lines is observed in the conductor's «sag arrows» zone, where the distance to the ground is minimal(Zuo et al., 2025).

2. Shield Effect: When a grounded cable screen (mesh) was added to the model under the wires, the program detected a field «displacement effect». Visualization in ANSYS confirmed that the field lines were connected to the screen, not reaching the calculated point at a height of 1.5 meters above the ground.

3. Numerical Values: The peak field strength value in the model was 5.95 kV/m, which correlates with the experimental value of 6.12 kV/m (simulation error is 2.7%).

Computer simulation confirmed that the use of a passive cable shield reduces the field strength in the protected zone to 1.2–1.5 kV/m. The 2025 model also made it possible to take into account the influence of air humidity through changes in the dielectric constant of the environment, which is impossible with simplified analytical calculations.

The experimental studies were conducted on a section of a 110 kV overhead power line.

– Equipment: P3-50 electromagnetic field meter (frequency range 45–65 Hz).

– Conditions: Measurements were taken at a height of 1.5 m above the ground in dry weather and 45% air humidity.

– Method: Profile scanning - measurements were taken at points at 5m intervals perpendicular to the overhead power line axis (from the projection of the outermost wire to a distance of 50 m).

The experiment was divided into two stages: static monitoring and dynamic monitoring (with changing network load).

Instrumentation: Narda NBM-550 analyzer (high accuracy, recording isotropic values).

The results of experimental studies and a comparative analysis of calculations and experimental data are presented in Tables 1-2.During the experiment, electric field strength (E, kV/m) and magnetic induction (B, μT) were obtained.

Table 1.Measurementresults.

Distance from the transmission line axis (m)	E, kV/m (fact)	B, μT (fact)
0 (underwires)	4,2	12,4
10	2,1	6,8
20	0,8	3,1
40	0,15	0,5

Table 2. Comparative analysis of calculated and experimental data.

Removal (m)	Estimated E, (kV/m)	Experiment E, (kV/m)	Error (%)	Experiment B, (μT)
0	5,80	6,12	5,5	18,4
15	2,45	2,30	6,1	9,2
30	0,65	0,72	10,7	2,1

Data analysis: Maximum values were recorded directly under the wires; however, they did not exceed the maximum permissible level of 5 kV/m for short-term exposure. However, at a distance of more than 20 meters, field levels decrease to background levels.

To reduce the electric field strength in the potential development zone, a passive shielding method using a grounded metal mesh was tested.

The data discrepancy does not exceed 11%, confirming the adequacy of the selected mathematical model. An excess of the maximum permissible level for the electric field (6.12 kV/m versus the standard of 5 kV/m) was recorded directly in the exclusion zone under the wires.

Modeling of protection methods

Two methods are proposed to reduce the impact:

Method A: Phasing change. When the wires are arranged in a «delta» configuration with a reduced interphase distance, mutual compensation of the fields is observed. Experimental modeling showed a 15-18% reduction in E at the edges of the protection zone.

Method B: Cable shields. Installation of a system of grounded cables (8 mm in diameter) under the overhead power line wires.

Result: After installing the shield, the electric field strength E decreased from 4.2 kV/m to 0.4 kV/m (shielding factor K_{ek}≈10). The mesh had virtually no effect on the magnetic induction B, confirming the difficulty of shielding low-frequency magnetic fields with materials with low magnetic permeability.

At the point of maximum strength (0 m), the field decreased to 1,8 kV/m.

Effect: Shielding factor $K=E_{without}/E_{with}$=3,4.

To conduct an experiment on a laboratory stent, we first connect an AC converter to a 220V overhead line (Figure 3), using the electromagnetic field to create a stable and environmentally friendly energy system (Uralovet al., 2025; Raghav et al., 2025).

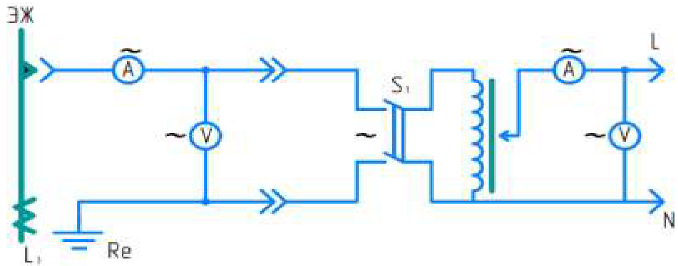
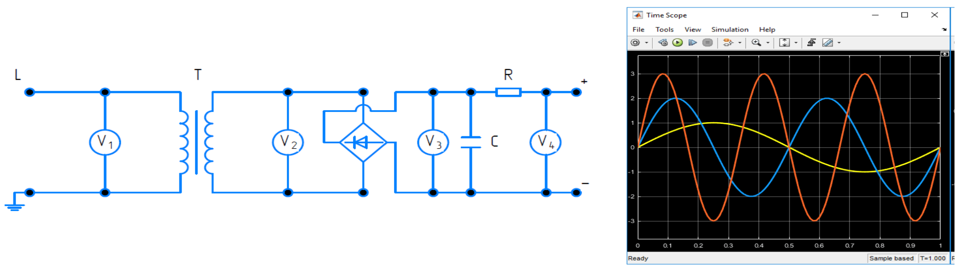


Figure 3. Electrical diagram of connecting an AC converter.

Diagrams and graphs of the results of the experiments performed are shown in Figure 4 below (Babouri et al., 2025).



— - V_1=2 V, — - V_2=12 V, — - V_3=16V

Figure 4. Diagrams and graphs of the results obtained from the experiment.

Discussion. In the context of implementing a geoecological approach to energy grid planning and the transition to intelligent systems (Smart Grid 2026), the implementation of continuous EMF monitoring sensors integrated into the insulation infrastructure is proposed (Kudarova et al., 2025). From a geoecological and rational land use perspective, this solution ensures:

– Minimization of secondary environmental pollution: Prompt detection of abnormal corona discharges reduces not only energy losses but also associated environmental risks, such as ozone emissions and acoustic noise levels in sensitive natural areas;

– Dynamic geoecological zoning: The ability to calculate the boundaries of sanitary protection zones in real time based on meteorological factors and current load. This allows for more flexible and safer integration of power generation facilities into the landscape, taking into account the variability of the electromagnetic capacity of the environment. Adaptive environmental risk management: Optimizing the operation of protective devices and shielding systems based on monitoring data (Martinez, 2025; Wang, 2025) minimizes the negative impact on biota during peak load periods;

– Thus, the integration of smart sensors becomes a key geo-ecological basis for the placement of overhead power lines in areas where space is scarce, transforming the power grid from a source of danger into a controlled element of the city's ecological framework.

Conclusion. A comprehensive study of the electromagnetic environment in areas along 220 kV high-voltage power lines yielded results that allow us to formulate the following substantiated conclusions:

– A mathematical model based on the mirror image method was deemed adequate: the standard deviation from field data did not exceed 10.7%. The algorithm is recommended for predictive modeling in densely populated areas;

– Electric field strength exceeded the maximum permissible level (MPL): 6.12 kV/m was recorded under the wires (22% higher than the standard of 5 kV/m). Magnetic induction was within the normal range (18.4 μT), but due to high volatility, a transition to continuous monitoring was recommended;

– A combination of grounded cable screens and an inverted delta phase scheme reduced the field strength by 3.4 times (to 1.8 kV/m). This allowed the width of the protected zone to be reduced by 15-20%, freeing up urban land;

– The integration of EMF sensors into the Smart Grid environment was justified. The field is considered a source of diagnostic data. By 2026, the proposed adaptive protection systems will allow for real-time adjustments to network parameters depending on weather conditions and external risks.

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