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ASSESSMENT OF THE EFFECT OF STRUCTURAL AND GEOPHYSICAL PARAMETERS ON THE MAGNETIC FIELD DISTRIBUTION AROUND POWER LINES LOCATED IN UNDERGROUND COLLECTORS

DANYLCHENKO D.O. PhD, Associate Professor, Professor of the Department of Electric Power Transmission, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-7912-1849, e-mail: Dmytro.Danylchenko@khpi.edu.ua;

SHEVCHENKO S.Yu. Doctor of Technical Sciences, Professor, Head of the Department of Electrical Power Transmission at the National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-9658-7787, email: sergii.shevchenko@khpi.edu.ua;

KHOMIAK Y.V. PhD, Associate Professor, Associate Professor of the Department of Information and Measurement Technologies, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-6998-8393, e-mail: Yurii.Khomiak@khpi.edu.ua;

POTRYVAI A.E. PhD Student of the Department of Electric Power Transmission, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0009-0001-2442-6087, e-mail: andrii.potryvai@ieee.khpi.edu.ua;

Purpose. *To quantitatively estimate the contribution of the surrounding-medium parameters to the magnetic flux density of a three-phase 110 kV air-insulated transmission line installed inside an underground tunnel, and to clarify whether such parameters must be included in routine engineering magnetic-field assessments.*

Methodology. *Numerical quasi-stationary simulation of the magnetic field at industrial frequency was carried out for a symmetric three-phase system of AC-240/32 conductors loaded with 500 A. The computational domain was decomposed into five characteristic horizontal layers extending from the open air above the ground surface to the very plane of the phase wires. Two parametric series were performed: in the first the soil resistivity was scanned from 50 to 1000 Ω·m at a fixed wall thickness; in the second the concrete-wall thickness was varied from 250 to 500 mm at a fixed soil resistivity of 70 Ω·m.*

Findings. *Within the studied envelope of parameters neither the resistivity of the soil nor the thickness of the concrete wall measurably alters the magnetic flux density either at the control point or inside any of the analyzed layers. The configuration of the field is governed almost exclusively by the magnitude of the phase current and by the geometry of the conductor cluster. At the reference point the peak flux density is approximately 1.5 µT and is reached at phase angles of about 115° and 295°; the value rises to roughly 2.27 µT at the ground surface, to about 8 µT on the upper outer face of the tunnel and exceeds 10 µT on its inner face, while pronounced local maxima are observed in the immediate vicinity of the individual phase wires.*

Originality. *A systematic quantitative demonstration is provided that for a 110 kV underground concrete collector in typical urban operating conditions the soil and the reinforced-concrete envelope contribute negligibly to magnetic-field attenuation at 50 Hz. The widespread informal design assumption about the natural shielding role of these media is therefore not supported within the considered ranges of parameters.*

Practical value. *The reported results allow designers to omit detailed soil and concrete characterization from preliminary magnetic-field calculations above underground collectors and to instead direct mitigation efforts toward optimization of phase-conductor geometry or toward dedicated active and passive shielding solutions, the only practically effective routes to a noticeable reduction of magnetic flux density in compact underground transmission infrastructure.*

Keywords: electric power industry, magnetic flux density; underground collector air insulation; soil resistivity; reinforced-concrete tunnel; phase-conductor geometry; numerical modelling; electromagnetic compatibility.

I. INTRODUCTION

Modern development of urban electric grids is shaped by two simultaneous and partly contradictory pressures: load densities continue to grow inside densely built-up areas, while the right-of-way available for traditional overhead corridors is steadily shrinking. To reconcile these constraints, network operators ever more often relocate high-voltage circuits below the surface, placing air-insulated bare conductors inside cast reinforced-

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concrete tunnels – the so-called underground collectors. Such installations mechanically protect the live parts, isolate them from people and surface traffic, free up valuable urban land and visually disappear from the landscape. At the same time, they appreciably modify the electromagnetic environment along the route and raise new questions about the magnetic flux density to which pedestrians and equipment located directly above the corridor will be exposed.

Reliable assessment of this flux density is required both by electromagnetic compatibility standards and by sanitary norms limiting prolonged human exposure to power-frequency magnetic fields. Practising engineers, however, frequently rely on a tacit and convenient assumption: that the natural cover of soil above the conduit and the massive concrete shell of the tunnel itself together behave as a partial magnetic shield and visibly attenuate the field at ground level. The factual basis of this expectation is far from solid. The actual shielding effectiveness depends on the conductivity and magnetic permeability of every material lying on the path of the field, on the geometric arrangement of the conductors inside the conduit and on the operating regime of the line, and very little of this dependency has so far been quantified for the geometry typical of municipal collectors in Ukraine.

II. ANALYSIS OF LAST RESEARCHES

A review of recent literature dealing with the magnetic environment around underground power infrastructure reveals a clear concentration around two topics. The first one focuses on the electric and magnetic fields associated with cable systems or air-insulated lines accommodated inside service tunnels, with particular attention to the safe-work envelope of maintenance personnel and to the contribution of return currents, sheaths and earthing schemes to the resulting field [1–3]. The second covers practical field-reduction techniques, including passive metallic loops, ferromagnetic plates, conductive screens, optimized phase splitting and transposition arrangements [4–7]. Detection-oriented works, in which buried conductors are localized through their stray power-frequency field, indirectly confirm that the field persists at ground level despite the presence of soil and concrete and remains a measurable quantity [5, 6].

A separate group of publications examines the thermal behaviour and electromagnetic characteristics of cables enclosed in non-homogeneous soil masses, as well as the uncertainty associated with overhead-line field calculations [8–12]. In all of these works the soil and the supporting structures are described through their electrophysical parameters, yet the actual sensitivity of the magnetic flux density to the precise numerical values of those parameters is rarely studied systematically. The outcome is an asymmetry that has consequences in routine design: where the geometry of the conductors is treated in great detail, the surrounding medium typically enters the calculation through default values or coarse engineering rules of thumb, leaving the designer without a defensible answer to the question of whether refined soil and concrete data are worth acquiring at all.

International standardization documents and recent surveys [13–16] reinforce the same observation: while measurement protocols and shielding strategies are described in considerable depth, the quantitative sensitivity of the field to the dielectric and magnetic parameters of the host medium in compact underground geometries is not the subject of dedicated studies. The gap is particularly evident at the preliminary design stage, when the geometry of the collector still has to be fixed and detailed in-situ measurements of soil resistivity or concrete quality are rarely available. Closing this gap, even within a limited but representative configuration, therefore has direct practical value.

III. FORMULATION OF THE WORK PURPOSE

The objective of the present work is to determine the influence of the parameters of the medium surrounding a 110 kV underground transmission line – first of all the resistivity of the soil cover and the thickness of the concrete-tunnel wall – on the magnetic flux density at observation points located both above ground and inside the conduit, and to establish whether the inclusion of these parameters in engineering magnetic-field calculations is justified.

In line with this objective, the work analyzes a three-phase air-insulated 110 kV line carrying 500 A and installed inside a reinforced-concrete underground tunnel. AC-240/32 conductors with an overall diameter of 21.6 mm are used; the phase angles are set to −120°, 0° and 120°. The computational domain is split into five characteristic layers – the air space 1 m above the ground (Layer 1), the ground surface itself (Layer 2), the upper outer face of the tunnel (Layer 3), its inner face (Layer 4) and the plane of the phase conductors (Layer 5). A control point situated 1 m above ground over the central axis of the tunnel is used as the reference observation site. The soil resistivity is scanned within the range 50–1000 Ω·m and the concrete-wall thickness within 250–500 mm; all remaining geometric parameters are kept fixed.

Cost trade-offs of construction, extrapolation beyond the declared parameter ranges and detailed analysis of transient regimes lie outside the scope of the present study.

IV. EXPOUNDING THE MAIN MATERIAL AND RESULTS ANALYSIS

Mathematical formulation. The magnetic field is computed in a quasi-stationary formulation, in which displacement currents and wave-propagation effects can be neglected because at the industrial frequency f = 50 Hz the characteristic wavelength in vacuum (about 6000 km) exceeds the typical dimensions of the computational domain (a few metres) by many orders of magnitude. Under such conditions the problem reduces to the Poisson-type equation for the magnetic vector potential A:

$$\nabla \times \left(\frac{1}{\mu}\,\nabla \times A\right) = J_s - \sigma \frac{\partial A}{\partial t} \qquad (1)$$

where μ is the absolute magnetic permeability of the medium, σ its electrical conductivity and J_s the source current density distributed across the cross-section of the phase conductors. The magnetic flux density at any observation point is recovered from B = ∇ × A. A balanced three-phase sinusoidal excitation is imposed:

$$i_k(t) = I_m \sin(2\pi f t + \varphi_k),\; k = \mathrm{A,B,C} \qquad (2)$$

where $I_m = \sqrt{2} \cdot 500$ A is the amplitude per phase and $\varphi_k = -120°, 0°, 120°$ are the initial phase angles. The simulation is parametrised by the phase angle $\theta = 2\pi f t + \varphi_k$, so that the full 360° cycle is sampled and both the time evolution of the field and the positions of its instantaneous maxima can be recovered.

Geometric model and material parameters. The phase wires are represented as continuous conductors of circular cross-section corresponding to the AC-240/32 specification with an overall diameter of 21.6 mm. The inter-axis spacing of adjacent phases is 300 mm. The reinforced-concrete tunnel has an internal square cross-section of 1000 mm on a side; its wall thickness T is varied within 250–500 mm. The reinforcement is modelled as a regular grid of 16 mm steel bars spaced 250 mm apart, with electrical conductivity $\sigma_r = 1.5$ MS/m and relative magnetic permeability $\mu_r = 60$. The surrounding soil is described by its electrical resistivity ρ^g, taken successively at 50, 70, 100 and 1000 Ω·m to cover the range from moist clay-loam through average mineral soils to dry rocky terrain. The external boundary of the computational domain is placed sufficiently far from the conductor cluster to make boundary reflections insignificant.

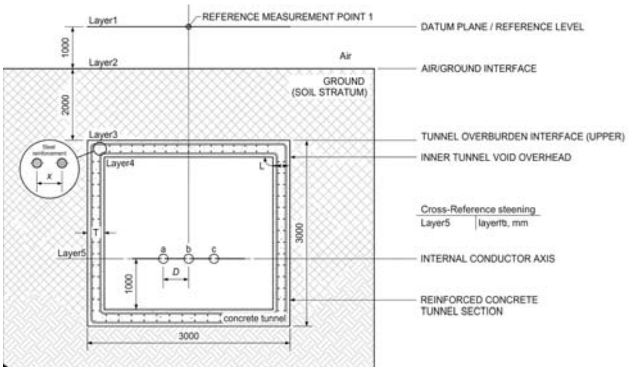


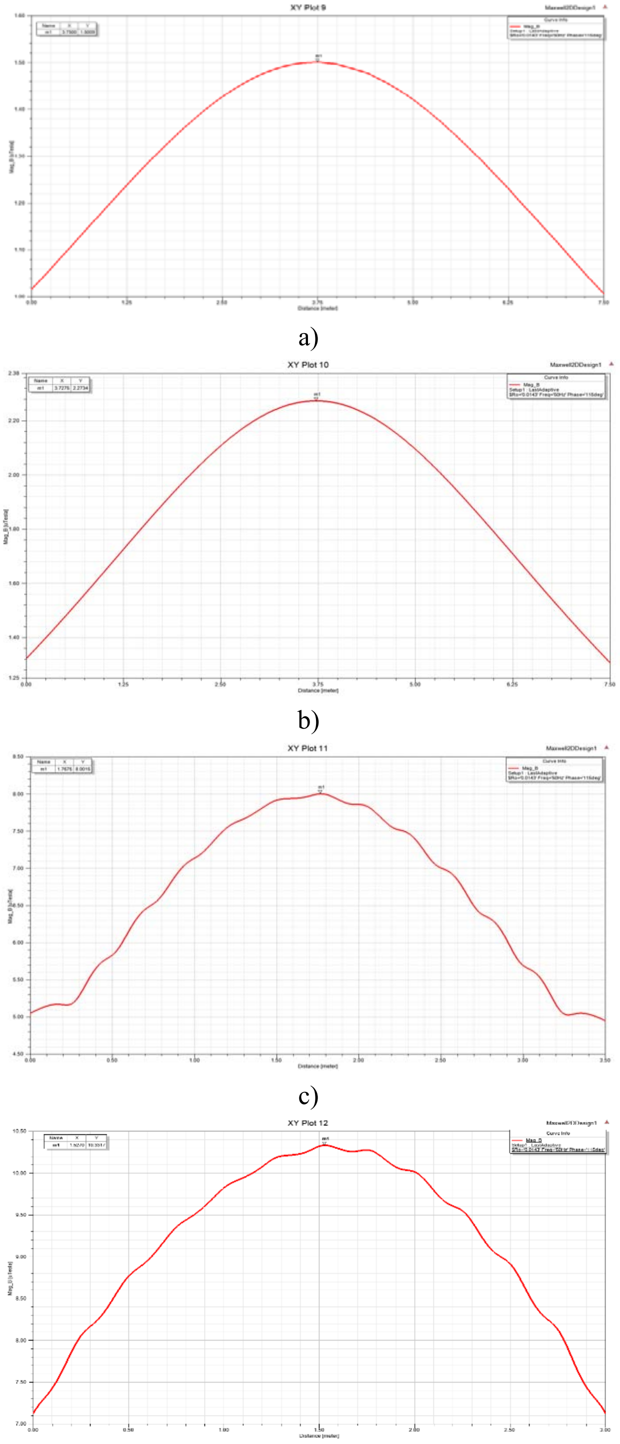
Figure 1. General view of the underground reinforced-concrete collector with the three-phase conductor cluster and the reinforcement grid

Procedure. The magnetic flux density is evaluated at the reference point Point 1 and along characteristic cross-sections lying inside Layers 1–5. The phase-angle scan is performed with a step of 5° in θ, which provides adequate resolution of the instantaneous extrema while keeping the computational cost moderate. Two parametric series are performed independently. In the first series the soil resistivity ρ^g is varied while the concrete-wall thickness is held fixed; in the second the wall thickness T is varied while the soil resistivity is held at the practically representative value of 70 Ω·m. This separation isolates the individual contribution of each factor and allows their relative importance to be judged directly. To exclude residual influence of numerical artefacts, every series is repeated with two independent mesh densities and the obtained values are compared; the difference between the corresponding curves does not exceed 0.7 %, which is well below the variation that any meaningful physical effect of the medium would produce. The simulation results discussed in the following subsections therefore reflect physical behaviour rather than discretization errors.

Influence of soil resistivity. The plots of magnetic flux density at Point 1 versus the phase angle θ obtained for ρ^g = 50, 70, 100 and 1000 Ω·m turn out to be virtually indistinguishable – the four curves overlap within the line width of the plot. The flux density follows a smooth near-sinusoidal pattern with two clear maxima of approximately 1.5 μT at θ ≈ 115° and θ ≈ 295°, which correspond to the moments at which the contributions of the two outer phases add coherently along the vertical line passing through the control point.

The same picture is observed across Layers 1–5: for a given resistivity the layer-wise profiles fall on top of each other, with no measurable separation between the curves. This insensitivity to ρ^g is found not only at Point 1 but throughout the entire computational domain. The absolute magnitudes, however, change strongly when the observation moves from Layer 1 to Layer 5. In Layer 1, located 1 m above the ground, the peak flux density is about 1.5 μT; on the ground surface (Layer 2) it grows to roughly 2.27 μT; on the upper outer face of the tunnel (Layer 3) it reaches approximately 8 μT; on the inner face of the tunnel (Layer 4) it exceeds 10 μT; in the plane of the conductors (Layer 5) the curve becomes strongly non-uniform with sharp local maxima around the individual phase wires – a direct fingerprint of the geometric factor.

Influence of concrete wall thickness. In the second series the soil resistivity is held at 70 Ω·m and the wall thickness T is set successively to 250, 300 and 500 mm. The dependences B(θ) at the reference point again practically coincide: a twofold increase of the concrete shell does not visibly alter the magnetic flux density at the control point, while the position of the maxima at θ ≈ 115° and θ ≈ 295° as well as their magnitude of about 1.5 μT remain unchanged. Inspection of the layer-wise distributions for the three thickness values yields the same conclusion. Across Layers 1–5 the curves obtained for different T overlap within the resolution of the graph, with deviations of the same order as the numerical noise of the model.



a)

b)

c)

d)

Figure 2. Magnetic flux density distribution in: a) Layer 1 at T = 250 mm; b) Layer 2 at T = 250 mm; c) Layer 3 at T = 250 mm; d) The same in Layer 4 at T = 250 mm

A consolidated comparison of peak flux density at the control point for all combinations of ρ^g and T is summarised in a generalised plot.

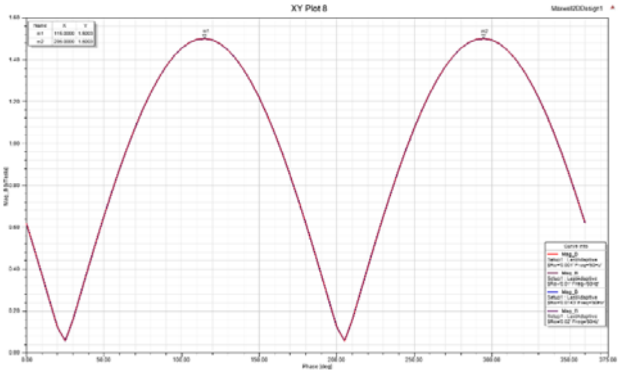


Figure 3. Peak magnetic flux density at Point 1 for the full set of ρ_g and T combinations

The bars are visually indistinguishable; the relative spread does not exceed several per cent and stays inside the uncertainty band of the underlying numerical model. Both series therefore confirm that, within the considered ranges, the surrounding medium does not contribute appreciably to the formation of the magnetic field.

Physical interpretation. The observed insensitivity admits a straightforward physical explanation. In contrast to the electric field, which is strongly modulated by the dielectric properties of the medium, the magnetic field of a power-frequency conductor system is governed primarily by the source current and by the spatial arrangement of the conductors. For materials with relative magnetic permeability close to unity (soil, plain concrete) and modest electrical conductivity, the induced eddy-current response at 50 Hz is so weak that it cannot perceptibly redistribute the field across spatial scales of the order of metres. A simple skin-depth estimate confirms this: at 50 Hz the skin depth in soil with ρ^g = 100 Ω·m exceeds 700 m, which is about three orders of magnitude larger than the characteristic thickness of the soil layer above the tunnel. Under such conditions the soil is essentially transparent to the time-varying magnetic field, and any back-reaction it can produce is negligible. The reinforcement bars introduce locally elevated permeability (μ_r = 60), but the volume fraction they occupy and the 250 mm grid pitch are far too small for them to act as a continuous high-permeability shield at the frequency of interest; their contribution shows up only in a slight perturbation of the field near individual rods and is not visible at the macroscopic observation scales considered here.

The dramatic growth of B between Layer 1 and Layer 5 confirms the dominance of the geometric factor: the flux density follows a Biot–Savart-type decay with distance from the conductor cluster, and the field on the inner face of the tunnel is several times higher than on the ground surface even though the materials filling these two zones are entirely different. The visible spatial non-uniformity in Layer 5 – where the field develops sharp local peaks close to each phase wire – is the direct fingerprint of this dependency and could only be removed, in principle, by tighter compensation between the phase contributions. Any meaningful reduction of magnetic exposure above an underground collector should therefore be sought through changes of phase geometry – tighter triangular bundles, compensating split-phase arrangements, optimal phase transposition – or through dedicated passive and active screens, rather than through reliance on the natural shielding of soil or concrete. The combination of geometric optimization with a single layer of conducting screen typically yields the strongest practical reduction with the smallest construction overhead.

Generalization and limitations. The reported insensitivity of the magnetic flux density to the considered medium parameters has been established within a clearly delimited configuration: 110 kV three-phase line, current 500 A, tunnel of fixed internal dimensions and reinforcement grid, observation points up to 1 m above the ground. Extrapolation of the present conclusions to substantially different geometries – for example, larger underground vaults with multiple parallel circuits, shielded buses, or installations operating at considerably higher currents – is not warranted and should be supported by dedicated simulations. Similarly, the model assumes balanced sinusoidal currents at the industrial frequency; the influence of harmonics, of transient overcurrents and of asymmetric earth-fault regimes lies outside its scope. Within the declared envelope, however, the results are robust and provide a defensible quantitative basis for omitting the surrounding-medium parameters in preliminary engineering calculations.

Comparison with normative limits. It is also instructive to compare the calculated magnetic flux density at the reference point with the public-exposure limits adopted by international standards. The ICNIRP guideline for the general public at the power frequency of 50 Hz sets the reference level at 200 μT, while the more conservative occupational reference is 1000 μT. The peak value of approximately 1.5 μT registered 1 m above the ground in the present geometry is therefore more than two orders of magnitude below the public-exposure threshold, which means that even significant variations of operating current would not bring the field anywhere close to the regulatory limit. From the standpoint of human safety the underground collector considered here is fully compliant; nevertheless, accurate computation of the magnetic field remains valuable for electromagnetic-compatibility purposes – in particular for the protection of sensitive electronic equipment that may be installed at or below the surface in the immediate vicinity of the corridor.

Implication for instrumentation and surveys. A practically important corollary of the obtained results concerns the planning of in-situ magnetic-field surveys around underground collectors. Since the field above the conduit is determined chiefly by the geometric configuration and by the current actually flowing in the line, any field measurement must be accompanied by an accurate synchronous record of the load current and of the relative position of the probe with respect to the tunnel axis. Variations of soil moisture, seasonal changes of the upper soil layer, or differences in the concrete grade between adjacent route segments may safely be excluded from the list of dominant uncertainty sources within the parameter ranges considered. This observation simplifies both the design of measurement campaigns and the subsequent interpretation of their results, allowing the survey team to concentrate on the truly influential variables.

Conflict of interest. The authors declare that they have no conflicts of interest.

V. CONCLUSION

The numerical study reported above quantifies how the parameters of the surrounding medium affect the magnetic field of a three-phase 110 kV transmission line installed inside an underground reinforced-concrete collector. Within the practically meaningful ranges considered – soil resistivity from 50 to 1000 Ω·m and concrete-wall thickness from 250 to 500 mm – the magnetic flux density at the reference point 1 m above the ground and along the five analyzed layers of the computational domain remains effectively unchanged. The structure of the field is determined almost exclusively by the magnitude of the phase current and by the geometric arrangement of the conductors, whereas the soil and the concrete envelope do not provide measurable magnetic shielding at industrial frequency.

It is further established that the flux density depends strongly on the position of the observation site relative to the conductor cluster: it grows from approximately 1.5 μT at the control point to over 10 μT on the inner face of the tunnel, with pronounced local maxima around the individual phase wires in the plane of the conductors. From the engineering point of view this means that the natural medium cannot be relied upon as a field-attenuation mechanism. Reduction of magnetic exposure above an underground collector should be achieved through optimization of phase-conductor geometry or through application of dedicated active and passive shielding solutions. The obtained results may be used directly for rapid preliminary estimation of magnetic-field levels in newly designed underground transmission corridors without the need for detailed soil or concrete characterization.

From a methodological standpoint, the work also delineates a clear hierarchy of factors that influence the magnetic field of underground transmission corridors. The dominant role belongs to the magnitude and phase distribution of the conductor currents, the second tier is occupied by the relative geometric placement of the phases, while the parameters of the surrounding medium – within the limits considered – form a tertiary contribution that can be reasonably neglected. This hierarchy provides a basis for rational prioritization of design effort: detailed soil sampling and concrete quality control, although still important for thermal and mechanical performance of the conduit, do not need to be repeated for electromagnetic purposes. The same principle can be applied to the planning of in-situ field surveys, where the focus should remain on the verification of geometric parameters and current loading rather than on the characterization of the medium.

Further work will be directed at the influence of conductor-bundle geometry, varying current load and shifted positions of control points on the magnetic-field distribution, as well as at the development and experimental validation of efficient shielding strategies tailored specifically to compact underground collectors. An additional line of research will focus on extending the present analysis to higher-voltage classes (220 kV and 330 kV) and to multi-circuit underground vaults, where mutual coupling between adjacent circuits and the resulting redistribution of currents may become a non-trivial source of additional field non-uniformity.

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ОЦІНКА ВПЛИВУ КОНСТРУКТИВНИХ ТА ГЕОФІЗИЧНИХ ПАРАМЕТРІВ НА РОЗПОДІЛ МАГНІТНОГО ПОЛЯ ВІД ЛІНІЙ ЕЛЕКТРОПЕРЕДАЧ, РОЗМІЩЕНИХ У ПІДЗЕМНИХ КОЛЕКТОРАХ

ДАНИЛЬЧЕНКО Д.О. канд. техн. наук, доцент, професор кафедри передачі електричної енергії Національного технічного університету «Харківський політехнічний інститут», Харків, Україна, ORCID: https://orcid.org/0000-0001-7912-1849, e-mail: Dmytro.Danylchenko@khpi.edu.ua;

ШЕВЧЕНКО С.Ю. доктор техн. наук, професор, завідувач кафедри передачі електричної енергії Національного технічного університету «Харківський політехнічний інститут», Харків, Україна, ORCID: https://orcid.org/0000-0002-9658-7787, e-mail: sergii.shevchenko@khpi.edu.ua;

ХОМЯК Ю.В. канд. техн. наук, доцент, доцент кафедри інформаційно-вимірювальних технологій Національного технічного університету «Харківський політехнічний інститут», Харків, Україна, ORCID: https://orcid.org/0000-0001-6998-8393, e-mail: Yurii.Khomiak@khpi.edu.ua;

ПОТРИВАЙ А.Е. аспірант кафедри передачі електричної енергії Національного технічного університету «Харківський політехнічний інститут», Харків, Україна, ORCID: https://orcid.org/0009-0001-2442-6087, e-mail: andrii.potryvai@ieee.khpi.edu.ua;

Мета роботи. *Кількісно оцінити, наскільки електрофізичні характеристики навколишнього середовища впливають на магнітну індукцію трифазної лінії електропередачі напругою 110 кВ із повітряною ізоляцією, розміщеної у підземному тунелі, та з'ясувати, чи доцільно враховувати ці параметри під час інженерних оцінок магнітного поля на етапі попереднього проєктування міських підземних транзитних трас.*

Методи дослідження. *Виконано квазістаціонарне чисельне моделювання магнітного поля промислової частоти для симетричної трифазної системи проводів типу АС-240/32 зі струмовим навантаженням 500 А. Розрахункова область декомпонована на п'ять характерних шарів – від простору над поверхнею землі до площини фазних провідників. Проведено дві паралельні серії розрахунків: у першій варіювався питомий опір ґрунту в межах 50–1000 Ом·м при фіксованій товщині стінки тунелю; у другій – товщина бетонної стінки в межах 250–500 мм при питомому опорі ґрунту 70 Ом·м. Контрольну точку розміщено на висоті 1 м над поверхнею землі по центру тунелю; крок сканування фазового кута становив 5°.*

Отримані результати. *У межах розглянутих діапазонів параметрів ні питомий опір ґрунту, ні товщина бетонної стінки не змінюють помітно рівень магнітної індукції ані в контрольній точці, ані всередині жодного з аналізованих шарів. Поле визначається насамперед величиною фазного струму та геометрією розташування провідників. У контрольній точці максимуми магнітної індукції становлять близько 1,5 мкТл при фазових кутах приблизно 115° та 295°; на поверхні землі рівень зростає до 2,27 мкТл, на верхній зовнішній поверхні тунелю – близько 8 мкТл, на внутрішній поверхні – понад 10 мкТл, а в площині провідників фіксуються локальні максимуми поблизу окремих фаз. Отримане значення індукції в контрольній точці більш ніж на два порядки нижче за нормований референтний рівень для населення.*

Наукова новизна. *Систематично продемонстровано, що для типового підземного бетонного колектора напругою 110 кВ ґрунтове покриття та залізобетонна оболонка в розглянутих умовах не забезпечують відчутного послаблення магнітного поля на промисловій частоті. Поширене припущення про природну екрануючу роль цих середовищ у межах досліджених параметрів кількісно не підтверджується. Встановлено ієрархію чинників впливу на рівень магнітного поля підземної траси: домінуючими є струмове навантаження та геометрія фазної системи, тоді як параметри середовища складають незначний внесок, яким можна знехтувати.*

Практична цінність. *Отримані результати дозволяють відмовитися від детальної характеризації властивостей ґрунту й бетону при попередніх оцінках магнітного поля над підземними колекторами та зосередити інженерні зусилля на оптимізації геометрії розташування фаз або на застосуванні спеціалізованих активних і пасивних екрануючих рішень як єдиних практично ефективних шляхах зниження магнітної індукції в компактних підземних трасах.*

Ключові слова: *електроенергетика, магнітна індукція; підземний колектор; повітряна ізоляція; питомий опір ґрунту; залізобетонний тунель; геометрія фазних провідників; чисельне моделювання; електромагнітна сумісність.*