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Influence of Ring Bonding at the Ground Level upon Current Distribution Between Down-Conductors

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***Abstract* — Present study considers distribution of currents and magnetic field in frame-type lightning protection systems (LPS). Influence of equipotentialization ring conductor (ERC) connecting vertical down-conductors at the ground level, as recommended by some normative documents, upon current distribution between mentioned conductors and magnetic field (MF) inside structures is numerically simulated. Analysis for a wide range of soils/water electrical conductivity ($\sigma_g = 0.67\cdot10^{-3}$ to 1 S/m) and various relative permittivity (ε_r = 4; 7; 15; 80) values is done. When one of the goals of LPS design is to achieve a uniform current distribution between down-conductors and MF reduction within structure, for large conductivities (> 0.1 S/m) the presence or absence of ERC do not make a significant difference. In case of lower conductivities (< $4\cdot10^{-3}$ S/m), advantages have structures without ERC.**

Keywords - earthing; electromagnetic environment; equipotentialization ring conductor; finite element method; frame structure; lightning current distribution; lightning down-conductor; lightning protection system; soil electrical conductivity & permittivity

I. Introduction

According to one of the LP national normative documents in Ukraine [1], vertical down-conductors of lightning protection system (LPS) should be connected at the ground level and each following 20 m upward along the structure height by horizontal ring conductors (equipotentialization ring conductor, ERC). The question discussed in present paper is related to the first ERC, at the bottom [1]. This ERC is not directly mentioned in [2] (Fig. E25). Regarding earthing system of type B, which is also encircling the protected structure, in normative documents it is clearly indicated the requirements to placement of contour conductor in soil: at least 80 % of its length should have contact at the depth of not less than 0.5 m and not closer than 1m to the structure walls/foundation [2, item 5.4.3]. But for the mentioned decision on ERC in [1], detailed explanations and recommendations are absent. Thus, some questions appear regarding practical realization of this requirement, such as: why and in what cases such ring conductor at the ground level is really necessary; whether it should have direct electrical contact to ground or not; what is its cross-section; what is the influence of the ring conductor upon current distribution between down-conductors of LPS and EM environment in protected volume; are there any peculiarities for various soils?

The influence of the ring conductor at the ground level upon lightning current distribution between conductive elements of LPS has been partly studied in [3] for two values of ground resistivity – 50 Ω·m and 500 Ω·m. Studies were performed for frame structures having dimensions of 48 m × 24 m × 12 m and 9 down-conductors, for the 10/350 μs current waveform. Lightning current distributions were calculated by numerical solution of electric field integral equations in frequency domain, and time domain solution was obtained using fast Fourier transform. Lightning channel was assumed as a long vertical conductor connected to the corner of the structure. In [3], ring conductor at the ground level was placed as follows: 1) around the structure buried at 0.6 m; 2) 1 m above the earth. Results have shown a noticeable difference in current distributions between cases of additional ring conductor absence and presence: for ground resistivity of 50 Ω·m and the absence of ERC, the difference of currents within vertical conductor under the striking point and one at the opposite side of the frame is 13.7 %, and for the same soil and presence of ERC, this difference is increasing to 27.3 %; for ground resistivity of 500 Ω·m, with absence and presence of ERC, they obtained 0.8 % and 23.3 %, respectively.

The influence of soil resistivity upon lightning current distribution between conductive elements of LPS having frame type has been studied also in [4] by using equivalent circuit of the conductive elements of the LPS. It was consisting of lumped resistances and self-inductances; and mutual capacitances and mutual inductances between frame elements also were taken into account. Calculations were performed for the 10/350 μs lightning current waveform according to [5]. Structures under study had dimensions of 48 m × 12 m × 12 m and 6 down-conductors of 8 mm in diameter. Lightning channel and actual permittivity of soil influences were neglected. Resistivity of soil was simulated as an equivalent resistance of 0 to 500 Ω connected to each down-conductor. Results have shown that when resistance of the earthing electrodes has values of 100 Ω and more, the partitioning of the lightning current in all down-conductors is practically even. With the decrease of equivalent soil resistance the difference in partitioning is increasing and can reach of about 47 % between current in down-conductor under the striking point and one at the opposite side of the frame.

In [6], studies of current distributions in small cage-type structures (1x1x1 m, 1x1x2 m) were presented, and the influences of channel length and inclination were addressed for the 1x1x1-m structure. In simulation, an ideal ground was considered.

Magnetic fields have been studied numerically in frame structures in many works (for example, [7, 8]), and some similar methods will be used in present study.

Thus, previous related works have studied current distributions for relatively narrow ranges and selected values of ground resistivity, and limited number of considered factors. On the other hand, practical realization of the requirements [1] regarding the arrangement of equipotentialization ring conductors also call for clarifying several listed above issues.

This paper presents a study on influence of ring conductor presence at the ground level, and its location (above or under ground level) upon current distribution between conductors of LPS for a wide range of soil or water electrical conductivity ($\sigma_g = 0.67 \cdot 10^{-3}$ to 1 S/m) and various relative permittivity (ε_r = 4; 7; 15; 80) values. Also, for selected cases, a magnetic field is defined within protected structure. Models include the presence of lightning channel and in some cases also of the wall encompassing the frame structure. Simulations are performed at Comsol Multiphysics by using the predefined physics “Magnetic and electric fields (mef)”. For several cases of structures earthed at specific soils and water, results are compared and discussed. Recommendations are done on the effectiveness of discussed horizontal equipotentialization ring conductors.

II. Research Models

Two groups of models are considered (Fig. 1): having two and four down-conductors. In each group, three their types are looked at: without equipotentialization ring conductor (ERC) at the bottom of down-conductors, with ERC at the depth of 0.1 m below the soil/water surface, and with ERC installed 0.1 m above the mentioned surface. Lightning channel is vertical; its length is defined in paragraph B of Section III and by using Fig. 2. Conductors of a frame structure are located in air or in concrete wall (indicated later in Fig. 3 as dashed-line contour and W). Earthing conductors are placed in soil or water, which characteristics are defined further. All conductors are made of regular steel (μ ≈1000) and have diameters of 0.03 m. Other dimensions are: w = 10 m, d = 6 m, h = 5 m, h_g = 3 m. For the lightning channel, conductivity and diameter are assumed same as for metallic conductors. Magnetic field was calculated for the whole volume of the computational domain and presented in this paper only for distributions along lines f2, f4 (middle height of the structure, 2.5 m) and f1, f3 (1-m height), shown in Fig. 1a, b, c, d.

Also the case when conductors of LPS are placed into wall has been investigated for the frame structure in Fig. 1a. It is assumed that the wall is made of concrete. As mentioned,

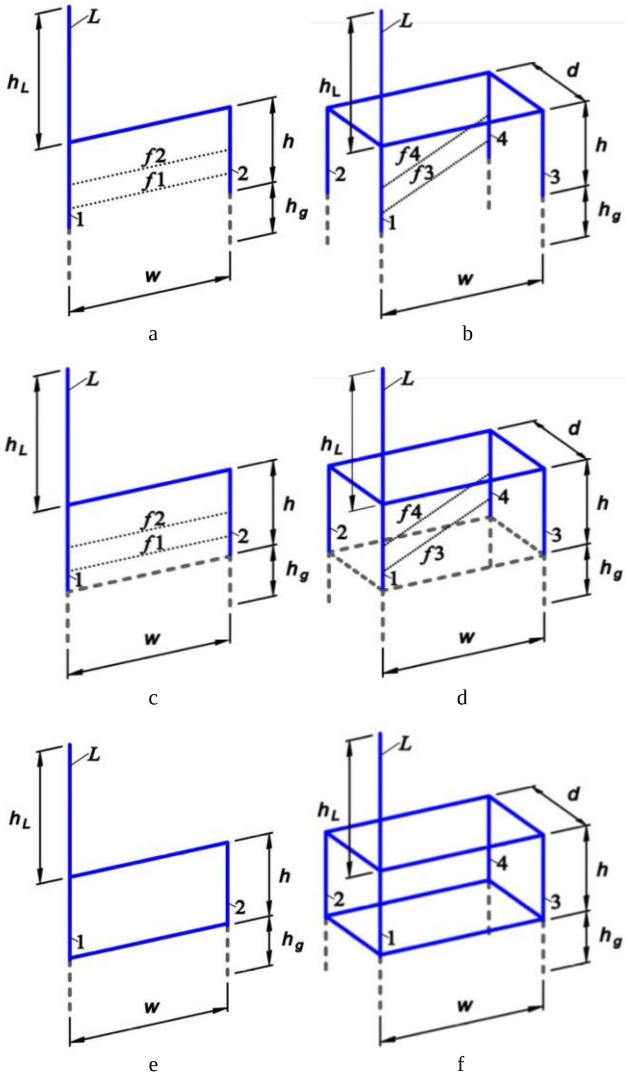


Figure 1. Frame structures, used in modeling: a, b – without ERC; c, d – with ERC buried in soil at a depth of 0.1 m; e, f – with ERC placed 0.1 m above the earth/water surface

the wall is shown schematically in Fig. 3 (“W” and dashed-line contour surrounding LPS conductors). Wall’s dimensions are: of 10.2 m × 0.2 m × 5.2 m. It is placed in such a way, that the thickness of concrete covering all conductors of LPS (besides earthing rods) is about 0.1 m. The wall is partly buried/submersed into ground/water for the depth of 0.1 m.

III. Computational Method And Modeling Conditions

A. *Computational Method*

Computations of lightning current distribution in LPS can be carried out using different approaches, which in general are based on electrical circuit theory and electromagnetic field theory. Considering multipart geometry of research models, this paper presents numerical electromagnetic analysis using finite element method (FEM) in frequency domain, which was applied to similar problems in [7, 8]. For the studied problem, it has a number of significant advantages compared to the circuit approaches: it considers in detail the system`s geometry and spatial interactions between conductors; it allows modeling of the lightning channel, which orientation relatively to the structure may influence upon current distribution; the result of calculation is not current distribution only, but as well distribution of electric and magnetic fields inside the building. Also, as conductors of earthing system are placed in other conducting media (soil/water), these are more difficult to simulate correctly by using the circuit approaches.

B. Lightning Channel Length

Orientation and length of the lightning channel affect upon current distribution between frame structure elements. Degree of this influence depends on spatial dimensions of studied structure. As mentioned, channel inclination influence for some of considered structures was addressed in [6]. In this work, results are presented only for the cases related to vertical lightning channel orientation. In order to determine the minimum length of lightning channel L_{ch}, which to be considered in computations, a modeling was carried out for structure type as in Fig. 1b, for the case of ideally conducting ground [6]. Results are presented in Fig. 2.

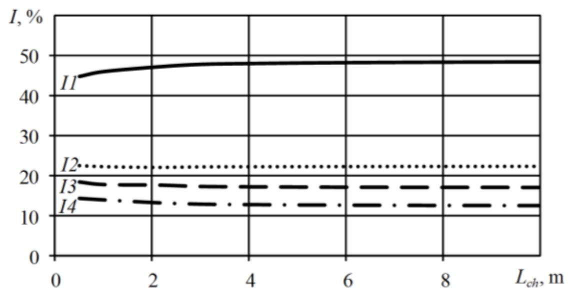


Figure 2. Current distribution dependence on lightning channel length for structure type as in Fig. 1b and ideally conducting ground: *I1* to *I4* – currents in down-conductors #1 to #4

From Fig. 2, one can conclude that lightning channel length of about 4 to 8 m is quite adequate for the structures in Fig. 1, and further its increase have small influence upon lightning current distribution between down-conductors. Thus, in present work, it is accepted the channel length is h_g = 8 m.

C. Calculation Model and Boundary Conditions

Calculation models consist of subdomains, such as air, soil, concrete and LPS conductors (lightning channel was modeled as conductor too). The example of model for the frame structure as in Fig. 1a is presented in Fig. 3. Herein: V – potential; V_L – potential at the top of the channel; **n** – normal unit vector to the boundary; $\boldsymbol{J}$ – current density. At some external boundaries, electric insulation boundary condition ($\mathbf{n}\cdot\boldsymbol{J}$ = 0) is applied; at all external boundaries, a magnetic insulation condition ($\mathbf{n}\cdot\boldsymbol{A}$ = 0) is applied.

D. Current Waveform

In simulations, following parameters of injected lightning current were assumed: negative return stroke having peak value

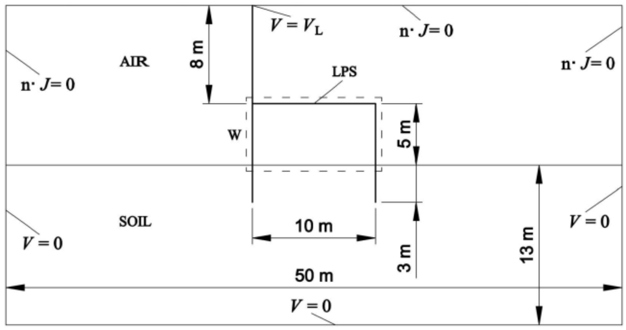


Figure 3. FEM model for calculation of lightning current distribution

of 100 kA, risetime of 1 μs and decay time of 200 μs [5]. Since computations are carried out in frequency domain, current waveform is simulated by an oscillating waveform exhibiting a frequency of 250 kHz [7, 8].

E. Characteristics of Materials

First group of simulations was performed for all models included in Fig. 1 for the wide range values of soil or water conductivity σ_g = $0.67\cdot10^{-3}$ to 1 S/m, and selected relative permittivity values ε_r = 4; 7; 15; 80.

Second group of simulations is related to particular cases of soil or water. Electrical characteristics of materials for this modeling are included in Table I. The characteristics of the soils and water were taken according to [9].

TABLE I. ELECTRICAL CHARACTERISTICS OF MODELING SUBDOMAINS

Medium			ε_r	μ_r	σ, S/m
1	Soil/water	river and lake water	80	1	$1\cdot10^{-3}$
2				1	$24\cdot10^{-3}$
3		wet soils	15	1	$3\cdot10^{-3}$
4				1	$10\cdot10^{-3}$
5		dry soils	4	1	$0.95\cdot10^{-3}$
6				1	$2\cdot10^{-3}$
7	air		1	1	0
8	steel		1	1000	$7.69\cdot10^{6}$
9	concrete		7	1	$1\cdot10^{-3}$

IV. RESULTS AND DISCUSSION

A. Current Distributions for Selected Permittivities of Soil

Results on current distributions between down-conductors for selected permittivity and wide range of conductivity values are presented in Figs. 4 to 7. In these Figures, following labels for curves of current portions are introduced: 1 to 4 – related to corresponding down-conductors in Figs. 1a and 1b (no ERC), 1' to 4' – to corresponding down-conductors in Figs. 1c and 1d (ERC is 0.1 m below the soil surface level), 1" to 4" – to Figs. 1e and 1f (ERC is 0.1 m above the soil surface level). In Fig. 7, related to ε_r = 80, four points are additionally included, which were calculated for the cases when frame conductors are laid in the concrete wall.

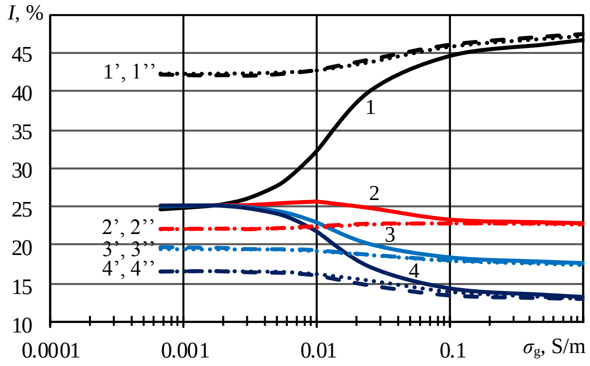


Figure 4. Current distribution dependences on soil/water conductivity for structures in Fig. 1b, d, f, when $\varepsilon_r = 7$: 1 to 4 – no ERC, 1’to 4’ – ERC at 0.1 m “below”, and 1” to 4” – ERC at 0.1 m “above” the soil surface

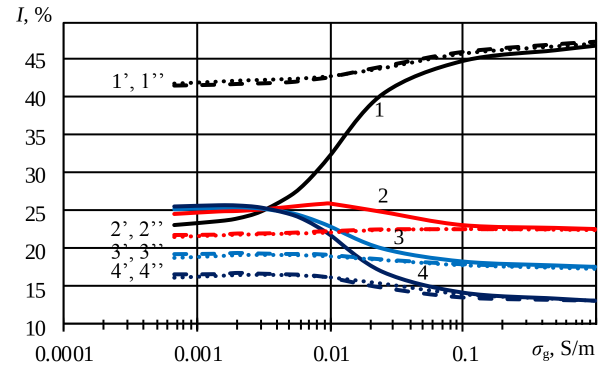


Figure 5. Current distribution dependences on soil/water conductivity for structures in Fig. 1b, d, f, when $\varepsilon_r = 80$: 1 to 4 – no ERC, 1’to 4’ – ERC at 0.1 m “below”, and 1” to 4” – ERC at 0.1 m “above” the soil surface

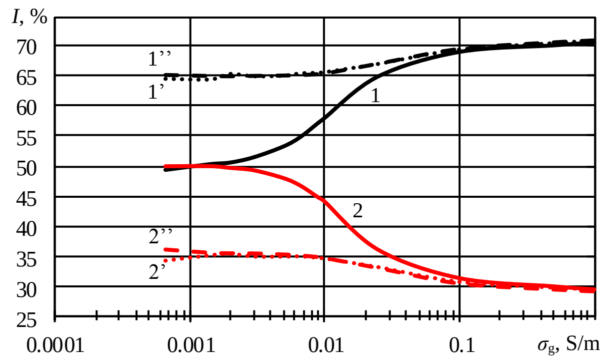


Figure 6. Current distribution dependences on soil/water conductivity for structures in Fig. 1a, c, e, when $\varepsilon_r = 7$: 1, 2 – no ERC, 1’, 2’ – ERC at 0.1 m “below”, and 1”, 2” – ERC at 0.1 m “above” the soil surface

From these results one can see that, for large conductivities and any of considered permittivity values, independently of ERC presence or absence, the discussed current distribution between conductors is not uniform: for frames having four down-conductors the difference between conductors #1 and #4 is about 34 %, and for frames having two down-conductors – 42 %.

When the soil/water conductivity is decreasing, again for all permittivity values, in case without ERC, a clear tendency is observed on becoming current distribution more uniform, and for low conductivity it is almost even. It is interesting to note

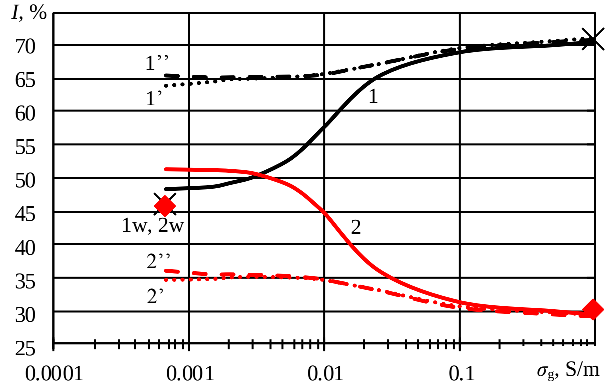


Figure 7. Current distribution dependences on soil/water conductivity for structures in Fig. 1a, c, e, when $\varepsilon_r = 80$: 1, 2 – no ERC, 1’, 2’ – ERC at 0.1 m “below”, and 1”, 2” – ERC at 0.1 m “above” the soil surface; 1w (cross), 2w (diamond) – no ERC, frame conductors in concrete wall

that, for the large soil/water permittivity ($\varepsilon_r = 80$), the portion of current going into conductor (#1, Fig.1) under the strike point becomes somewhat smaller than that in remote conductor. But for the case with the wall, ERC absence and low soil/water conductivity the distribution is totally uniform.

For cases with ERC, the reduction of soil conductivity down to the level of $\sigma_g = 0.67 \cdot 10^{-3}$ S/m is causing some changes in current distributions: for frames having four down-conductors the difference between conductors #1 and #4 becomes about 24 %, and for frames having two down-conductors – 30 %. But these are still far from the uniform distribution. Moreover, independently on the way of placing ERC (below or above the soil surface), all curves for corresponding conductors are coinciding (1’ and 1”, etc.).

Thus, cases of configurations having ERC, when compared to that without ERC, give much less uniform current distributions, if conductivity is not too large (below ~0.1 S/m).

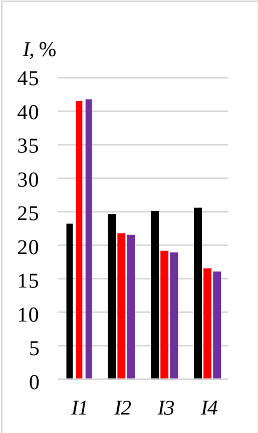
B. Current distributions for particular soils

Results on some particular soils/water [9] and related parameters for calculations are presented in Fig. 8. These parameters are also gathered in Table I (lines 1 to 6). Herein included cases only for the frame having four down-conductors and, again, for variants similar to previously discussed: without ERC and with ERC (below/above ground surface). Diagrams show the same tendencies as described in previous paragraph, and again confirm that installation of ERC close to soil/water surface do not provide any advantages, if obtaining of uniform current distribution between down-conductors is intended.

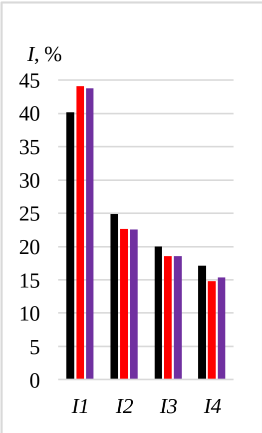
C. Magnetic field inside structure

Results on magnetic field simulation for structures in Fig. 1b and Fig. 1d are presented in Fig. 9 for two levels along horizontal lines f3 and f4 between vertical down-conductors #1 and #4, for the dry soil type (Table I, line 5).

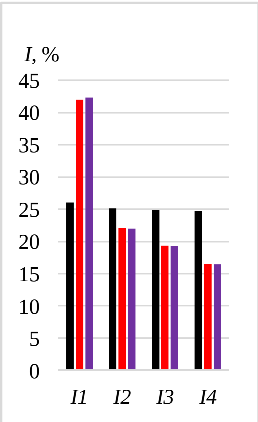
As seen from calculations, structure without ERC (Fig. 1b), when compared to that with ERC (Fig. 1d) is characterized by lower magnetic field magnitudes in vicinity of conductor #1



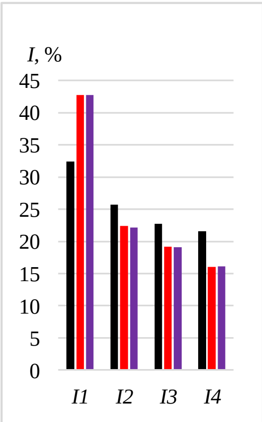
a) Rivers and lakes water,
$\varepsilon_r = 80$, $\sigma_g = 1\cdot 10^{-3}$ S/m



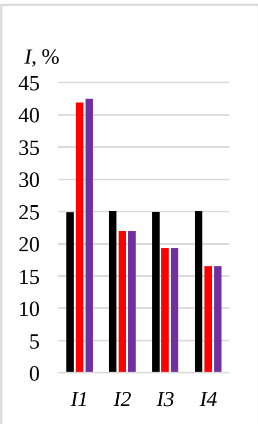
b) Rivers and lakes water,
$\varepsilon_r = 80$, $\sigma_g = 24\cdot 10^{-3}$ S/m



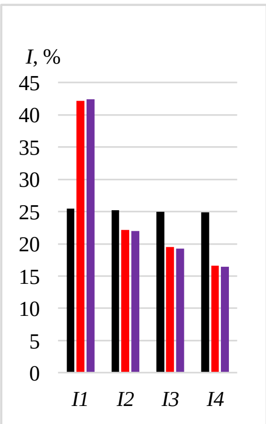
c) Wet soils,
$\varepsilon_r = 15$, $\sigma_g = 3\cdot 10^{-3}$ S/m



d) Wet soils,
$\varepsilon_r = 15$, $\sigma_g = 10\cdot 10^{-3}$ S/m



e) Dry soils,
$\varepsilon_r = 4$, $\sigma_g = 0.95\cdot 10^{-3}$ S/m



f) Dry soils,
$\varepsilon_r = 4$, $\sigma_g = 2\cdot 10^{-3}$ S/m

– case 1: without ERC (equipotentialization ring conductor)
– case 2: with ERC buried/immersed in soil/water
– case 3: with ERC placed above the soil/water surface

Figure 8. Current distributions *I1* to *I4* between four down-conductors at structures shown in Figs. 1b, c, d, for particular soils

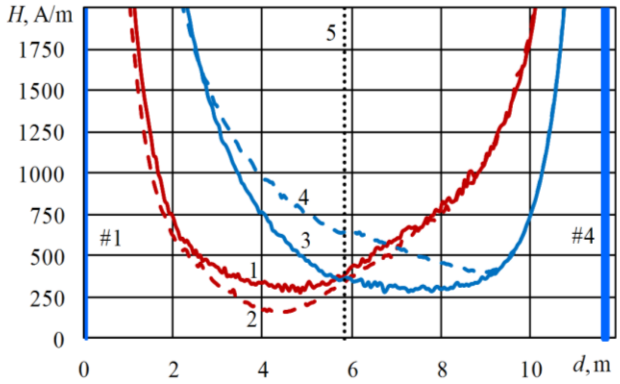


Figure 9. Magnetic field distribution for dry soil having conductivity $0.95\cdot 10^{-3}$ S/m, for structure in Fig. 1b: 1 – 1-m level, along line f3; 2 – 2.5-m, f4; and Fig.1d: 3 – 1-m, f3; 4 – 2.5-m, f4; #1and #4 – axes of corresponding down-conductors; 5 – central vertical axis between #1and #4

located under the strike point; minimal field value at the level 2.5 m is also smaller in this structure (without ERC). At the central axis of structures at the level of 1 m, in both cases the magnetic field magnitudes are similar.

V. Conclusion

1. Numerical analysis of *I* and *H* distributions in frame-type LPS was performed for the wide range of soil/water electrical conductivity ($0.67\cdot 10^{-3}$ to 1 S/m) and various relative permittivity (4 to 80) values.

2. When one of the goals of LPS design is to achieve a uniform current distribution between vertical down-conductors and magnetic field reduction within structure, in case of large soil/water conductivities (> 0.1 S/m) the presence or absence of ERC do not result in a significant difference.

3. In case of lower soil/water conductivities ($< 4\cdot 10^{-3}$ S/m), for the same goals, advantages have structures without ERC.

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