Overhead and Cable Transmission Lines Magnetic Fields: Standardization, Estimation, and Design

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Abstract— Overhead and cable power transmission lines magnetic field strength estimation algorithm is presented. Example of 500 kV overhead transmission line power frequency MF strength distribution is presented in comparison with 500 kV cable transmission line MF distributions. According with the problem of general public electromagnetic safety maintenance is suggested the optimal circuits' arrangement with changed order of the phases that allow reducing the 50 Hz MF values to maximal permissible levels (hygienic standards of general public exposure).

It is shown that multiphase sources create the field of elliptic polarization, which most root-mean square strength value is on the ellipse major axis, whereas result values calculation by components with Pythagorean Theorem use lead to errors with the increase of real value to 41%. By the example of 500 kV lines is shown the differences between results of the applied calculation methods. For 500 kV cable lines the ways of MF value decrease to permissible levels under different kinds of it lying are examined.

There is shown that socket joint use with cables and its locations in the corners of equilateral triangle under correctly changed order of the phases as well as slight increase of cable depth gives the possibility to avoid the ferromagnetic screens arrangement, and to cut costs.

1. INTRODUCTION

Power frequency (PF) electromagnetic field (EMF) general public electromagnetic safety ensuring is a significant problem, especially in terms of magnetic field (MF) exposure, in connection with increased risk of health loss. The main sources of PF EMF are the current facilities involved in power generation, transmission and utilization. The most important are overhead and cable power transmission lines (OTL and CL).

PF EMF human health hazard effects safety system three principle includes: safety by time, safety by distance, and safety by protective means.

Safety by time is realized in Russian occupational and general public PF EMF hygienic standards, that are partially different from international and some national standards. Russian PF electric (EF) and magnetic field maximal permissible levels are one of the strictest in the world. In addition, in order to general public protect from PF EF on both sides of the OTL: from 20 m for 330 kV OTL to 55 m for 1150 kV OTL. Sanitary protection zone are established according to PF EF permissible value 1 kV/m, and not take into account PF MF hygienic standard (8 A/m).

For CL sanitary protection zone is not defined, and 1 m security zone is only. This problem is of particular relevance due to the fact that CLs are the source of PF MF mainly, that were classified by International Agency for research on cancer (IARC) in 2002 as potential carcinogens (2b″) on leukemia for children, which led to WHO recommendations for "precautionary principle" introduction in general public hygienic regulation.

Urgent necessity not only overhead transmission line, but cable line (110–500 kV) electromagnetic safety problem adequate solutions, design stage including it follows.

2. OTL AND CL MF STRENGTH CALCULATION METHOD

OTL single phase has current $\dot{I}$, with wire at h distance from the earth (for underground CL h has negative value) on the Y axis and at Y distance from the origin along the X axis creates MF in point D of surrounding space, the intensity of which is determined by Ampere's circuital law:

$$\dot{H} = \dot{I} \Big/ (2\pi r), \quad \text{where} \quad r^2 = (a-x)^2 + (y-h)^2 \, .$$

MF strength components along the X and Y axes are determined by the expressions:

$$H_X = H\,(y-h)\,/r \quad \text{and} \quad H_Y = H\,(a-x)\,/r.$$

If the line consists not one but i wires having $\dot{I}_i$ currents, created by every wire i MF intensity vector components module $\dot{\mathbf{H}}_{Xi}$ and $\dot{\mathbf{H}}_{Yi}$ are determined by formula:

$$\dot{H}_{Xi} = \frac{\dot{I}_i}{2\pi}\frac{y-h_i}{(a_i-?)^2+(y-h_i)^2},\quad \dot{H}_{Yi} = \frac{\dot{I}_i}{2\pi}\frac{a_i-?}{(a_i-?)^2+(y-h_i)^2}.$$

MF intensity components full values in D point are determined by the addition of similar components:

$$\dot{H}_{XD} = \sum_{i=1}^{N}\dot{H}_{Xi};\quad \dot{H}_{YD} = \sum_{i=1}^{N}\dot{H}_{Yi}.$$

If all of $\dot{I}_i$ currents have the same argument (initial phase angle), MF intensity polarization will be linear, and $\dot{\mathbf{H}}_D$ full vector module is determined by expression of Pythagorean Theorem $H_D = \sqrt{H_{XD}^2 + H_{YD}^2}$. In case of $\dot{I}_i$ currents arguments are not equally, MF polarization is elliptical.

MF strength components effective values changes in time for D arbitrary point are described by equation:

$$H_{XD}(t) = H_{XD}\sin(\omega t + \varphi_{XD})\quad H_{YD}(t) = H_{YD}\ \text{in}\ (\omega t + \varphi_{YD}).$$

Under $\varphi_{XD} - \varphi_{YD} = \pm n\pi/2$, where n — even integer, or 0, MF polarization is linear, under $\varphi_{XD} \neq \varphi_{YD}$ — is elliptical, and under $H_{XD} = H_{YD}$, and $\varphi_{XD} - \varphi_{YD} = \pm n\pi/2$, where n — integer is an odd number, — is circular. Under elliptical polarization [1, 2] $\mathbf{H}_D(t)$ resulting vector rotates in the space by ellipse (Figure 1) with variable angular velocity ω_0:

$$\omega_0 = \frac{H_{XD}H_{YD}\sin(\varphi_{YD}-\varphi_{XD})}{H_{XD}^2\sin^2(\omega t+\varphi_{XD}) + H_{YD}^2\sin^2(\omega t+\varphi_{YD})}.$$

Passing $\mathbf{H}_D(t)$ vector of extrema, i.e., $\mathbf{H}_{\max}$ and $\mathbf{H}_{\min}$ positions occurs at time point t_{ex}:

$$t_{ex} = \frac{1}{2\omega}\text{arctg}\left[(-1)\frac{H_{XD}^2\sin(2\varphi_{XD}) + H_{YD}^2\sin(2\varphi_{YD})}{H_{XD}^2\cos(2\varphi_{XD}) + H_{YD}^2\cos(2\varphi_{YD})}\right],$$

At that between $\mathbf{H}_{\max}$ under $t_{ex}^{\max}$ and $\mathbf{H}_{\min}$ under $t_{ex}^{\min}$ for $f = 50$ Hz frequency and $\omega = 2\pi f$ time distance is 0,005 c. MF polarization elliptical form factor $\mathcal{K}_e = H_{\min}/H_{\max}$.

If, neglecting the changes in time, to determine MF strength current value by Pythagorean Theorem expression $H = \sqrt{H_{XD}^2 + H_{YD}^2}$, we will get H value that will always be greater than $Hmax$ (Figure 1).

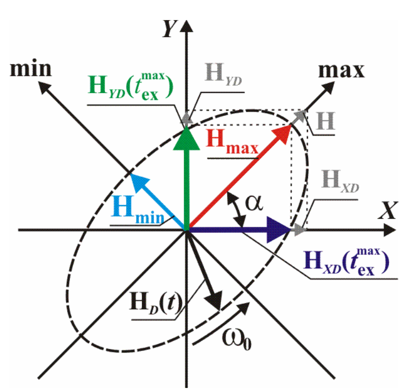


Figure 1: MF elliptical polarization in point D.

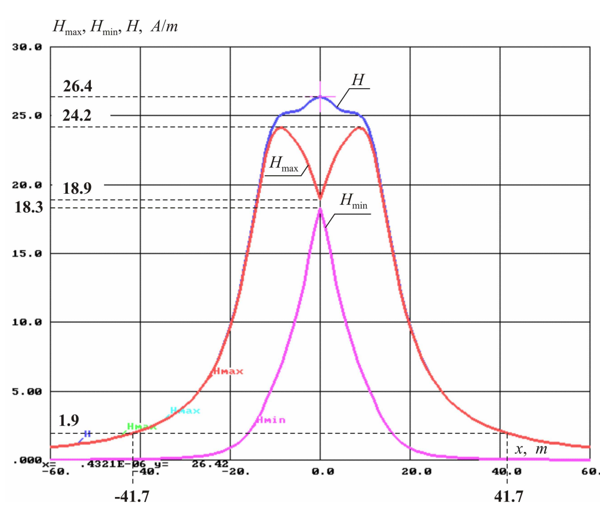


Figure 2: Distribution of MF strength created by 500 kV OTL currents at 1.8 m high for $h_\Gamma = 8$ m conductors distance to the ground.

$H_{\max}$ and $H_{\min}$ values can be determined by expression [2]:

$$H_{\substack{\max\\ \min}} = \sqrt{\frac{1}{2}\left(H_{XD}^2 + H_{YD}^2\right) \pm \frac{1}{2}\sqrt{\left(H_{XD}^2 + H_{YD}^2\right)^2 - 4H_{XD}^2 H_{YD}^2 \sin^2\left(\varphi_{YD} - \varphi_{XD}\right)}}, \quad (1)$$

???, ?? [2]??? [3].

3. OVERHEAD TRANSMISSION LINES MAGNETIC FIELDS

Overhead transmission line MF are reviewed by 500 kV OTL posted on intermediate tower with horizontal phases disposition example. OTL phase are made three wires AC-400/51 brand with $d = 0.4$ m bundle conductors step ($R_P = 0.231$ m bundle conductors radius). Distance between middle and extreme phases centers $-b = 11.5$ m. Minimal distance to the ground is $h_\Gamma = 8$ m. Phase current values are: $\dot{I}_A = 1$ kA, $\dot{I}_B = 1e^{-j120^\circ}$ kA, and $\dot{I}_C = 1e^{-j120^\circ}$ kA.

Figure 2 show MF $H_{\max}$, $H_{\min}$ and H values distribution, created by the same 500 kV TL the same currents at 1.8 m above the ground. On the OTL axis under $x = 0$ m $H_{\max} = 18.9$ A/m, $H_{\min} = 18.3$ A/m, $\mathcal{K}_e = 0.97$ and $H = 26.4$ A/m. H more $H_{\max}$ on 7.5 A/m or on 39.7%. Maximal value $H_{\max} = 24.2$ A/m is achieved under $x = \pm 8.5$ m. At the border of sanitary protection zone under $x = \pm 41.7$ m $H_{\max} = 1.9$ A/m.

Maximal excess of MF strength real value ?????? in computing by expression of Pythagorean Theorem is in case of field circular polarization, when $H_{\max} = H_{\min}$ and $\mathcal{K}_e = 1.0$. In this case $H = \sqrt{2}H_{\max}$ excess H above $H_{\max}$ is 41.4%.

4. POWER CABLE LINE MAGNETIC FIELDS

CL cables due to the presence of the current carrying conductor insulation can be located in close proximity to each other. Underground CL cables are located either in the horizontal or vertical plane, or a triangle. At the intersection of communications and roadways each cable is placed in a plastic tube (PT). Each phase cables are connected along CL by means of socket joint. As a rule cables and socket joint in places of cable connections are located horizontal. CL depth of lying is 1.5–2.5 m. CL are places in security zone, where hygienic standard is 16 A/m. Outside the border of security zone (at 1 m distance from extreme cable), MF value should not be more 8 A/m (hygienic standard for territory of housing estate). Examine MF values at 2 m distance from extreme cable too.

CL MF are reviewed by 500 kV CL two parallel circuit connected to the same busline as at its beginning and end example. It means that currents in the same named phases of even circuit are equal (same values). 500 kV CL made by Suedkabel cable 2XS(FL)2Y 1× 2500RMS/300 290/500 kV make-up with 150 mm outside diameter, in places of socket joint are used Suedkabel electrically-operated clutch SEHDVCB 362/420/550 make-up with c 510 mm outside diameter. When crossing with communications 500 kV CL each cable is laid inside PT 280 mm diameter with 20.6 mm wall thickness. 500 kV CL phase current module is 1 kA for each circuit. CL load is symmetric.

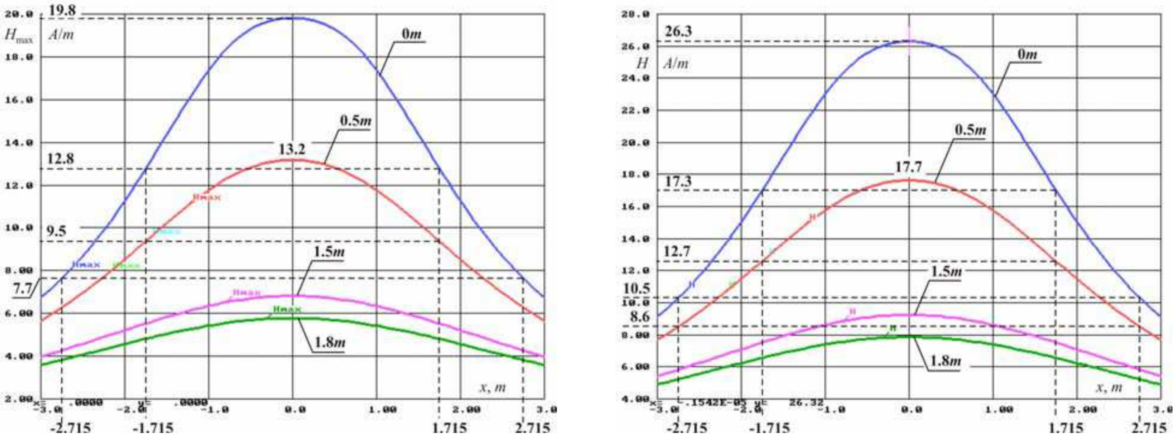
Review 500 kV CL part laid in tube, placed in a triangle at 2.0 m depth with 1.0 m distance between the centers of circuits. Figure 3(a) shows MF $H_{\max}$ calculative values distribution; Figure 3(b) shows MF H calculative values distribution at 0 m, 0.5 m, 1.5 m and 1.8 m above the ground.

$H_{\max}$ value at the earth surface is over than 16 A/m above the CL and over than 8 A/m at the border of security zone (1 m) (Figure 3(a), 0 m line), but in 2 m distance from CL extreme cable PF level is lower than hygienic standard. At 0.5 m above the ground $H_{\max}$ is lower 16 A/m inside the security zone and 8 A/m in 2 m distance from CL, but is above 8 A/m in 1 m distance. At 1.5 m and 1.8 m above the ground PF MF levels not exceed hygienic standards.

MF calculation by H expression shows exceeding of permissible values in 1 m and 2 m distance from CL at ground and 0.5 m above the ground level, and standard compliance at 1.5 m and 1.8 m above the ground only (Figure 3(b)). H values are much more $H_{\max}$ strength.

MF $H_{\max}$ value decrease above 500 kV CL two circuits is possible by deepening of line laying as well as by increase the distance between b circuits centers.

To achieve 16 A/m and 8 A/m permissible levels compliance without increase $b = 1.0$ m and $h = 2.0$ m distances for 500 kV CL two circuits is possible by one of circuit cable order of the phase change. Still considered a symmetric version of the alternation of 500 kV CL two circuits cables phases: $\begin{smallmatrix} & A_1 & \\ C_1 & & B_1 \end{smallmatrix}$ of left circuit and $\begin{smallmatrix} & A_2 & \\ C_2 & & B_2 \end{smallmatrix}$ of right circuit. If you leave CL left circuit order



(a) (b)

Figure 3: Distribution of (a) $H_{\max}$ and (b) H, created by 500 kV CL, laid triangle.

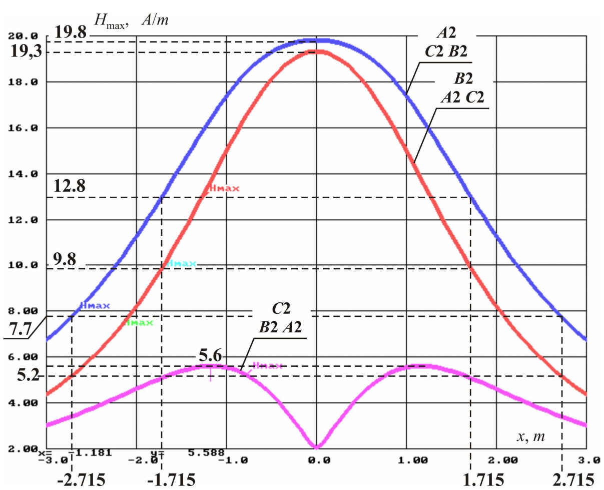


Figure 4: Distribution of created by 500 kV CL MF $H_{\max}$ values at ground surface under laying in tubes with $b = 1.0\,\mathrm{m}$ and $h = 2.0\,\mathrm{m}$, and right circuit cables order of the phase $\genfrac{}{}{0pt}{}{A_2}{C_2\ B_2}$, $\genfrac{}{}{0pt}{}{B_2}{A_2\ C_2}$ and $\genfrac{}{}{0pt}{}{C_2}{B_2\ A_2}$.

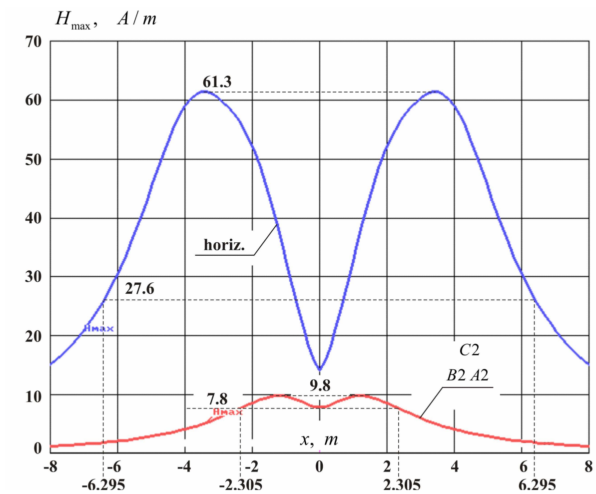


Figure 5: Distribution of MF value $H_{\max}$, created at ground surface by socket joint with horizontal cables ("horiz." line) and triangle with changed $\genfrac{}{}{0pt}{}{C_2}{B_2\ A_2}$ order of phase socket joint of 500 kV double-circuit CL.

of the phase without change, and right circuit order of the phase change to $\genfrac{}{}{0pt}{}{C_2}{B_2\ A_2}$, MF strength sharply reduced. Figure 4 shows created at ground surface by 500 kV CL currents MF $H_{\max}$ value distribution, under left circuit order of the phase $\genfrac{}{}{0pt}{}{A_1}{C_1\ B_1}$, and right circuit order of the phase $\genfrac{}{}{0pt}{}{A_2}{C_2\ B_2}$, $\genfrac{}{}{0pt}{}{B_2}{A_2\ C_2}$, and $\genfrac{}{}{0pt}{}{C_2}{B_2 A_2}$.

Under right circuit cables order of the phase $\genfrac{}{}{0pt}{}{C_2}{B_2\ A_2}$ MF strength at ground surface is lower than $H_{\max} = 5.6\,\mathrm{A/m}$ inside and outside of security zone. However, the design can not prevent the error in order of the phase because under and right phase cables order of the phase $\genfrac{}{}{0pt}{}{B_2}{A_2\ C_2}$ the effect of MF compensation is practically absent.

The maximal MF values are observed places of cable with horizontal cables and couplings socket joint. To socket joint place cables are suitable triangle in the ground or in the tubes, and connections are transferred to the horizontal position. Cable and socket axis are located in the ground at $h_s = 1.925\,\mathrm{m}$ depth. The distance between same circuits nearby cables is 1.32 m, and between first and second circuits nearby cables is 2.4 m.

Figure 5 shows the distribution of MF level, created at ground surface by socket joint with horizontal cables and couplings ("horiz." line). MF value inside of 1 m security zone is very high (61.3 A/m), and at its border MF value is 27.6 A/m (substantial higher permissible levels 16 A/m, and 8 A/mm). Traditionally MF level decrease is achieved by socket joint covering by means of expensive ferromagnetic screen.

Under cables and sockets arrangement at equilateral triangles vertexes with 0.6 m side, and left circuit cables order of the phase $\begin{smallmatrix} & A_1 & \\ C_1 & & B_1 \end{smallmatrix}$, and right circuit cables order of the phase $\begin{smallmatrix} & C_2 & \\ B_2 & & A_2 \end{smallmatrix}$, and under arrangement of cable (socket) axis of top triangle vertex at 1.905 m depth, and lower vertexes — at 2.425 m depth MF value at ground surface will reduce to 9.8 A/m inside of 1 m zone and — to 7.8 A/m at its border (Figure 5, $\begin{smallmatrix} & C_2 & \\ B_2 & & A_2 \end{smallmatrix}$ line). Deepening of socket joint only 0.5 m more horizontal leads to significant reduce of MF levels up to accepted standards without expansive ferromagnetic screen placing.

5. CONCLUSION

Some optimal ways of occupational and environmental OTL and CL electromagnetic safety maintenance are presented. Adequate methods of PF MF values calculation let even at the design stage to solve this problem. The particular importance is played by light of MF elliptical polarization when the calculation without regard to its temporal parameters leads to errors upwards from true MF value to 41.4%.

Presented data substantiate the necessity of 110–500 kV CL sanitary protection zone organization. To ensure PF MF permissible levels for residential construction compliance (8 A/m in Russia) at 1 m distance is possible only at CL laying considerable depth, which is expensive, laborious and adversely affects CL operation and maintenance. This determines the size of sanitary protection zone must be not less than 2 m from CL.

Socket joints with cable and coupling arrangement at equilateral triangles vertexes with properly modified phase sequence under slight increase of their laying depth application allows to PF MF hygienic standards maintenance without ferromagnetic screen installation.

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