

Magnetic field of tubular screened phase conductor in a system with grounded or shorted shield

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In the paper discusses the influence of grounding or shorting of the screen on the magnetic field of screened phase conductor. This phenomenon has been described with the formulas relevant to the relative values of the field and the parameters allowing the frequency, conductivity, and the cross-section dimensions of screen. Into account was taken skin, internal and external proximity effects. Components of this field were expressed through modified Bessel's functions as a function r and θ of cylindrical coordinates. As a consequence this the magnetic field is a rotating elliptical field.

KEYWORDS: magnetic field, tubular screen, tubular conductor, high-current busduct

1. Introduction

In high current transmission lines (busducts) one or more phase tubular conductors are isolated with a tube screen. The magnetic field of the conductor induces eddy currents in the shield which generate a reverse reaction magnetic field. The resultant magnetic field within the internal and external area of the shield is the vector sum of these fields [1]. In the general case of two concentric tubular conductors the axes of the conductors do not coincide, and create the so-called non-coaxial system – Figure 1 [2].

Let us consider the shield (Fig. 1) of conductivity γ_2 , with internal radius R_3 and external radius R_4 , parallel to a non-coaxial internal tubular conductor with conductivity γ_1 , internal radius R_1 and external radius R_2 with complex rms current \underline{I}_1 . The distance between the axes of the conductors is d .

The phase conductor with the current \underline{I}_1 and grounded or shorted (e.g. by steel structures enclosing the high-current busduct) ends of a conductive guard or casing is shown in Fig. 2.

The return current in the screen define the formula [3]

$$\underline{I}_e = -\underline{k}_i \underline{I}_1 \quad (1)$$

where complex coefficient

$$\underline{k}_i = \frac{\underline{Z}_{e1}}{\underline{Z}_e + \underline{Z}_u} \quad (2)$$

in which the impedance \underline{Z}_e is the self-impedance of the shield of the finite length, \underline{Z}_{e1} is the mutual impedance between the shield and the phase conductor, and the \underline{Z}_u is the impedance of the grounding or the circuit shorting the guard.

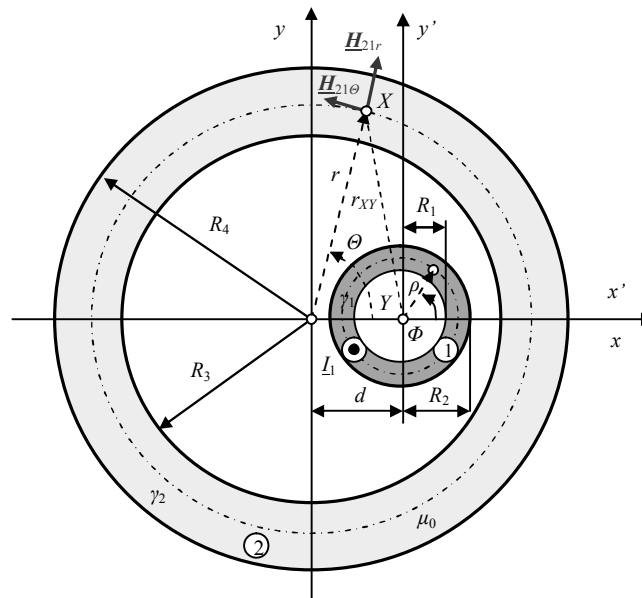


Fig. 1. Tubular screen with an internal non-coaxial tubular conductor

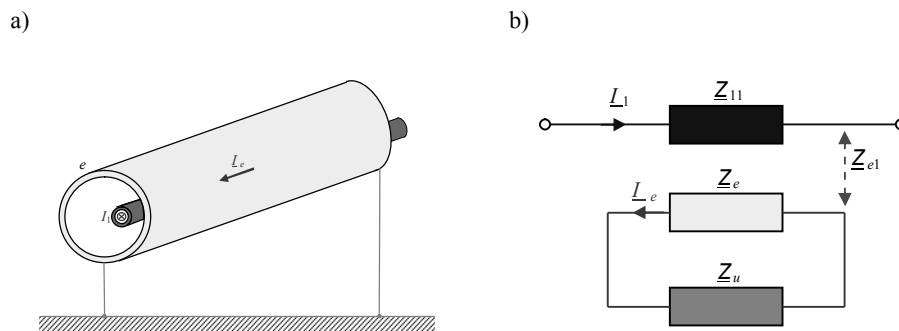


Fig. 2. A shielded phase conductor with non-coaxial conductive guard grounded at its ends; a) general view, b) substitute diagram

2. Impedance of the screen

Impedance of the screen

$$\underline{Z}_e = R_e + j\omega L_e \quad (3)$$

and to references [4-6] Z. Piątek and B. Baron introduce, that do not take the skin effect, the resistance of the screen

$$R_{e0} = \frac{l}{\pi \gamma_2 (R_4^2 - R_3^2)} \quad (4)$$

and its inductance

$$L_{e0} = \frac{\mu_0 l}{2\pi} \left[\ln \frac{2l}{R_4} - 1 + \frac{R_3^4}{(R_4^2 - R_3^2)^2} \ln \frac{R_4}{R_3} - \frac{1}{4} \frac{3R_3^2 - R_4^2}{R_4^2 - R_3^2} \right] = L_{ez} + L_{e0w} \quad (5)$$

where the external inductance

$$L_{ez} = \frac{\mu_0 l}{2\pi} \left(\ln \frac{2l}{R_4} - 1 \right) \quad (6)$$

and the internal inductance

$$L_{e0w} = \frac{\mu_0 l}{2\pi} \left[\frac{R_3^4}{(R_4^2 - R_3^2)^2} \ln \frac{R_4}{R_3} - \frac{1}{4} \frac{3R_3^2 - R_4^2}{R_4^2 - R_3^2} \right] \quad (7)$$

If we take skin effect into account, the resistance of the screen

$$R_e = \frac{\underline{\Gamma}_2 l}{4\pi \gamma_2 R_4} \frac{\underline{a}}{\underline{b} \underline{b}^*} \quad (8)$$

where

$$\begin{aligned} \underline{a} = & K_1(\underline{\Gamma}_2 R_3) K_1^*(\underline{\Gamma}_2 R_3) \left[I_0(\underline{\Gamma}_2 R_4) I_1^*(\underline{\Gamma}_2 R_4) - j I_1(\underline{\Gamma}_2 R_4) I_0^*(\underline{\Gamma}_2 R_4) \right] - \\ & - I_1(\underline{\Gamma}_2 R_3) I_1^*(\underline{\Gamma}_2 R_3) \left[K_0(\underline{\Gamma}_2 R_4) K_1^*(\underline{\Gamma}_2 R_4) - j K_1(\underline{\Gamma}_2 R_4) K_0^*(\underline{\Gamma}_2 R_4) \right] + \\ & + I_1(\underline{\Gamma}_2 R_3) K_1^*(\underline{\Gamma}_2 R_3) \left[K_0(\underline{\Gamma}_2 R_4) I_1^*(\underline{\Gamma}_2 R_4) + j K_1(\underline{\Gamma}_2 R_4) I_0^*(\underline{\Gamma}_2 R_4) \right] - \\ & - K_1(\underline{\Gamma}_2 R_3) I_1^*(\underline{\Gamma}_2 R_3) \left[I_0(\underline{\Gamma}_2 R_4) K_1^*(\underline{\Gamma}_2 R_4) + j I_1(\underline{\Gamma}_2 R_4) K_0^*(\underline{\Gamma}_2 R_4) \right] \end{aligned} \quad (9)$$

$$\underline{b} = I_1(\underline{\Gamma}_2 R_4) K_1(\underline{\Gamma}_2 R_3) - I_1(\underline{\Gamma}_2 R_3) K_1(\underline{\Gamma}_2 R_4) \quad (10)$$

$$\underline{b}^* = I_1^*(\underline{\Gamma}_2 R_4) K_1^*(\underline{\Gamma}_2 R_3) - I_1^*(\underline{\Gamma}_2 R_3) K_1^*(\underline{\Gamma}_2 R_4) \quad (11)$$

Then the inductance of the screen

$$L_e = \frac{\mu_0 l}{2\pi} \left\{ \ln \frac{2l}{R_4} - 1 + \frac{1}{\underline{\Gamma}_2 R_4 \underline{b}} \left[K_1(\underline{\Gamma}_2 R_3) I_0(\underline{\Gamma}_2 R_4) + I_1(\underline{\Gamma}_2 R_3) K_0(\underline{\Gamma}_2 R_4) - \frac{a}{2 \underline{b}^*} \right] \right\} = L_{ez} + L_{ew} \quad (12)$$

where the internal inductance

$$L_{ew} = \frac{\mu_0 l}{2\pi} \left\{ \frac{1}{\underline{\Gamma}_2 R_4 \underline{b}} \left[K_1(\underline{\Gamma}_2 R_3) I_0(\underline{\Gamma}_2 R_4) + I_1(\underline{\Gamma}_2 R_3) K_0(\underline{\Gamma}_2 R_4) - \frac{a}{2 \underline{b}^*} \right] \right\} \quad (13)$$

In the above formulas $I_1(\underline{\Gamma}_2 R_3)$, $K_1(\underline{\Gamma}_2 R_3)$, etc. are the modified Bessel's functions of the firsts and second kind respectively, the first and the second order [7].

The formulas (8) and (12) we obtain the self impedance of the screen

$$\underline{Z}_e = j\omega \frac{\mu_0 l}{2\pi} \left\{ \ln \frac{2l}{R_4} - 1 + \frac{1}{\underline{\Gamma}_2 R_4 \underline{b}} \left[K_1(\underline{\Gamma}_2 R_3) I_0(\underline{\Gamma}_2 R_4) + I_1(\underline{\Gamma}_2 R_3) K_0(\underline{\Gamma}_2 R_4) \right] \right\} \quad (14)$$

and the internal impedance

$$\underline{Z}_{ew} = j\omega \frac{\mu_0 l}{2\pi} \left\{ \frac{1}{\underline{\Gamma}_2 R_4 \underline{b}} \left[K_1(\underline{\Gamma}_2 R_3) I_0(\underline{\Gamma}_2 R_4) + I_1(\underline{\Gamma}_2 R_3) K_0(\underline{\Gamma}_2 R_4) \right] \right\} \quad (15)$$

If we introduce the relative variables $\beta = \frac{R_3}{R_4}$ and $\alpha = k_2 R_4$ ($k_2 = \sqrt{\omega \mu \gamma_2 / 2} = 1/\delta_2$), lets us express the resistance of the screen without regard to skin effect through the formula

$$R_{e0} = \frac{l}{\pi \gamma_2 (1 - \beta^2) R_4^2} \quad (16)$$

and its inductance

$$L_{e0} = \frac{\mu_0 l}{2\pi} \left[\ln \frac{2l}{R_4} - 1 + \frac{\beta^4}{(1 - \beta^2)^2} \ln \frac{1}{\beta} - \frac{1}{4} \frac{3\beta^2 - 1}{1 - \beta^2} \right] = L_{ez} + L_{e0w} \quad (17)$$

where the internal inductance

$$L_{e0w} = \frac{\mu_0 l}{2\pi} \left[\frac{\beta^4}{(1 - \beta^2)^2} \ln \frac{1}{\beta} - \frac{1}{4} \frac{3\beta^2 - 1}{1 - \beta^2} \right] \quad (18)$$

Taking into account the skin effect we determine the resistance of the screen by the following formula

$$R_e = \frac{\sqrt{2j} \alpha l}{4 \pi \gamma_2 R_4^2} \frac{a}{\underline{b} \underline{b}^*} \quad (19)$$

where

$$\begin{aligned} \underline{a} = & K_1(\sqrt{2j} \alpha \beta) K_1^*(\sqrt{2j} \alpha \beta) \left[\begin{array}{l} I_0(\sqrt{2j} \alpha) I_1^*(\sqrt{2j} \alpha) - \\ - j I_1(\sqrt{2j} \alpha) I_0^*(\sqrt{2j} \alpha) \end{array} \right] - \\ & - I_1(\sqrt{2j} \alpha \beta) I_1^*(\sqrt{2j} \alpha \beta) \left[\begin{array}{l} K_0(\sqrt{2j} \alpha) K_1^*(\sqrt{2j} \alpha) - \\ - j K_1(\sqrt{2j} \alpha) K_0^*(\sqrt{2j} \alpha) \end{array} \right] + \\ & + I_1(\sqrt{2j} \alpha \beta) K_1^*(\sqrt{2j} \alpha \beta) \left[\begin{array}{l} K_0(\sqrt{2j} \alpha) I_1^*(\sqrt{2j} \alpha) + \\ + j K_1(\sqrt{2j} \alpha) I_0^*(\sqrt{2j} \alpha) \end{array} \right] - \end{aligned} \quad (20)$$

$$\begin{aligned} & - K_1(\sqrt{2j} \alpha \beta) I_1^*(\sqrt{2j} \alpha \beta) \left[\begin{array}{l} I_0(\sqrt{2j} \alpha) K_1^*(\sqrt{2j} \alpha) + \\ + j I_1(\sqrt{2j} \alpha) K_0^*(\sqrt{2j} \alpha) \end{array} \right] \\ \underline{b} = & I_1(\sqrt{2j} \alpha) K_1(\sqrt{2j} \alpha \beta) - I_1(\sqrt{2j} \alpha \beta) K_1(\sqrt{2j} \alpha) \end{aligned} \quad (21)$$

$$\underline{b}^* = I_1^*(\sqrt{2j} \alpha) K_1^*(\sqrt{2j} \alpha \beta) - I_1^*(\sqrt{2j} \alpha \beta) K_1^*(\sqrt{2j} \alpha) \quad (22)$$

and its the self inductance

$$L_e = \frac{\mu_0 l}{2\pi} \left\{ \ln \frac{2l}{R_4} - 1 + \frac{1}{\sqrt{2j} \alpha \underline{b}} \left[\begin{array}{l} K_1(\sqrt{2j} \alpha \beta) I_0(\sqrt{2j} \alpha) + \\ + I_1(\sqrt{2j} \alpha \beta) K_0(\sqrt{2j} \alpha) - \frac{a}{2\underline{b}^*} \end{array} \right] \right\} = L_{ez} + L_{ew} \quad (23)$$

where the internal inductance

$$L_{ew} = \frac{\mu_0 l}{2\pi} \left\{ \frac{1}{\sqrt{2j} \alpha \underline{b}} \left[\begin{array}{l} K_1(\sqrt{2j} \alpha \beta) I_0(\sqrt{2j} \alpha) + \\ + I_1(\sqrt{2j} \alpha \beta) K_0(\sqrt{2j} \alpha) - \frac{a}{2\underline{b}^*} \end{array} \right] \right\} \quad (24)$$

The relative change of the resistance can be presented by the quotient of the conductor resistance with the consideration of the skin effect – formula (19) and the resistance without taking into account of this effect – formula (16), that is we have

$$k_R = \frac{R_e}{R_{e0}} = \frac{\sqrt{2j} \alpha}{4} (1 - \beta^2) \frac{a}{\underline{b} \underline{b}^*} \quad (25)$$

Similarly, for the total inductance, based on the formulas (17) and (23), we have

$$k_L = \frac{L_e}{L_{e0}} = \frac{\ln \frac{2l}{R_4} - 1 + \frac{1}{\sqrt{2j} \alpha b} \left[K_1(\sqrt{2j} \alpha \beta) I_0(\sqrt{2j} \alpha) + I_1(\sqrt{2j} \alpha \beta) K_0(\sqrt{2j} \alpha) - \frac{a}{2b^*} \right]}{\ln \frac{2l}{R_4} - 1 + \frac{\beta^4}{(1-\beta^2)^2} \ln \frac{1}{\beta} - \frac{1}{4} \frac{3\beta^2 - 1}{1-\beta^2}} \quad (26)$$

The dependence of the above coefficients on coefficient α for a few values of parameter β is shown in Figures 3, 4 and 5.

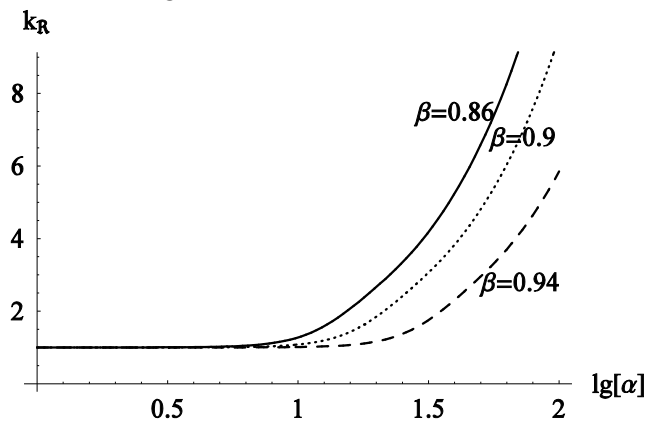


Fig. 3. Dependence of the resistance of the tubular screen (shield) on parameter α

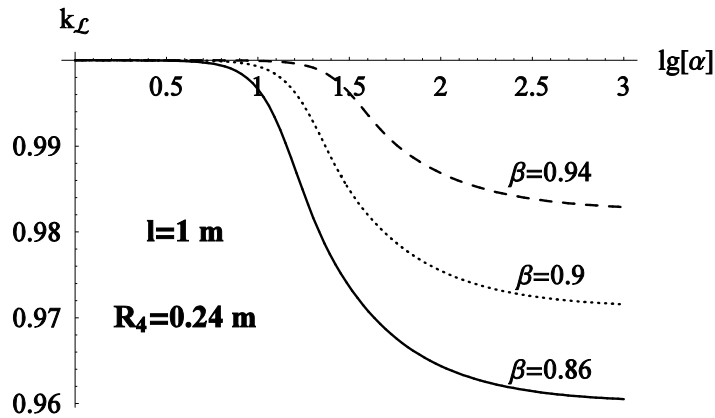


Fig. 4. Dependence of the inductance of the tubular screen on parameter α with the constant length and the various values of the relative thickness β

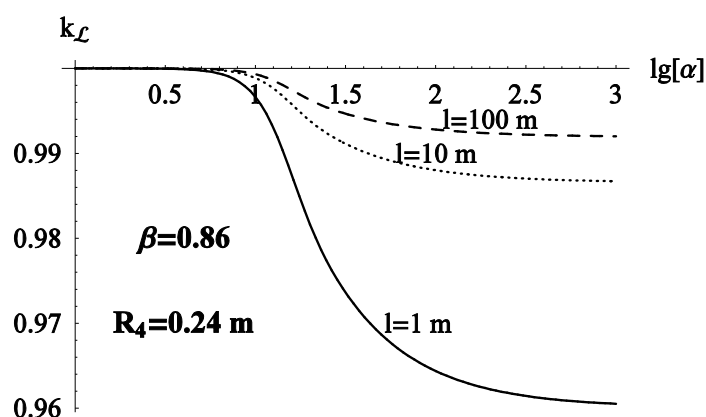


Fig. 5. Dependence of the inductance of the tubular screen on parameter α with the constant thickness β and various lengths

Self impedance of the screen for relative parameters has the form

$$\underline{Z}_e = j\omega \frac{\mu_0 l}{2\pi} \left[\ln \frac{2l}{R_4} - 1 + \frac{K_1(\sqrt{2j} \alpha \beta) I_0(\sqrt{2j} \alpha) + I_1(\sqrt{2j} \alpha \beta) K_0(\sqrt{2j} \alpha)}{\sqrt{2j} \alpha \underline{b}} \right] \quad (27)$$

and the internal impedance

$$\underline{Z}_{ew} = j\omega \frac{\mu_0 l}{2\pi} \frac{K_1(\sqrt{2j} \alpha \beta) I_0(\sqrt{2j} \alpha) + I_1(\sqrt{2j} \alpha \beta) K_0(\sqrt{2j} \alpha)}{\sqrt{2j} \alpha \underline{b}} \quad (28)$$

3. Mutual impedance: phase conductor - shield

In [8-9] studies Z. Piątek and B. Baron derive the mutual impedance between the phase conductor and the shield of finite lengths without regard the skin and proximity effects in the form of the formula

$$M_{e10} = M_{1e0} = M_{e0} = \frac{\mu_0 l}{2\pi} \left[\frac{R_4^2 \ln \frac{2l}{R_4} - R_3^2 \ln \frac{2l}{R_3}}{R_4^2 - R_3^2} - \frac{1}{2} \right] \quad (29)$$

and the mutual impedance with the consideration of those effects

$$\underline{Z}_{1e} = j \omega \frac{\mu_0 l}{2 \pi} \left\{ \ln \frac{2l}{R_4} - 1 + \frac{K_1(\underline{\Gamma}_2 R_3) [I_0(\underline{\Gamma}_2 R_4) - I_0(\underline{\Gamma}_2 R_3)] + I_1(\underline{\Gamma}_2 R_3) [K_0(\underline{\Gamma}_2 R_4) - K_0(\underline{\Gamma}_2 R_3)]}{\underline{\Gamma}_2 R_4 \underline{d}_0} \right\} \quad (30)$$

or

$$\underline{Z}_{e1} = \frac{j \omega \mu_0 l}{2 \pi} \left[\ln \frac{2l}{R_4} - 1 + \frac{b_0 I_0(\underline{\Gamma}_2 R_4) + c_0 K_0(\underline{\Gamma}_2 R_4)}{\underline{\Gamma}_2 R_3 \underline{d}_0} \right] \quad (31)$$

or parameters of relative

$$\underline{Z}_{1e} = j \omega \frac{\mu_0 l}{2 \pi} \left\{ \ln \frac{2l}{R_4} - 1 + \frac{K_1(\sqrt{2j} \alpha \beta) [I_0(\sqrt{2j} \alpha) - I_0(\sqrt{2j} \alpha \beta)] + I_1(\sqrt{2j} \alpha \beta) [K_0(\sqrt{2j} \alpha) - K_0(\sqrt{2j} \alpha \beta)]}{\sqrt{2j} \alpha \underline{d}_0} \right\} \quad (32)$$

and

$$\underline{Z}_{e1} = \frac{j \omega \mu_0 l}{2 \pi} \left[\ln \frac{2l}{R_4} - 1 + \frac{b_0 I_0(\sqrt{2j} \alpha) + c_0 K_0(\sqrt{2j} \alpha \beta)}{\sqrt{2j} \alpha \beta \underline{d}_0} \right] \quad (33)$$

The structure of the impedance \underline{Z}_{1e} is different than that of the \underline{Z}_{e1} . However, due to the Bessel function properties, regardless of the $\underline{\Gamma}_2 R_3$ and $\underline{\Gamma}_2 R_4$ parameters we obtain, that

$$\underline{Z}_{e1} = \underline{Z}_{1e} \quad (34)$$

The imaginary parts, divided by ω , of the mutual impedances are the mutual inductances, whereby

$$M_{e1} = \frac{1}{\omega} \text{Im}\{\underline{Z}_{e1}\} = M_{1e} = \frac{1}{\omega} \text{Im}\{\underline{Z}_{1e}\} = M_e \quad (35)$$

The share of the real part of the mutual impedance \underline{Z}_{e1} in its total value can be characterized by the coefficient $k_{e1} = \text{Re}\{\underline{Z}_{e1}\} / \underline{Z}_{e1}$, whereas the change of the mutual inductance, depending on the parameter α , with the coefficient $k_M = M_e / M_{e0}$. The relationship between the above coefficients and the parameter $\alpha = k_2 R_2$ value is shown in Fig. 6 and 7.

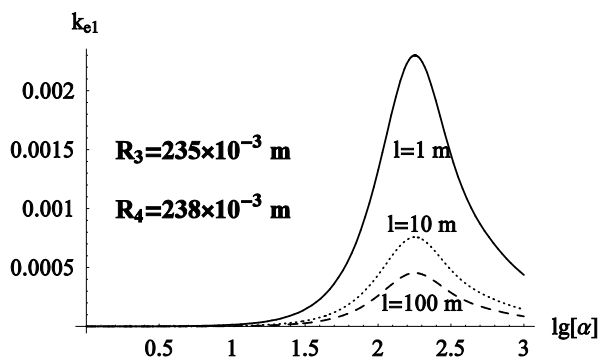


Fig. 6. Dependence of the mutual impedance on parameter α of the real part

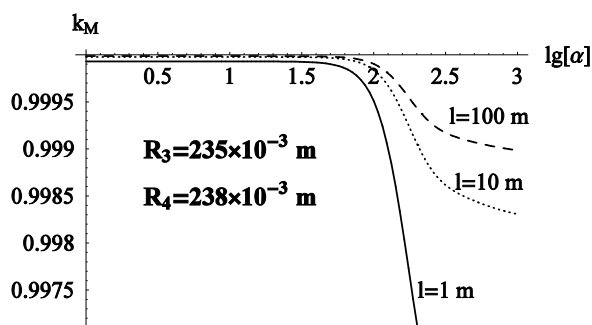


Fig. 7. Dependence of the the mutual impedance on parameter α of the relative mutual impedance

4. Impedance of the earth-return loop

For a high-current busduct running above ground the complex coefficient \underline{k}_i can be presented in the form of the formula [3]

$$\underline{k}_i = \frac{\underline{Z}_{e1}}{\underline{Z}_{pz}} = k_i \exp[j\varphi_i] \quad (36)$$

where the impedance of the earth-return loop is given as

$$\underline{Z}_{pz} = \underline{Z}_{ew} + \underline{Z}_{ez} \quad (37)$$

where \underline{Z}_{ew} is the internal impedance, and \underline{Z}_{ez} is the external impedance of the shield [10].

The external impedance takes into account the earth influence as the result of the effect of the currents flowing in the earth. It is a complex number with the

real part different from zero and it is expressed by the approximate formula (for the unit length of the shield) [10]

$$\underline{Z}_{ez} = \frac{\omega \mu_0}{2\pi} \left[\frac{\pi}{4} + j \ln \frac{1,85}{R_4 \sqrt{\omega \mu_0 \gamma_g}} \right] = R_{ez} + j X_{ez} \quad (38)$$

where γ_g is the soil conductivity which varies within the limit of $10^{-4} \div 10^{-2} \text{ S} \cdot \text{m}^{-1}$. The external resistance R_{ez} does not depend on the soil conductivity, and the external conductivity X_{ez} depends on the soil conductivity only slightly.

The internal impedance, while neglecting the skin effect, can be expressed with the formula [11]

$$\underline{Z}_{e0w} = R_{e0} + j \omega L_{e0w} \quad (39)$$

where the internal resistance R_{e0} is given by the formula (3) or (16), and the inductance by the formula (7) or (18)

When taking into account the skin effect then the internal impedance can be expressed as [12]

$$\underline{Z}_{ew} = R_e + j \omega L_{ew} \quad (40)$$

where the internal resistance R_e is given by the formula (8) or (19), and the internal inductance is expressed as (13) or (24).

5. Current in the shield

The current value in the shield in comparison with the current in the phase conductor is given by the complex coefficient \underline{k}_i expressed by the formula (36). The relationship between the module and the argument of this coefficient and the parameter α is shown in Fig. 8 and 9.

The \underline{I}_e current in the shield, inside it, according to the Ampere law, does not produce any magnetic field, and outside of the shield a field with a tangential component is created [13, 14].

$$\underline{H}_{e\theta}^{ext} = \frac{\underline{I}_e}{2\pi r} \quad (41)$$

In such a situation the total magnetic field in the external area has a radial component determined by the formula [1]

$$\underline{H}_r^{ext}(r, \Theta) = -\frac{\underline{I}_1}{2\pi} \sum_{n=1}^{\infty} \left\{ \frac{1}{r} \left(\frac{d}{r} \right)^n - \left[\left(\frac{d}{R_4} \right)^n - \frac{R_4}{R_3} \left(\frac{d}{R_3} \right)^n \frac{s_n}{d_n} \right] \frac{R_4^n}{r^{n+1}} \right\} \sin n\Theta \quad (42)$$

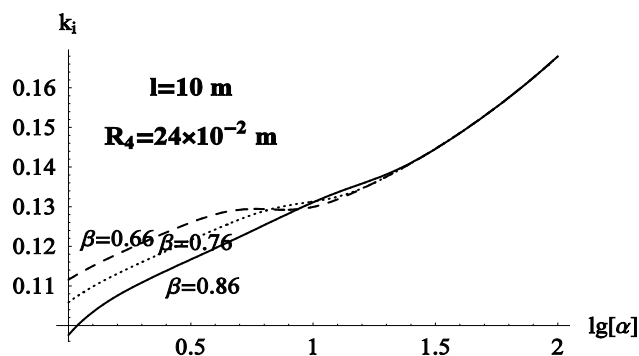


Fig. 8. Dependence of the coefficient k_i on the parameter α - module

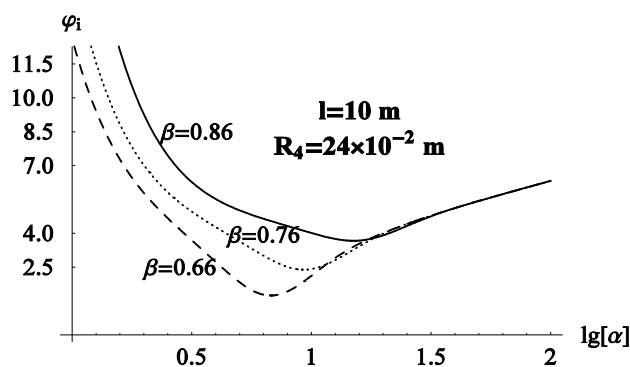


Fig. 9. Dependence of the coefficient k_i on the parameter α - argument

whereas the tangent component has the form

$$\begin{aligned}
 \underline{H}_{\theta}^{ext}(r, \Theta) &= \\
 &= \frac{I_1 + I_e}{2\pi r} + \frac{I_1}{2\pi} \sum_{n=1}^{\infty} \left\{ \frac{1}{r} \left(\frac{d}{r} \right)^n - \left[\left(\frac{d}{R_4} \right)^n - \frac{R_4}{R_3} \left(\frac{d}{R_3} \right)^n \frac{s_n}{d_n} \right] \frac{R_4^n}{r^{n+1}} \right\} \cos n\Theta = \quad (43) \\
 &= \frac{(1 - k_i) I_1}{2\pi r} + \frac{I_1}{2\pi} \sum_{n=1}^{\infty} \left\{ \frac{1}{r} \left(\frac{d}{r} \right)^n - \left[\left(\frac{d}{R_4} \right)^n - \frac{R_4}{R_3} \left(\frac{d}{R_3} \right)^n \frac{s_n}{d_n} \right] \frac{R_4^n}{r^{n+1}} \right\} \cos n\Theta
 \end{aligned}$$

The distribution of this field on the external area of the shield is presented in Fig. 10 and 11.

The magnetic field in the shield ($R_3 < r < R_4$) produced by the return current \underline{I}_e has a tangent component only. Due to the skin effect this component is determined by the formula [15, 16]

$$\underline{H}_{ee\Theta}(r) = \frac{\underline{I}_e}{2\pi R_4} \frac{K_1(\underline{\Gamma}_2 R_3) I_1(\underline{\Gamma}_2 r) - I_1(\underline{\Gamma}_2 R_3) K_1(\underline{\Gamma}_2 r)}{I_1(\underline{\Gamma}_2 R_4) K_1(\underline{\Gamma}_2 R_3) - I_1(\underline{\Gamma}_2 R_3) K_1(\underline{\Gamma}_2 R_4)} \quad (44)$$

Therefore, the total magnetic field in that area has the radial component determined by the formula [2, 9].

$$\underline{H}_{elr}(r, \Theta) = \frac{\underline{I}_1}{\pi R_3} \frac{1}{\underline{\Gamma}_2 r} \sum_{n=1}^{\infty} n \underline{g}_n(r) \sin n\Theta \quad (45)$$

where

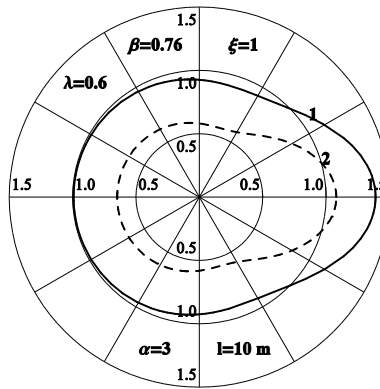


Fig. 10. The distribution of the relative value of the module of the total magnetic field in the external area: 1- not grounded shield, 2- grounded shield – non-coaxial arrangement

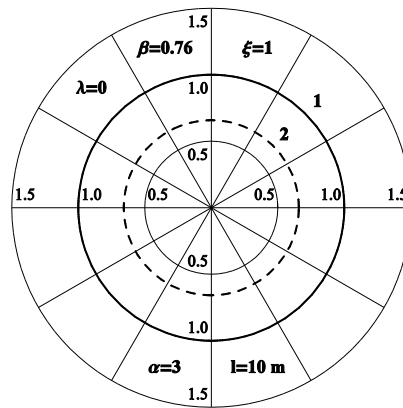


Fig. 11. The distribution of the relative value of the module of the total magnetic field in the external area: 1- not grounded shield, 2- grounded shield – coaxial arrangement

$$\underline{g}_n(r) = - \left(\frac{d}{R_3} \right)^n \frac{K_{n-1}(\underline{\Gamma}_2 R_4) I_n(\underline{\Gamma}_2 r) + I_{n-1}(\underline{\Gamma}_2 R_4) K_n(\underline{\Gamma}_2 r)}{\underline{d}_n} \quad (46)$$

and the tangent component

$$\underline{H}_{e1\theta}(r, \Theta) = \underline{H}_{e1\theta 0}(r) + \sum_{n=1}^{\infty} \underline{H}_{e1\theta n}(r, \Theta) \quad (47)$$

The first element of this sum ($n = 0$)

$$\underline{H}_{e1\theta 0}(r) = \frac{\underline{I}_1}{2\pi R_3} \frac{\underline{b}_0 I_1(\underline{\Gamma}_2 r) - \underline{c}_0 K_1(\underline{\Gamma}_2 r)}{\underline{d}_0} \quad (48)$$

where

$$\underline{b}_0 = \beta K_1(\underline{\Gamma}_2 R_3) - K_1(\underline{\Gamma}_2 R_4) \quad (49)$$

$$\underline{c}_0 = \beta I_1(\underline{\Gamma}_2 R_3) - I_1(\underline{\Gamma}_2 R_4) \quad (50)$$

and

$$\underline{d}_0 = I_1(\underline{\Gamma}_2 R_4) K_1(\underline{\Gamma}_2 R_3) - I_1(\underline{\Gamma}_2 R_3) K_1(\underline{\Gamma}_2 R_4) \quad (51)$$

The second element ($n \geq 1$)

$$\underline{H}_{e1\theta n}(r, \Theta) = \frac{\underline{I}_1}{\pi R_3} \frac{1}{\underline{\Gamma}_2 r} f_n(r) \cos n\Theta \quad (52)$$

where

$$f_n(r) = \left(\frac{d}{R_3} \right)^n \frac{1}{\underline{d}_n} \left\{ K_{n-1}(\underline{\Gamma}_2 R_4) [n I_n(\underline{\Gamma}_2 r) - \underline{\Gamma}_2 r I_{n-1}(\underline{\Gamma}_2 r)] + \right. \\ \left. + I_{n-1}(\underline{\Gamma}_2 R_4) [n K_n(\underline{\Gamma}_2 r) + \underline{\Gamma}_2 r K_{n-1}(\underline{\Gamma}_2 r)] \right\} \quad (53)$$

The component $\underline{H}_{e1\theta 0}(r)$ has to be complemented with the formula (9). Then we have, that

$$\underline{H}_{e1\theta 0}(r) = \frac{(1-k_i) \underline{I}_1}{2\pi R_3} \frac{\underline{b}_0 I_1(\underline{\Gamma}_2 r) - \underline{c}_0 K_1(\underline{\Gamma}_2 r)}{\underline{d}_0} \quad (54)$$

The distribution of the magnetic field in the grounded shield is presented in Fig. 12 and 13.

The substantial reduction of the magnetic field value in the external area can be obtained by increasing the level of the return current \underline{I}_e in the shield by shorting the guards (e.g. in case of a double wire line) or by steel structures enclosing the high-current busduct. This is illustrated in Fig. 14 and 15.

The distribution of the magnetic field on the external surface of the shield with this type of shorting is presented in Fig. 16.

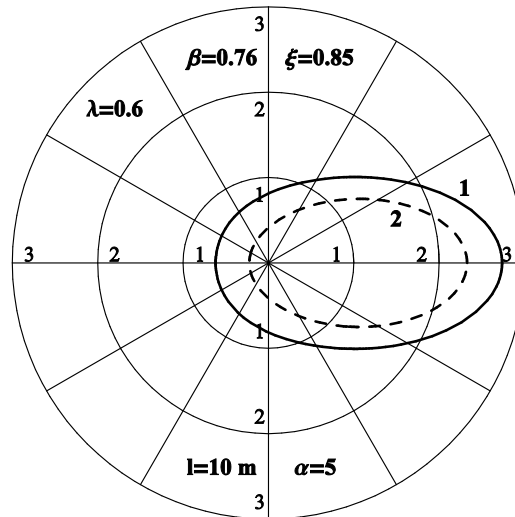


Fig. 12. The distribution of the relative module of the total magnetic field in the shield:
 1 – non-grounded, 2 – grounded; non-coaxial arrangement

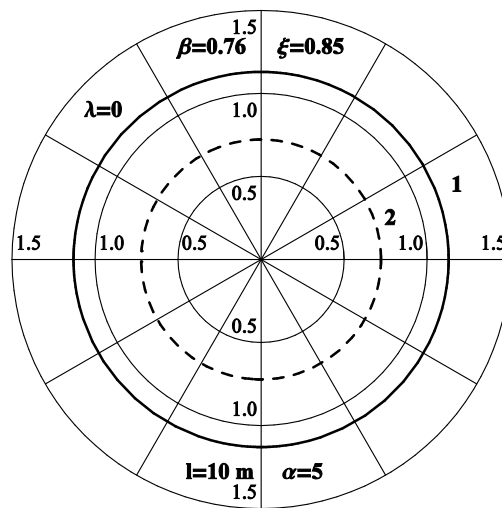


Fig. 13. The distribution of the relative module of the total magnetic field in the shield:
 1 – non-grounded, 2 – grounded; coaxial arrangement

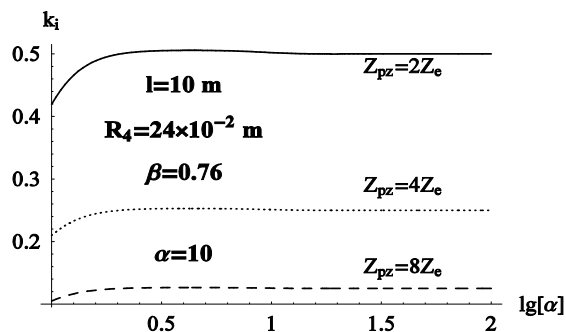


Fig. 14. Dependence of the coefficient k_i on the parameter α for different values of the earth fault loop impedance- for the module

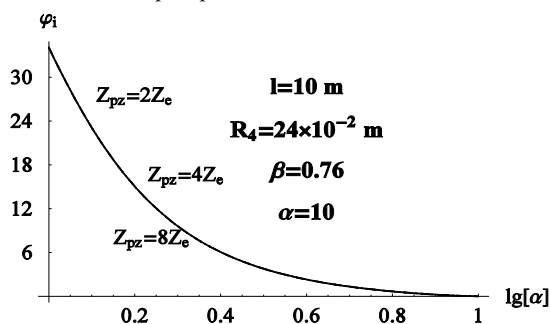


Fig. 15. Dependence of the coefficient k_i on the parameter α for different values of the earth fault loop impedance- for the argument

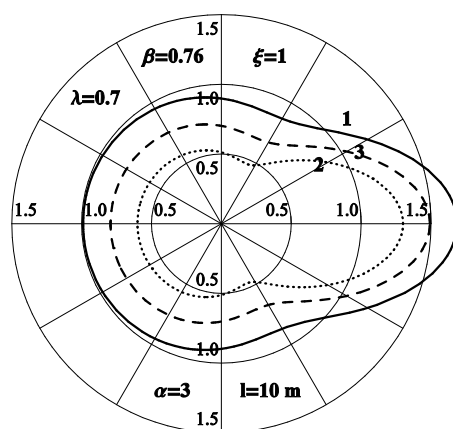


Fig. 16. The distribution of the relative module of the total magnetic field in the external area of the shield: 1 – insulated, 2 – shortened with the impedance $Z_{pz} = 2Z_e$, 3 – shortened with the impedance $Z_{pz} = 4Z_e$

6. Conclusions

The Fig. 3, 4 and 5 show that the skin effect brings on first of all a substantial change of the self-resistance of the shield. This phenomenon, as depended on the conductivity, the transverse dimensions of the screen, including the thickness of its walls, should be taken into account when determining the self-impedance of the screen, even for the industrial frequency.

The Fig. 6 and 7 shows that the share of the real part of the mutual impedance in the total module of this impedance is insignificant, and it does not exceed 0.2% for $\alpha \cong 100$. The variations of the mutual inductance do not exceed 0.2% of the mutual inductance determined from the formula (32).

For the high-current busducts constructed in practice the value of the parameter α of the guard is within the limits from 10 to 20. Therefore, it results from the Fig. 8 and 9 that for a grounded guard the module of the return current constitutes 12 up to 14% of the phase current module. It means that the magnetic field in the external area of the shield will be also reduced to the same degree. This also proves that in practise the magnetic field in this area may reach great values despite the guard is grounded.

The Fig. 14 and 15 indicates that the return current module, as the parameter α increases, stabilizes and it reaches the maximum value equal to about 50% of the phase current module at the fault loop impedance amounting to the double value of the self-impedance of the shield. The argument of this current does not depend on the fault impedance, and then it approaches the phase current argument with opposite sign, i.e. the \underline{I}_e current is in the opposite phase in comparison with the phase current.

The Fig. 16 shows that the full reduction of the magnetic field in the external area of the shield is not possible by its short-circuiting. The full reduction is possible for the case when $\underline{I}_e = -\underline{I}_1$ only, i.e. for a bifilar line.

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